Technical Overview on the AC-DC Thermal Transfer Standards

M. M. Halawa

National Institute for Standards (NIS), Tersa St., El-Haram, Giza, Egypt
(E-mail: mamdouh_halawa@yahoo.com)

Abstract

Recent improvements in commercial ac instruments have led to worldwide activities in the field of basic standards for AC-DC transfer measurements using the thermal converter. Thermal converters are the most accurate devices used by National Metrology Institutes (NMIs) for the transfer of AC voltage and current to equivalent DC quantities. The current developments in this domain are discussed in this article. The results obtained with the recently improved single junction and multijunction thermal converters experiment shows an agreement at the uncertainty level of l ppm. To improve the standards for the measurement of the AC-DC transfer difference in the range up to 100 MHz, many improved kinds of thermal converters has been developed to meet the need of accurate in the AC voltage/current domain. Thin-film or planar multijunction thermal converters, for example, are employed in the frequency range from 10 Hz up to 1 MHz with uncertainties between 1 µV/V to 13 µV/V. Improved standards have been developed for the mV-range, but also for the high-voltage ranges. At low frequencies the application of the D/A conversion technique for the transfer of dc to ac seems to be advantageous.

Detailed investigations were initiated to improve the standards. New measurement set-ups, mostly automated and new transconductance amplifiers, which allow driving both series-connected converters at earth-potential, have been developed. Single Junction Thermal Converters (SJTC) are widely used for ac-dc transfer because of their simple construction and easy availability. Thermoelectric effects such as Thomson and Peltier effects in the heater circuit have been identified as major sources for ac-dc transfer differences in the audio frequency range. All of these effects and facts are discussed in this article.

Index Terms: Electrical measurements; thermal voltage converter; Single junction thermal converters, multijunction thermal converter; thin film multijunction thermal converter; electrical simulation; uncertainty analysis

Historical Background

In Metrology domain, the primary electrical standards are those of voltage and current which are defined in terms of the Josephson Effect and the quantum Hall effect. The DC voltage standards are established using a Josephson voltage standard with uncertainty better than 10^{-7}. This conventional value of the Josephson accuracy used as the starting point of electrical calibrations is fixed by international agreement. On the other hand, it is necessary to provide a means of maintaining the traceability chain when AC measurements are required. This is usually done by a thermal technique although non thermal methods are also used. In order to determine AC quantities in terms of these units accurately, it is necessary to transfer AC to DC, hence the importance of the AC-DC transfer standard.

Simply, the AC-DC transfer standard is one of the basic electrical standards, by which the AC voltage and AC current are deduced from their DC counterparts in the frequency range between 10 Hz and 1 MHz. AC-DC transfer standards are then required for this purpose, and are fundamental to the electrical system of measurements. The operating principle of the thermal AC-DC transfer standards is based on Joule heating, to convert electrical energy of an AC waveform into heat, which leads to an increase in temperature which can be detected thermoelectrically. The converted AC voltage can be compared with the voltage produced when the same device is operated with DC excitation. Thus the rms quantity is related to the DC quantity and the technique is commonly referred to ac AC-DC transfer measurement. Thermal converters arte widely used in both national and industrial laboratories as the basis for AC-DC transfer.

The use of thermal devices for accurate AC-DC transfer measurements was introduced in 1952 when Hermach [1] reported on the use of single-junction thermal converters (SJTCs). During the sixties and seventies, the sources of AC-DC transfer differences (correction factors of the thermal converters) in single-junction thermal converters were extensively investigated. The uncertainty in this domain may be reduced to some parts in 10^6 in the audio-frequency range [2]. The second development, which was realized during the seventies and eighties, is the three-dimensional multijunction thermal converter (MJTC), which allowed the ac-dc transfer difference to be reduced below 10^{-6} for audio-frequencies [3].

At the end of the eighties, the development of the thin-film techniques and the silicon micromechanics enabled the NMI of Germany (PTB) [4] to fabricate the thin-film or planar multijunction thermal converter (PMJTC). The thin-film and photolithographic techniques permit the device to be optimized by thermal modeling [5, 6], thus providing sensitives of up to 16 V/Watt in air and up to 120 V/Watt in the vacuum, and ac-dc transfer difference below 1 µV/V up to 100 kHz. Above all, the initial thin-film devices suffered from a large ac-dc difference at low frequencies, which was due principally to non-linearities in the heater-thermocouple system. This error was explained by Laiz [7], who provided a reduction of the ac-dc difference at low frequencies, including the deposition of Ni resistor connected in parallel with the output voltage.

Recently, there have been two strong impulses in the field of basic standards for ac-dc transfer. The first has been the development of a new generation of commercial AC instruments with improved stability and uncertainty in the traditional voltage range from 1 V to 1000 V, and in the current range from 5 mA to 20 A [8]. These have also included low voltage measurement capabilities in the mV-range up to the highest frequency of I MHz, and in the low frequency area down to 1 MHz. The second is the IS0 9000 standard, which demands traceability to national standards of standards used in calibration work. These two points led worldwide to activities in the national laboratories which aimed at providing traceability in the whole measurement field with adequate uncertainties.

For many decades the uncertainty of the thermal converters in the national laboratories was several orders of magnitude lower than that of commercial instruments, and the voltage and current ranges covered by thermal converters with range resistors and shunts were sufficient for industry. Modem instruments demand improvements in this traditional range but also require extension of the voltage, current and frequency ranges. Current developments in the different areas are discussed in the following paragraphs. A comprehensive report on the status quo of ac-dc transfer standards was given by Inglis in 1992 including a complete list of publications of this field [9].

According to the definition of the AC signal (Section 1) it is possible to compare the AC voltage with the DC by way of the electrical power. In the thermal method, DC and AC voltage are alternately applied to the heater of a thermal converter. Then the amounts of joule heating are compared by measuring the temperature of the heater by a thermocouple. When DC and AC voltage of equal power are applied to the input of an ideal thermal converter, output electro motive forces (EMFs) should be the same for both of the inputs. However, in the case of an actual thermal converter, the outputs EMFs are influenced by the effect of non-joule heating and frequency characteristic of heater circuit. The “ac-dc transfer difference” (or the correction factor) is the principal quantity in the ac-dc transfer standard. In the last few years, the source of these correction factors (or transfer differences) of the thermal converters has been the subject of through investigations. This article focuses on these sources and the technical methods for determining the transfer differences for the single-junction thermal converters.

Preliminaries

Electrical Measurements

Measurements of the many quantities by which the behavior of electricity is characterized. Measurements of electrical quantities extend over a wide dynamic range and frequencies ranging from 0 to 10^{12} Hz [10]. The International System of Units (SI) is in universal use for all electrical measurements. Electrical measurements are ultimately based on comparisons with realizations, that is, reference standards, of the various SI units. These reference standards are maintained by the national standards laboratories of many countries.

Direct-current (dc) measurements include measurements of resistance, voltage, and current in circuits in which a steady current is maintained. Resistance is defined as the ratio of voltage to current. For many conductors this ratio is nearly constant, but depends to a varying extent on temperature, voltage, and other environmental conditions. The best standard resistors are made from wires of special alloys chosen for low dependence on temperature and for stability.

The SI unit of resistance, the ohm, is realized by means of a quantized Hall resistance standard. This is based upon the value of the ratio of fundamental constants h/e^2, where h is Planck's constant and e is the charge of the electron, and does not vary with time.

The principal instruments for accurate resistance measurement are bridges derived from the basic four-arm Wheatstone bridge, and resistance boxes. Many multirange digital electronic instruments measure resistance potentiometrically, that is, by measuring the voltage drop across the terminals to which the resistor is connected when a known current is passed through them. The current is then defined by the voltage drop across an internal reference resistor. For high values of resistance, above a megohm, an alternative technique is to measure the integrated current into a capacitor (over a suitably defined time interval) by measuring the final capacitor voltage. Both methods are capable of considerable refinement and extension.

The SI unit of voltage, the volt, is realized by using arrays of Josephson junctions. This standard is based on frequency and the ratio of fundamental constants *e/h*, so the accuracy is limited by the measurement of frequency. Josephson arrays can produce voltages between 200 µV and 10 V. At the highest levels of accuracy, higher voltages are measured potentiometrically, by using a null detector to compare the measured voltage against the voltage drop across a tapping of a resistive divider, which is standardized (in principle) against a standard cell.

The Zener diode reference standard is the basis for most commercial voltage measuring instruments, voltage standards, and voltage calibrators. The relative insensitivity to vibration and other environmental and transportation effects makes the diodes particularly useful as transfer standards. Under favorable conditions these devices are stable to a few parts per million per year.

Most DC digital voltmeters, which are the instruments in widest use for voltage measurement, are essentially analog-to-digital converters which are standardized by reference to their built-in reference diodes. The basic range in most digital voltmeters is between 1 and 10 V, near the reference voltage. Other ranges are provided by means of resistive dividers, or amplifiers in which gain is stabilized by feedback resistance ratios. In this way these instruments provide measurements over the approximate range from 10 nanovolts to 10 kV.

The most accurate measurements of direct currents less than about 1 A are made by measuring the voltage across the potential terminals of a resistor when the current is passed through it. Higher currents, up to about 50 kA, are best measured by means of a DC current comparator, which accurately provides the ratio of the high current to a much lower one which is measured as above. At lower accuracies, resistive shunts may be used up to about 5000 A, but the effective calibration of such shunts is a difficult process.

Alternating-current (AC) voltages are established with reference to the DC voltage standards by the use of thermal converters (Section 2). These are small devices, usually in an evacuated glass envelope, in which the temperature rise of a small heater is compared by means of a thermocouple when the heater is operated sequentially by an alternating voltage and by a reference (DC) voltage. Resistors, which have been independently established to be free from variation with frequency, permit direct measurement of power frequency voltages up to about 1 kV. Greater accuracy is provided by multijunction (thermocouple) thermal converters, although these are much more difficult and expensive to make. Improvements in digital electronics have led to alternative approaches to ac measurement. For example, a line frequency waveform may be analyzed by using fast sample-and-hold circuits and, in principle, be calibrated relative to a DC reference standard. Also, electronic root-mean-square detectors may now be used instead of thermal converters as the basis of measuring instruments.

Voltages above a few hundred volts are usually measured by means of a voltage transformer, which is an accurately wound transformer operating under lightly loaded conditions. The principal instrument for the comparison and generation of variable alternating voltages below about 1 kV is the inductive voltage divider, a very accurate and stable device. They are widely used as the variable elements in bridges or measurement systems.

Alternating currents of less than a few amperes are measured by the voltage drop across a resistor, whose phase angle has been established as adequately small by bridge methods. Higher currents are usually measured through the use of current transformers, which are carefully constructed (often toroidal) transformers operating under near-short-circuited conditions. The performance of a current transformer is established by calibration against an ac current comparator, which establishes precise current ratios by the injection of compensating currents to give an exact flux balance.

Commercial instruments for measurement of AC quantities are usually DC measuring instruments, giving a reading of the voltage obtained from some form of ac-dc transducer. This may be a thermal converter, or a series of diodes arranged to have a square-law response, in which case the indication is substantially the root-mean-square value. Some lower-grade instruments measure the value of the rectified signal, which is usually more nearly related to the peak value.

There has been a noticeable trend toward the use of automated measurement systems for electrical measurements, facilitated by the readiness with which modern digital electronic instruments may be interfaced with computers. Many of these instruments have built-in microprocessors, which improve their convenience in use, accuracy, and reliability. For power measurements

SI units

From the (mksa) system the present-day SI (Système Internationale), formally adopted in 1954, has developed, by the addition of further base units to include other fields of measurement. The seven base units of SI are the kilogram (kg; mass); second (s; time); meter (m; length); ampere (A; electric current); kelvin (K; thermodynamic temperature); candela (cd; luminous intensity); and mole (m; amount of substance). The units of other physical quantities (derived units) are derived from the base units by simple numerical relations [10].

The SI base unit for electrical measurements is the ampere (A), the unit of electric current. It is defined in terms of a hypothetical experiment as that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

The volt (V) is the unit of potential difference and of electromotive force. It is defined as the potential difference between two points of a conducting wire carrying a constant current of 1 ampere when the power dissipated between these points is equal to 1 watt. From the ampere and the volt, the ohm is derived by Ohm's law, and the other derived quantities follow in a similar manner by the application of known physical laws [10].

Electrical Units

The process of measurement consists in finding out how many times the quantity to be measured contains a fixed quantity of the same kind, called a unit. The definitions of the units often involve complex physical theory and do not lend themselves readily to practical realization. The concrete representations of units are known as measurement standards. In practice, measurements are made by using an instrument calibrated against a local reference standard, which itself has been calibrated either directly or by several links in a traceability chain against the national standard held by the national standards laboratory.

A proposal by W. E. Weber in 1851 led to the absolute (cgs) system in which all units of quantities to be measured could be derived from the base units of length, mass, and time—the centimeter, gram, and second [10]. This system was widely adopted although it had three weaknesses: the size of the units was inconvenient for practical use; it was difficult to realize the units from their definitions; and there were separate sets of units for electrostatic and electromagnetic quantities, based respectively on the inverse-square laws of force between electric charges and between magnetic poles.

Realization of the values of the electrical and other units from their SI definitions involves great experimental difficulties. For this reason, it is customary for national standards laboratories to maintain stable primary standards of the units against which other reference standards can be compared. From time to time, absolute determinations of the values of these primary standards are made in terms of their definitions. By the late 1980s, the Josephson Effect and the quantum Hall effect had made possible the standardization of the volt and the ohm by relation to fundamental physical constants. The recommendation by the CCE of the values to be adopted for these constants in 1990 led to a complete change in primary electrical standards and the method of handling them; and all the major national laboratories, and the BIPM, now use this method.

For many years the primary standards maintained by most laboratories were the volt, in terms of the mean electromotive force of a group of Weston cells, and the ohm, using a group of standard resistors. A range of reference standards of other quantities are derived from these, including direct-current (DC) voltage and resistance at a variety of levels; alternating-current (AC) voltage, resistance, and power; capacitance and inductance; radio-frequency (rf) and microwave quantities; magnetic quantities and properties of materials; dielectric properties; and other quantities. These secondary standards are used for day-to-day measurements and for the calibration of local reference standards of other users in the national measurement system.

Definition of rms Value

The root mean square (rms) value is an important parameter for the description of an AC variable, since it is an amplitude characteristic which is independent of the waveform [11]. It is defined as:

$$V_{rms} = \sqrt{\frac{1}{t_0}\int_0^{t_0} V^2(t)\,dt} \tag{1}$$

where V_{rms} denotes the rms value, $V(t)$ the time-dependent signal and t_0 the averaging time which for a periodic signal is equal to its period T [12]. This definition is related to the traditional rms measurement method, measuring the temperature increase in a resistor which is heated by application of a signal of unknown rms value to its terminals, producing the same time-averaged heating power in the resistor as the DC signal.

Traceability of AC Measurements

As mentioned before, one of the seven base units in the IS is the Ampere. The Ampere is maintained and disseminated in terms of the SI units of voltage and resistance. Achievements of quantum mechanics have enabled the construction of voltage and resistance standards based on the Josephson Effect and the quantum Hall effect, respectively. A methodology for proceeding in such cases is shown in Fig. 1.

The unit of DC voltage is reproduced by means of the Josephson Effect with reproducibility of the order of 10^{-10} [13]. The quantum-related realizations of the resistance, based on the Quantum Hall effect, enable an uncertainty of the order of 10^{-8} to be reached [14]. In practice, units for the electrical quantities of current, power and energy are derived from the volt and the ohm. The AC-DC transfer is a secondary standard which enables realization of the rms measures for AC voltage, current and power on the basis of their DC units.

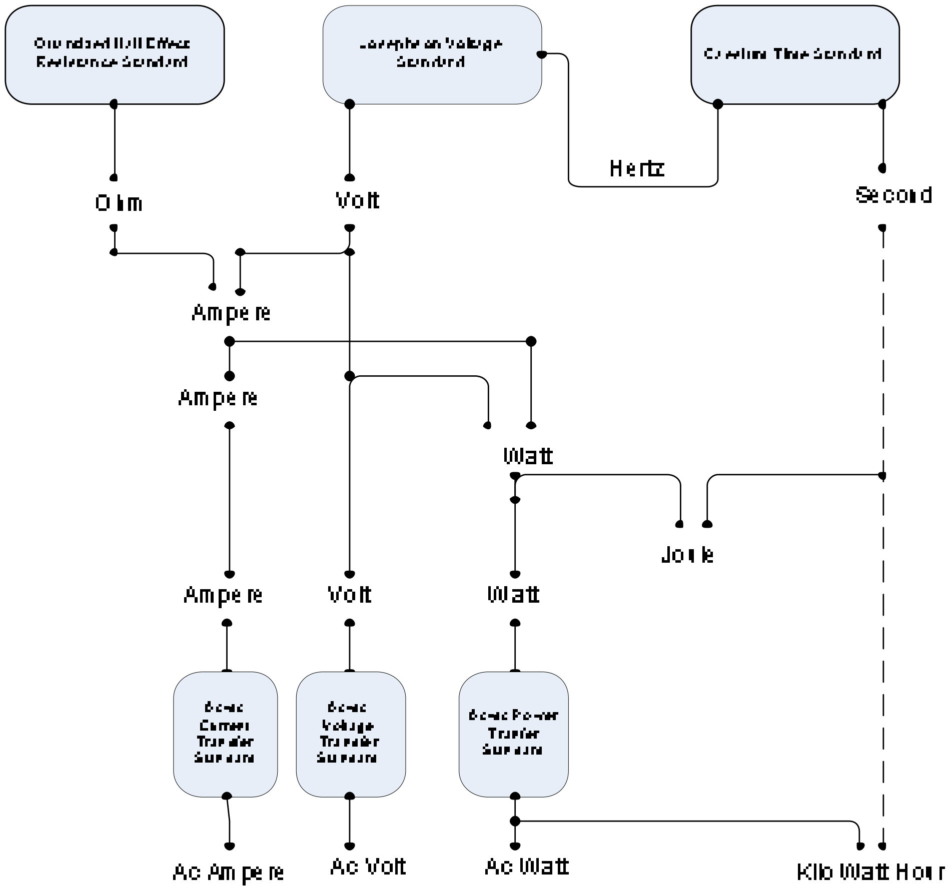


Fig. 1: Derivation of Electric Quantities in Terms of the SI Units

Thermal Converters (TCs)

Introduction

Thermal converters (TCs) are used for true root mean square (r.m.s.) voltage and AC signal measurements [15-16]. The basic measurement principle of thermal converters is to convert the electrical signal to a heat power and measure the dissipated power as the temperature elevation of a (micromachined) structure with a temperature sensor. This technique allows the true r.m.s. measurement of the signal, independent of the signal waveform. Those converters are the most widely used form of primary AC-DC transfer standards and provide the most accurate link between AC and DC voltage and current.

Basically, the ac voltage standard in the frequency range 10 Hz to 1 MHz are derived from the dc voltage standard by the following two methods, as illustrated in figure 2.

(a) Direct synthesizing of ac (sine) waveform by the use of high-precision Digital/Analog (D/A) converter.

(b) Comparison of electric power between ac and dc voltage by converting the power to force or heat.

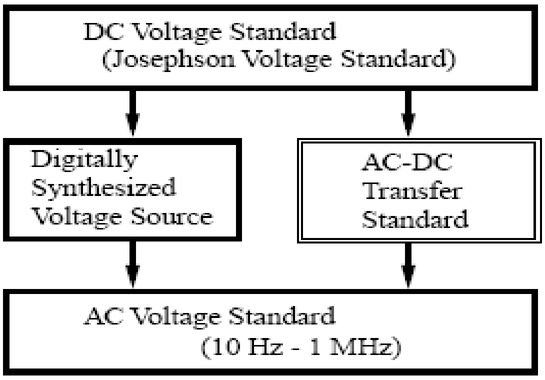


Figure 2: Two methods to derive ac voltage standard in the frequency range 10 Hz to 1 MHz

In the latter case, converters may be recognized as a reference standard, and the system of the standard based on this principle is called the "ac-dc transfer standard". The most accurate ac-dc transfer standards are realized by the use of "thermal converters". The thermal converter is capable of comparing the joule heating between ac and dc modes at 0.1 ppm level, and is widely employed as the primary standard in the most of the national standard laboratories [15].

As shown in figure 3, the thermal converters were developed in the 1950s and are still widely used in the field of ac-dc transfer standards [16]. Four types of thermal converters have been developed as ac-dc transfer standards, that is, Single-Junction thermal converters (SJTCs), Multijunction thermal converters (MJTC), thin-film (planar) MJTC, and semiconductor rms sensors. The detailed descriptions on the four types of the thermal converters are given in the following section.

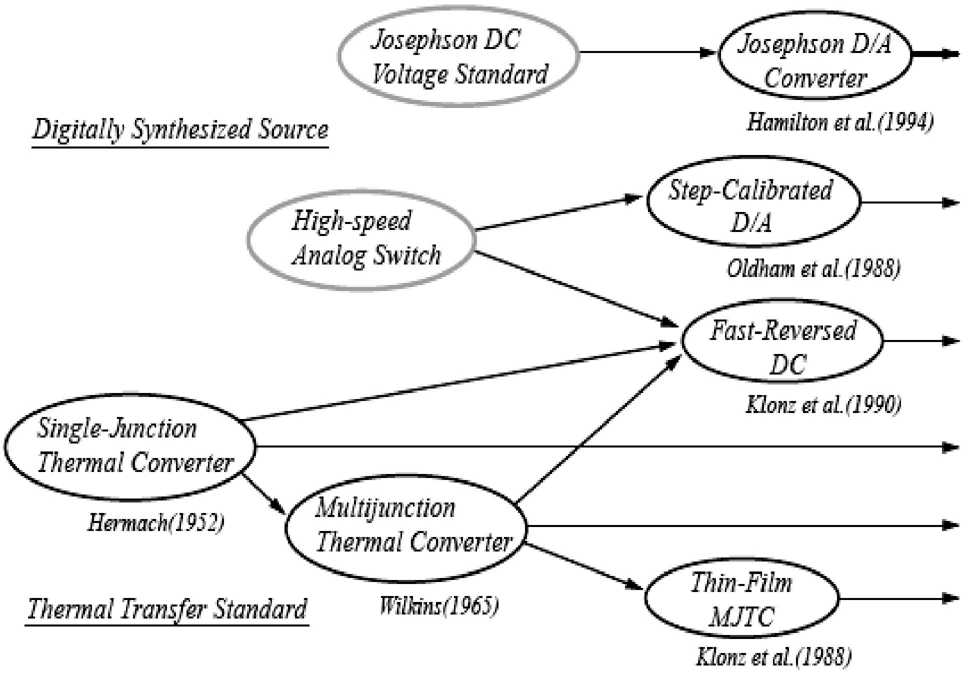


Fig. 3: Schematic diagram for illustrating the historical relationship between various methods developed for the realization of ac voltage/current standards.

Common Types of Thermal Converters

Single Junction Thermal Converter (SJTC)

Single-Junction Thermal Converters (SJTCs) were developed in the 1950s [15]. The SJTVCs are used for true root mean square (r.m.s.) voltage and AC signal measurements. The basic measurement principle of thermal converters is to convert the electrical signal to a heat power and measure the dissipated power as the temperature elevation of a (micromachined) structure with a temperature sensor. This technique allows the true r.m.s. measurement of the signal, independent of the signal waveform. The structure of a typical SJTC element is shown in Fig. 4. A thin filament-heater and a thermocouple are enclosed in an evacuated glass bulb. The thermocouple junction is in thermal contact with the heater at the midpoint of the heater, but is electrically insulated from it by a bead of glass or ceramic.

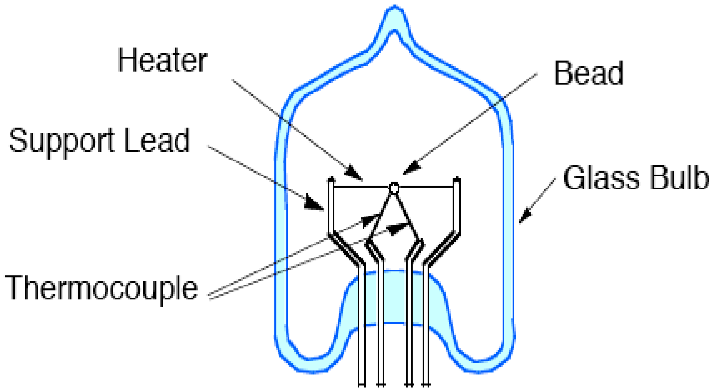


Fig. 4: Structure of Single-Junction Thermal Converter

In general, the SJTCs have one thermocouple fixed to the heater wire, have outputs of 7 mV to 12 mV for full scale input, and respond in a roughly square-law manner to changes in the input signal. These are found in a wide range of commercial instruments and are useful from about 10 Hz to several hundred megahertz. The best uncertainty for these devices, exclusive of the measurement process and any range or shunt resistors, is a few microvolts-per-volt (µV/V) or better at audio frequency and full-scale input. The uncertainty increases at the extremes of the frequency range and at input levels below about half of full scale.

For instance, the 1394 Holt series of Thermal Voltage Converters (Fig. 5) offer a high precision, coaxial configuration, inside a sturdy cylindrical, highly polished enclosure of nickel plated brass. These units, specifically for making ac voltage measurements using AC-DC transfer techniques, offer a fully shielded case with a highly polished reflective outer coating offering excellent isolation from thermal gradients. These units offer exceptionally flat frequency response from DC to 100 MHz and nearly constant input impedance.

Fig. 5: A 1394 Holt series of Thermal Voltage Converter

The voltage ranges of this type are listed in the following tables:

Table 1: Voltage and frequency ranges of the 1394 Holt TVC

Model	Usable Voltage Range	Frequency Range
1394A-0.25	0.1 to 0.25V	5 to 30 MHz
1394A-0.5	.16 to .67 V	dc, 10 to 100 MHz
1394A-1	.32 to 1.33 V	dc, 10 to 100 MHz
1394A-2	.63 to 2.66 V	dc, 10 to 100 MHz
1394A-3	.95 to 3.99 V	dc, 10 to 100 MHz
1394A-5	1.58 to 6.65 V	dc, 10 to 100 MHz
1394A-10	3.16 to 13.3 V	dc, 10 to 100 MHz
1394A-20	6.32 to 26.6 V	dc, 10 to 100 MHz
1394A-50	16 to 66.5 V	dc, 10 to 30 MHz

Frequency response is calibrated with a standard converter traceable to NIST. Voltages are measured at a point equivalent to the center of a Type 874 Tee connected to the converter

Table 2: Uncertainty calculations of the 1394 Holt TVC

Frequency	Uncertainty of Correction Factor	Ref. Standard Uncertainty*
10 to 20 Hz	± 0.0160%	± 0.013%
20 to 20 kHz	± 0.0025%	± 0.0017%
20 k to 50 kHz	± 0.0040%	± 0.003%
50 k to 100 kHz	± 0.0065%	± 0.005%
100 M to 1 MHz	± 0.0095%	± 0.008%
1 M to 10 MHz	± 0.1%	± 0.1%
10 M to 30 MHz	± 0.2%	±0.2%
30 M to 100 MHz	± 1.0%	± 1%

The Thermoelement (T.E) of this type (Fig. 6) is common used in the most different types of SJTVCa. The following are the main technical data of this type:

- Nominal Heater Current: 5 mA rms, Max.
- Heater Current: 7.5 mA rms
- Couple Output: 7 mV ± 12% at nominal heater current.
- Couple Resistance: 8 W ± 20%.
- Maximum DC Reversal Error: ± 0.04%
- Couple Output Voltage to Heater (ground): ± 50 V (dc + ac pk-pk) max.

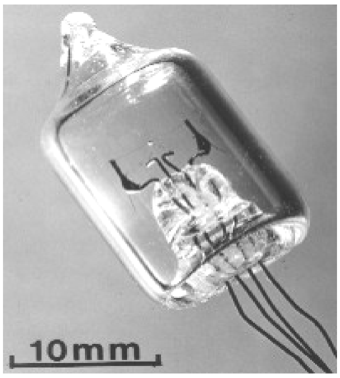


Fig. 6: Thermoelement of the SJTVC

Present commercially available ac-dc thermal transfer standards1 are commonly based on either single-junction thermal converters (SJTCs) or solid-state transfer standards [17]. The SJTCs have one thermocouple fixed to the heater wire, have outputs of 7 mV to 12 mV for full scale input, and respond in a roughly square-law manner to changes in the input signal. These are found in a wide range of commercial instruments and are useful from about 10 Hz to several hundred megahertz. The best uncertainty for these devices, exclusive of the measurement process and any range or shunt resistors, is a few microvolts-per-volt (µV/V) or better at audio frequency and full-scale input. The uncertainty increases at the extremes of the frequency range and at input levels below about half of full scale.

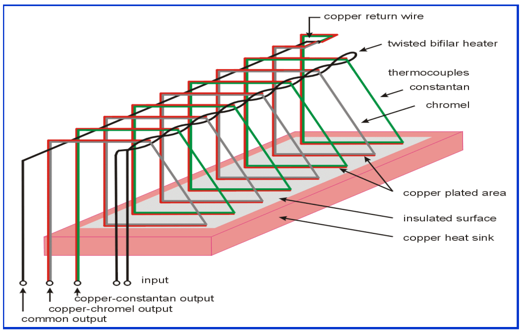
As a class, coaxial thermal voltage converters consist of thermoelements mounted coaxially with range resistors to make a single voltage range. The TE and resistor may or may not be mounted in the same enclosure. For low-frequency measurements (up to 100 kHz), the coaxial TVC is generally comprised of one or more TEs and several resistors in separate enclosures; different voltage ranges are formed from various combinations of TEs and resistors. These devices are used from about 0.5 V up to 1000 V at frequencies up to 1 MHz. High-frequency coaxial TVCs are comprised of a TE and resistor in the same enclosure. These devices are generally used from 0.5 V to 100 V, and at frequencies up to 1 GHz [18].

As a different methodology, the Solid-state thermal transfer standards have thermal converters based on transistor sensors and respond linearly to the input signal. The model most often calibrated at NIST, the Fluke Corporation 792A, has an output of 2 V for full-scale input, and is specified at frequencies from 10 Hz to 1 MHz for voltages from 2 mV to 1000. The uncertainties of this instrument are comparable to or better than those of SJTCs at audio frequency, but, owing to the extremely short time constant of the thermal sensor, it is degraded at frequencies below about 40 Hz.

Multi Junction Thermal Converter (MJTC)

The Multijunction Thermal Converters (MJTC) are developed in 1970s to 1980s [12-15]. The MJTCs are still widely used in the national standard laboratories as the most reliable basis for the AC-DC transfer standard. These types of thermal converters are designed to reduce the thermoelectric effect, which is the main cause of ac-dc difference around 1 kHz. For instance, the construction of a Wilkins-type MJTC [13] developed at Physikalisch Technische Bundesanstalt (PTB: Germany) is shown in figure 7. The MJTC employs many numbers of thermocouples along the heater for the purpose of producing uniform temperature distribution in the heater. The twisted bifilar heater is used for the purpose of compensating the first-order thermoelectric effects.

In the case of PTB-design MJTC, the series-connected Cu-Cu Ni thermocouples are produced by puttering copper to half-circumference of the rectangular oil made of thin Cu Ni wire. Owing to the uniform temperature distribution, the thermoelectric effects along the heater are reduced, and the AC-DC difference better than 0.1 ppm is obtained. The output emf is also increased to 100 mV level due to the increased number of thermocouples. The disadvantages of the MJTC originate from its complex structure. The MJTCs have larger frequency dependence, weakness to electrostatic breakdown, and difficulty in mass-production.



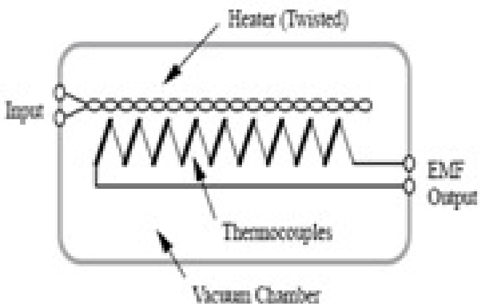


Fig. 7: Construction of a Wilkins-type MJTC.
Use of many numbers of thermocouples and the twisted bifiler heater
is for compensating the thermoelectric effects.

A through design, optimization of the materials to be used and construction under carefully controlled conditions led to in the three-dimensional MJTC of the PTB [19]. The basic design of the PTB's 3d-MJTC can be seen in Fig. 8. The bifilar construction of the heater and the periodic structure of the thermocouple significantly reduce the Thomson effect. The distance between the first thermocouple and the connection between heater and intermediate leads was optimized to reduce the effect of the temperature gradient at the two heater ends. Both ends of the heater are thermally short-circuited by an Al_2 O_3 bead and attached to a copper post to reduce the Peltier effect.

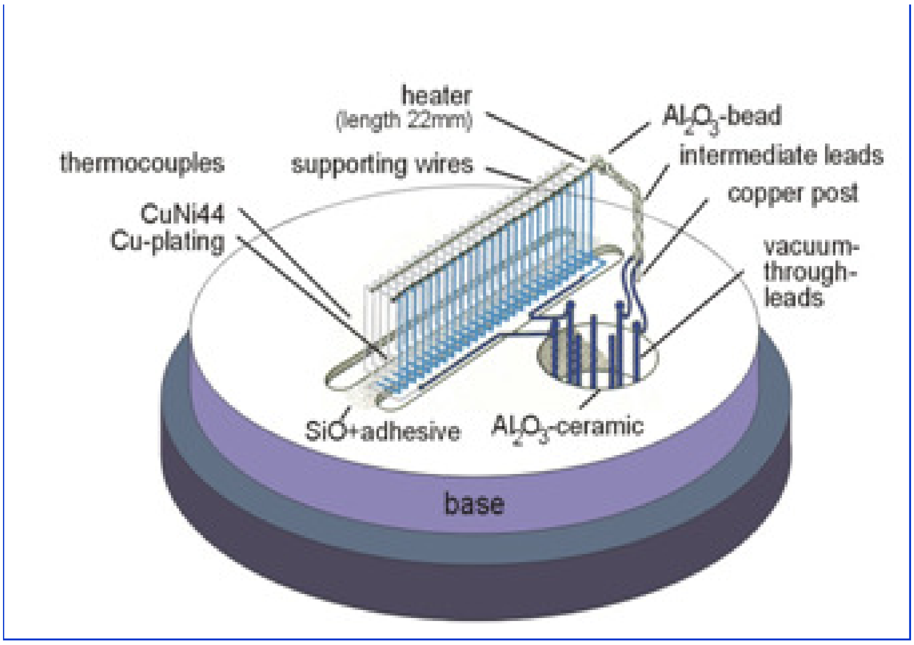


Fig. 8: "3d-MJTC of PTB"

The heater resistance and the number of thermocouples were optimized to reduce both the low-and the high-frequency transfer differences. A modified design was realized to provide an output voltage proportional to the square of the heater current [20]. Klonz [21 , 22] carried out a detailed measurement of all transfer difference sources leading to an estimated AC-DC difference of less than

0.1 µV/V. Moreover, the frequency transfer difference was evaluated with uncertainties of less than 0.5 µV/V up to 100 kHz and 10 µV/V up to 1 MHz. Unfortunately, these devices are difficult to fabricate and, thus, costly.

Thin-Film Multijunction Thermal Converters

New thin-film designs of the MJTC are going now to be used widely in the world. Modern fabrication technology using thin-film heaters and thermocouples on a thin dielectric membrane (Fig. 9) offers very low thermal conductance and therefore high responsivity of the device. The nearly ideal periodic structure of the thermal element optimized by computer modeling and manufactured by a photolithographic process results in a constant temperature along the heater and negligibly small ac-dc transfer differences. The use of anisotropic etching and thin-film technology allows low-cost mass production [23, 24]. This type of MJTC has been realized by the advance in the technology of forming the thin-films using the isotropic etching. The advantage of the thin-film MJTC is that it is suitable to mass-production. The development of thinfilm MJTCs are one of the main subjects in the research of AC-DC transfer standard, and are expected to replace the conventional thermal converters in near future.

The planar MJTC offers the possibility of increased responsivity (defined as the ratio of output voltage to input power) of ac-dc transfer standards to be used in the mV-range. Table 3 gives an overview of the responsivity of different converter constructions. With the planar MJTC and Cu-Cu Ni thermocouples the responsivity has been doubled, even for use in air, and with Bismuth/Antimony thermocouples a factor of 6 in air and nearly 50 in vacuum compared to the three-dimensional MJTC has been accomplished. Such planar MJTC'~ will be used in PTB for ac-dc transfer down to the 10-mV level [25].

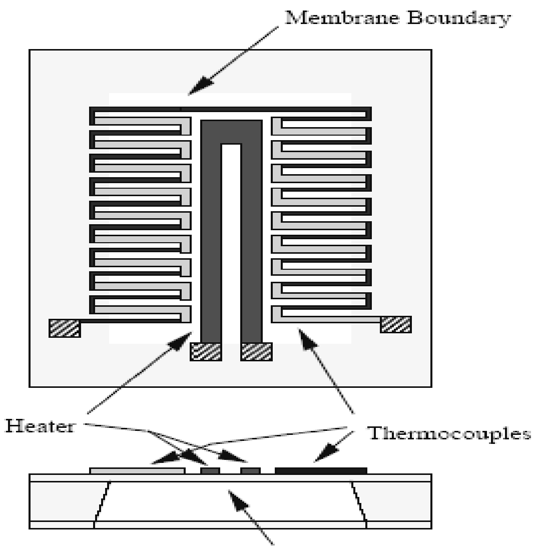


Fig. 9: Construction of a thin-film MJTC developed at PTB.
The heater and the hot-junctions of the thermocouples are formed on SiO_2 / Si_3N_4 sandwich membrane made with an isotropic etching.

Table 3: Responsivity of difference thermal converter designs

	SJTC vacuum	PTB-MJTC vacuum	PMJTC Cu–CuNi in air	PMJTC Bi–Sb in air	PMJTC Bi–Sb vacuum
Rated voltage in V	0.45	2.3	1.32	0.8	0.3
Heater resistance in Ω	90	180	90	90	90
Input power in mW	2.25	40	20	6.6	1
Output voltage in mV	7	100	100	100	100
Responsivity in V/W	3.1	2.5	5	15–17	105–120
Input voltage in V for 1 mV output	0.17	0.23	0.15	0.08	0.03
Heater resistance in Ω for an input voltage of 0,1 V and rated output voltage	4	0.34	0.5	1.5	10

AC-DC Differences of Thermal Converters

Definition

As stated before in Section 1.4, the ac voltage is defined by the root-mean square (rms) value of the sinusoidal waveform:

$$V_{AC}(rms) \equiv \sqrt{\frac{1}{T}\int_0^T \{V(t)\}^2 dt}$$

In accordance with this definition, it is possible to compare an ac voltage with a dc voltage by alternately applying them to the same heater in a thermal converter (TC) and measuring the temperature rise with a thermocouple. When dc and ac voltages that result in equal power output are applied to the input of an ideal thermal converter, the resultant EMFs are the same. In the case of an actual TC, however, the output EMFs is influenced by the effect of non-joule heating and the frequency dependent characteristics of the heater circuit.

The ac/dc transfer difference (or the correction factor of the TC) is the difference between the ac and the dc signals that are required to give the same output of the thermocouple. It is usually expressed as parts-per-million (ppm) of the total dc signal. The AC-DC transfer difference is conveniently defined by the following equation.

$$\delta_{AC-DC} \equiv \left. \frac{V_{AC} - V_{DC}}{V_{DC}} \right|_{E_{AC}=E_{DC}} \tag{2}$$

Related to the Fig. 10, the quantities E_{DC} and E_{AC} represent the output EMFs of the thermocouple when the dc voltage V_{DC} and the ac voltage V_{AC}, respectively, are applied to a thermal converter.

In the case of an ideal thermal converter ($\delta_{AC-DC} = 0$), we get the condition $E_{AC} = E_{DC}$ for the equal input voltage ($V_{DC} = V_{AC}$). While in the case of an actual thermal converter, the V_{AC} is adjusted by an amount $\delta_{AC\text{-}DC} \times V_{DC}$ with respect to V_{DC} in order to get the condition $E_{AC} = E_{DC}$. If larger ac-input voltage is required to produce the same EMF output for the dc voltage, the thermal converter has a positive ac-dc difference. (The ac-dc transfer difference $\delta_{AC\text{-}DC}$ is often abbreviated as "ac-dc difference or the correction factor").

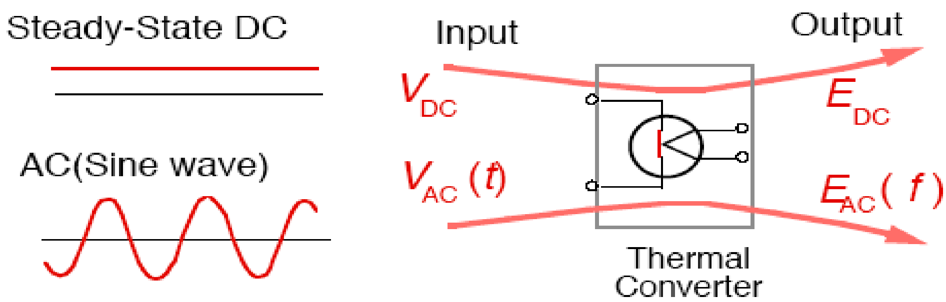


Fig. 10 Thermal converter for AC-DC transfer Standard

It is often more convenient to modify the definition of the ac-dc transfer difference (Eq. 2) such that the condition ($E_{AC} = E_{DC}$) is replaced by the input condition ($V_{DC} = V_{AC}$). Since the V_{AC} is very close to V_{DC}, the input-output characteristic of a thermal converter $E_{DC}(V_{DC})$, $E_{AC}(V_{AC})$ can be approximated by a linear function in the vicinity of the input voltage V_0;

$$E_{AC}(V_{AC}) \cong E_{AC}(V_0) + \frac{dE}{dV}(V_{AC} - V_0)$$
$$E_{DC}(V_{DC}) \cong E_{DC}(V_0) + \frac{dE}{dV}(V_{DC} - V_0) \qquad (3)$$

Using (3), the following equality is deduced:

$$\frac{E_{AC}(V_{AC}) - E_{DC}(V_{DC})}{n \cdot E_{DC}(V_{DC})} = \frac{E_{AC}(V_0) - E_{DC}(V_0)}{n \cdot E_{DC}(V_0)} + \frac{V_{AC} - V_{DC}}{V_{DC}}$$

$$\text{here, } n \equiv \left(\frac{dE}{E}\right) \Big/ \left(\frac{dV}{V}\right). \qquad (4)$$

The "normalized index" n is of the order of 2, which represents the square characteristic of input-output response function of thermal converters. From (2) and (4), we get the equation to calculate the ac-dc transfer difference from the output quantities:

$$\delta_{AC-DC} \cong \left. \frac{E_{AC} - E_{DC}}{n \cdot E_{DC}} \right|_{V_{AC}=V_{DC}} \tag{5}$$

In order to measure the ac-dc difference of a thermal converter with an accuracy of 1 ppm, the ac input voltage with a precision of better than 1 ppm is required. In a reversed way, if the ac-dc difference of a thermal converter is evaluated with a precision of 1 ppm, it is possible to measure the ac voltage with 1-ppm accuracy. Due to these circumstances, the ac-dc difference is recognized as the most important quantity in the ac voltage/current standard, and the term "ac-dc transfer standard" is frequently used as an equivalent term to the "ac voltage/current standard".

AC-DC Difference Measurement

The purpose of the AC-DC difference (comparison) measurement is to determine the relative difference in the AC-DC difference between two TVCs, usually specified as TC(X) and TC(S). The symbol "X" refers to the unit under test while the symbol "S" refers to the standard unit. For instance, the ET2001 ADS system, which has been designed by Nano-Electronics Research Institute / AIST, Japan, performs the AC-DC difference measurement based on the dual-channel method [26]. The schematic diagram of the dual channel method is shown in Fig. 11. In this method, the two nV-detectors measure the output EMF voltages of the two TVCs separately.

The EMF output of a TVC is approximately proportional to the square of the input voltage. The output-quantity X_{DC} and S_{DC} represent the EMF outputs from TVC(X) and TVC(S) for the dc input voltage V_{DC}. Similarly, the output-quantity X_{AC} and S_{AC} represent the EMF outputs for the ac input voltage V_{AC}. The input quantity V_X and V_S represent the ac input voltages which produce the same EMF voltage (X_{DC}, S_{DC}) as in the case of applying the dc input voltage V_{DC}.

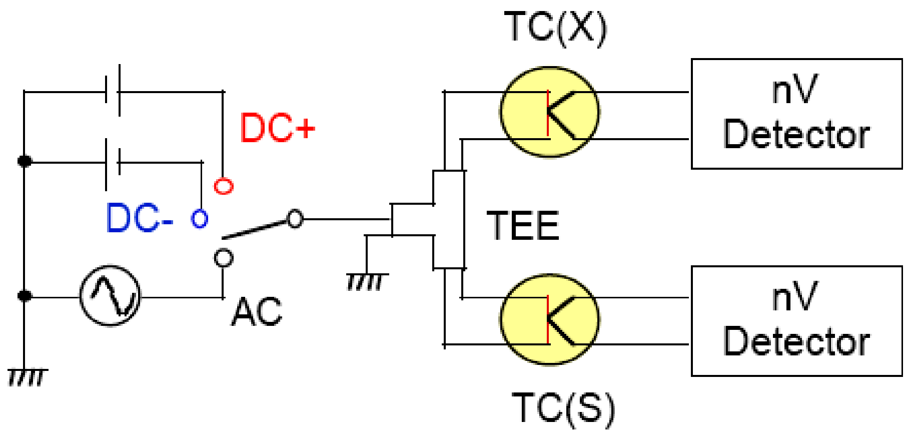


Fig. 11: AC-DC difference measurement circuit.

Using the definition of the AC-DC difference of a TVC given in (2), the relative AC-DC difference between TVC(X) and TVC(S) is deduced as

$$\delta_X - \delta_S \equiv \left. \frac{V_X - V_S}{V_{DC}} \right|_{\substack{X_{AC} = X_{DC} \\ S_{AC} = S_{DC}}} \quad (6)$$

If the difference between the dc input voltage V_{DC} and ac input voltage V_{AC} is small, the input-output characteristic of the two TVCs may be approximated to be linear in the small voltage range. In this case, the following approximation is possible:

$$\begin{cases} V_X \cong V_{AC} + \left(X_{DC} - X_{AC}\right) / k_X \\ V_S \cong V_{AC} + \left(S_{DC} - S_{AC}\right) / k_S \end{cases}$$

$$\text{Where } k_X = \frac{\Delta X}{\Delta V},\ k_S = \frac{\Delta S}{\Delta V}. \tag{7}$$

Here, ΔX and ΔS represent the change in the EMF output from TVC(X) and TVC(S) when a small change in the input voltage ΔV is applied. Mathematically, the relative AC-DC difference δ_X - δ_S is determined by the following equation:

$$\delta_X - \delta_S \cong \frac{S_{AC} - S_{DC}}{n_S S_{DC}} - \frac{X_{AC} - X_{DC}}{n_X X_{DC}}$$

$$\text{Where } n_X = \frac{\left(\Delta X / X_{DC}\right)}{\left(\Delta V / V_{DC}\right)},\quad n_S = \frac{\left(\Delta S / S_{DC}\right)}{\left(\Delta V / V_{DC}\right)} \tag{8}$$

The normalized indices n_X and n_S are of the order of 2 for the TVCs with square-output characteristics. Some of the semiconductor-based AC-DC transfer standards, like Fluke 792A or Datron 4920, have linear output characteristics, resulting in normalized indexes close to unity. The input-output characteristics of this system are plotted in Fig. 12.

Based on this Japanese system (Fig. 11), the procedure of an AC-DC difference measurement employs the standard sequence (AC/DC+/DC-/AC). Flow-chart of an automated measurement routine is shown in Fig 13 [26].

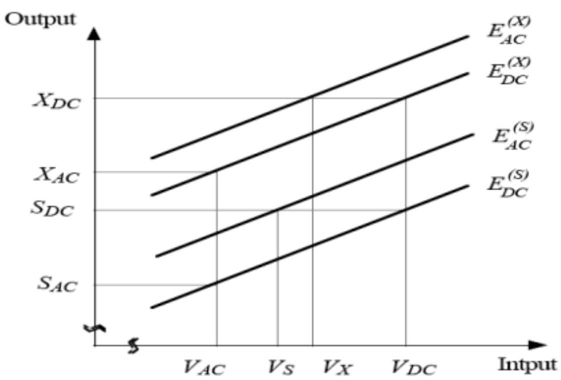


Fig. 12: Input-Output Characteristic

After registering all the parameter or the desired options, the program will go to stand-by mode, ready for a fully automated AC-DC difference measurement. When "GO" or “Start” button is pressed, the program will apply voltage to the TC module and waits for a specified period of time (normaly 10 – 15 minutes) to avoid the effects from initial warm-up drift. Then the program repeats the following procedure # 1 to # 3 at each test points (Measurement Loops).

1. Measurement of sensitivity indices (n)

The control program measures the normalized sensitivity indices of two TVCs (n_X and n_S) *at* each test point. The normalized sensitivity indices are obtained by changing the input voltage by *dV* (normally 0.1%).

2. Determination of AC-DC difference

The difference in the AC-DC differences (δx - δs) between the two TVCs, TVC-X and TVC-S, are calculated by using formula (5). In the case of standard measurement condition, one measurement loop takes about one hour. For a set of 17 standard test points from 10 Hz to 1MHz repeated twice (total 34 points), whole measurement takes approximately 20 hours.

3. Storing measurement data

After measurements for all test points are executed, summery of measurement data are stored to the hard disk of the system controller. Then instruments are reset to initial condition preparing for the exit from the measurement program.

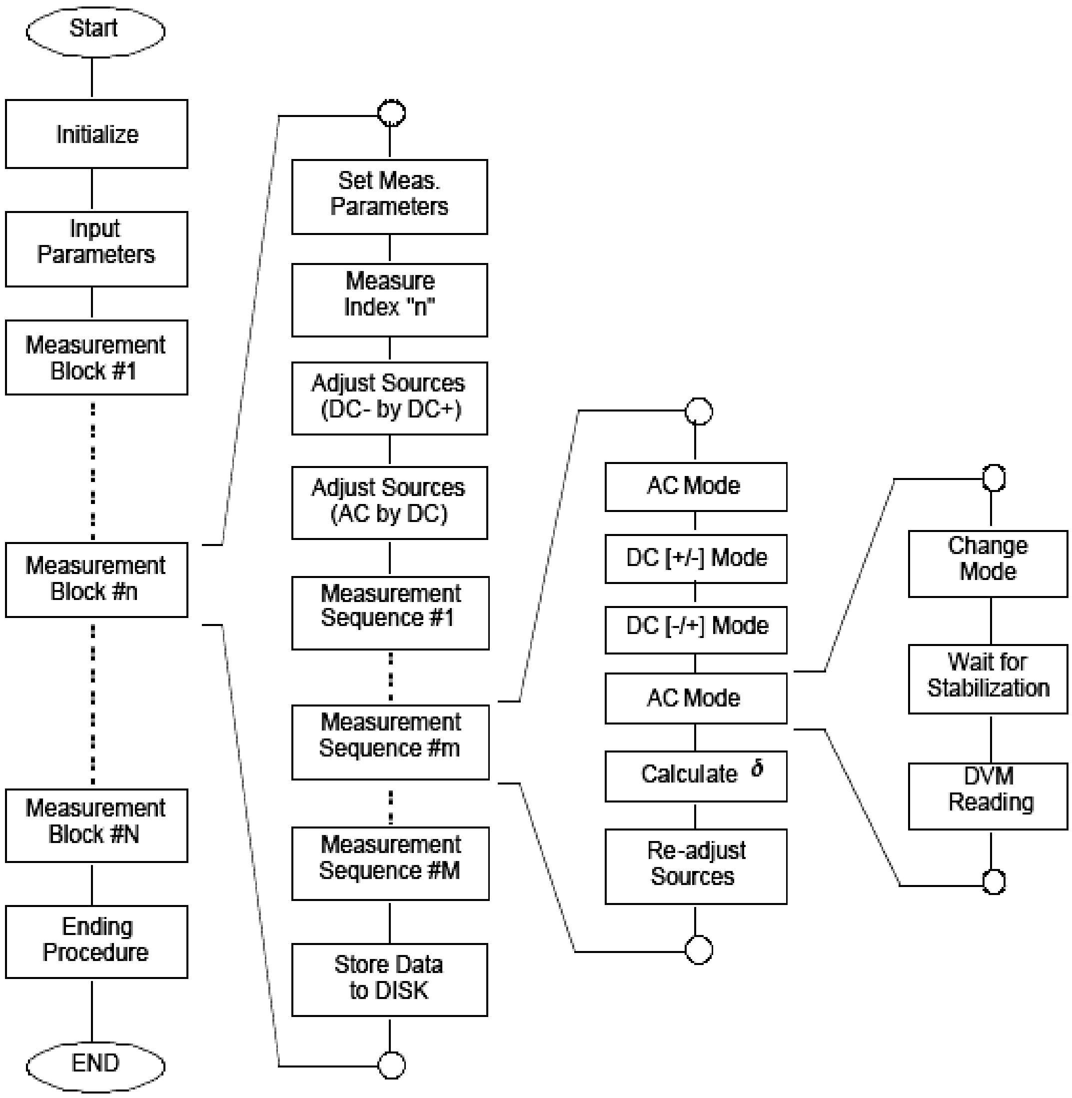


Fig. 13: Flow-chart of AC-DC difference measurement program.

4. Data Format

The results from the AC-DC difference measurement are stored into the specified data file.

The data-file consists of the following records.

- Title "Data from AC-DC difference measurement."

- Revision Number of the control program
- ID (serial) number of the modules,
- Name, ID (serial) number, and description of modules,
- Number of repetition for one measurement blocks,
- Waiting time for initial warm-up time.
- Time constant of TC (measured).
- Date and Time of each measurement block,
- Test Voltage for each block,
- Test (& Reference) frequency for each block.
- Results of TC Index measurement (n),
- EMF outputs for each mode,
- Average standard deviation of EMF outputs in ppm,
- AC-DC difference for each sequence in ppm,
- Average AC-DC difference for each measurement-block
- Standard deviation of AC-DC difference in ppm.
- Summary of the measurement.

Slight different systems are achieved for determining the AC-DC Difference at different NMIs. Figures 15 and 16 show samples of the different systems which have been designed for this type of measurement at KRISS (South Korea) and NIS (Egypt), respectively.

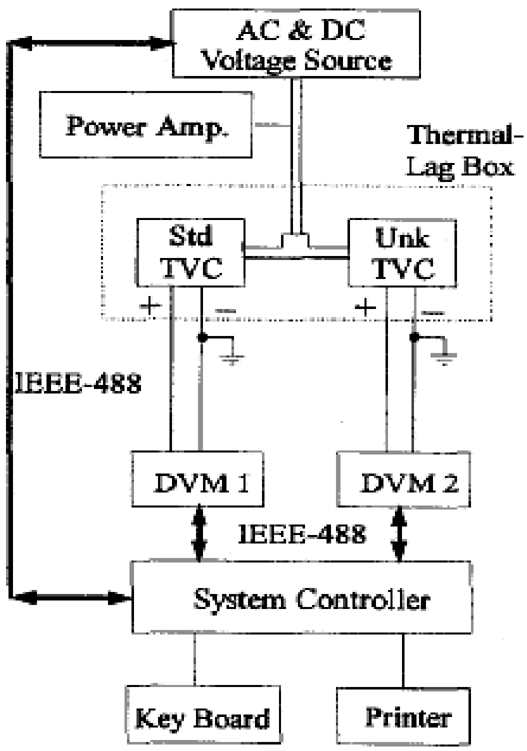


Fig. 15: Block diagram of the two-channel automatic ac-dc difference measurement system at KRISS (Korea)

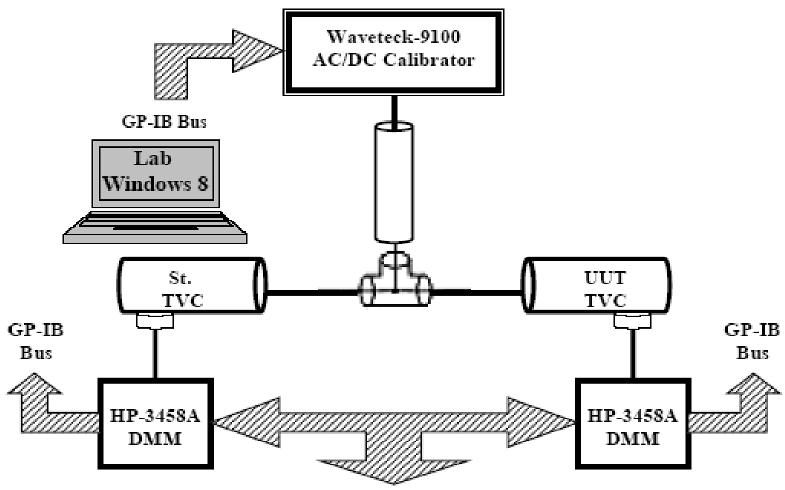


Fig. 16: Block diagram of the automatic ac-dc difference measurement system at NIS (Egypt)

At National Institute for Standards and Technology (NIST-USA), as an another example of different automated system (Fig. 17), thermal converters are characterized or calibrated by the comparison with another converter by the application of dc(plus), ac, dc(minus) signals in a timed sequence. Voltage converters are connected in parallel through a coaxial tee, and current converters or transfer shunts are usually connected in series. AC-DC difference uncertainties range from less than 10^{-6} at the primary standard level, to 70×10^{-6} for voltage at 1 MHz, and to about 100×10^{-6} at 20 A and 100 kHz [19].

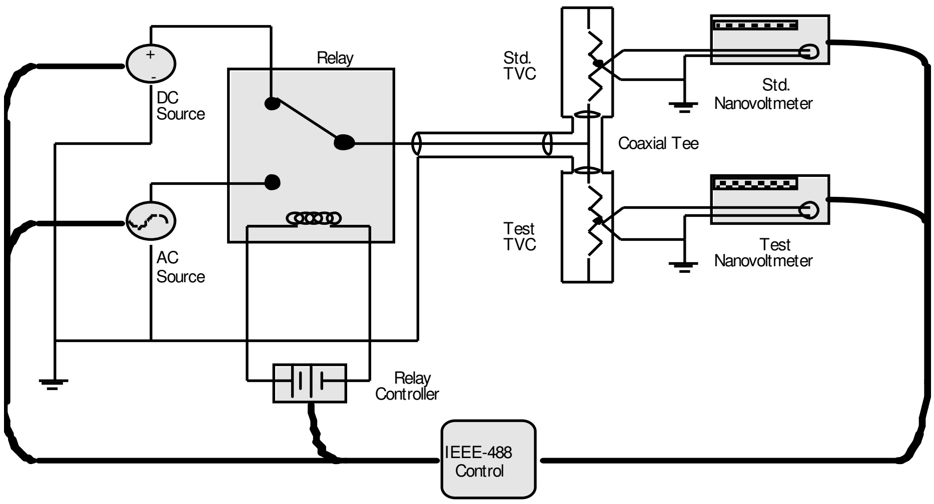


Fig. 17: Block diagram of the automatic ac-dc difference measurement system at NIST (USA)

To calibrate a coaxial thermal voltage converter, follow these steps (Fig. 18):

i. Connect the UUT to one leg of a GR 874 Tee. It will be need to use an adapter to connect the UUT to the Tee, since some high-frequency thermal converters use BNC or Type N connectors for the input signal.

ii. Connect the NIST standard to a second leg of the Tee3

iii. Connect the cable from the automated system to the third leg of the Tee.

iv. Connect the detector cables to the thermoelements, making sure that the standard channel detector cable is connected to the NIST standard, and the test channel cable to the UUT.

v. Connect the ground wires from the low side of the thermoelement output connector to the shell of the detector cable for both channels.

vi. Cover the TVCs, if necessary, to prevent problems with changes in ambient temperature.

vii. Launch the Ac-dc Difference according to Eq. (5).

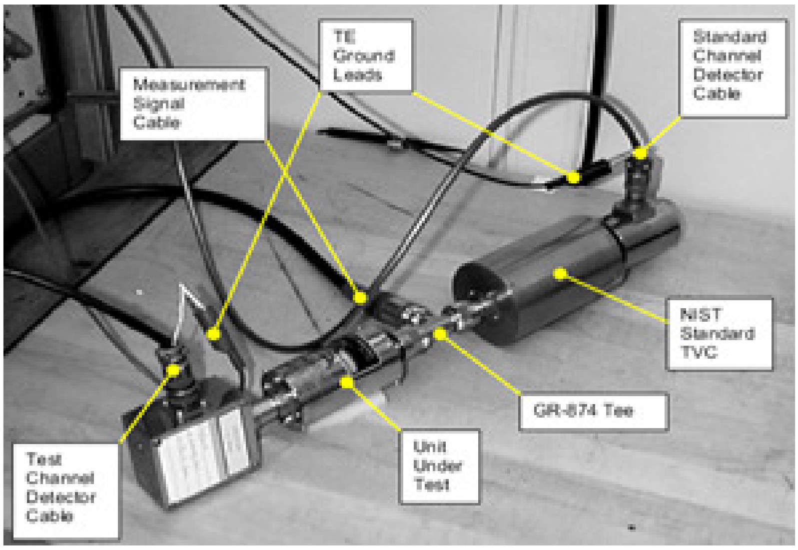


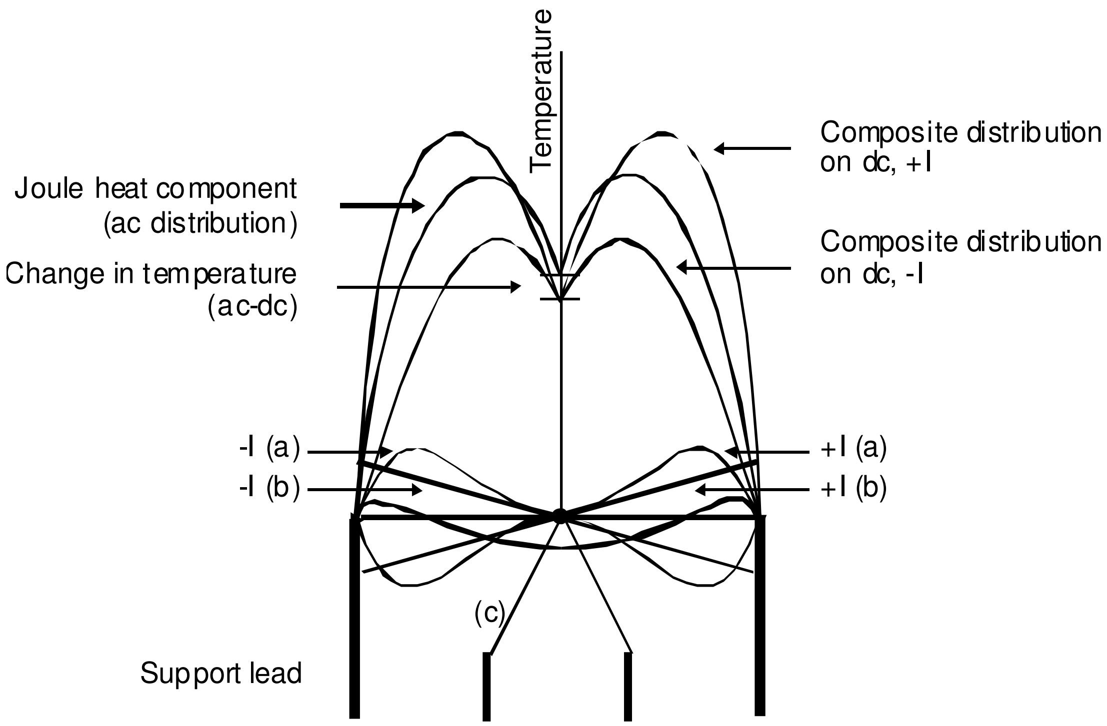
Fig. 18: Photograph of a coaxial thermal voltage converter connected to one of the NIST automated systems.

Origin of AC-DC Difference

There are three main causes of the ac-dc transfer difference in the case of an SJTC [27]: (a) thermoelectric Effect (dc offset) due to the Thomson or Peltier effect, (b) high-frequency characteristics of the input circuit, and (c) low-frequency characteristics due to thermal ripple

Thermoelectric effect (DC offset):

When the dc current is passed through the heater of an SJTC, non-joule heating/ cooling takes place along the heater due to thermoelectric effects such as Thomson or Peltier effect. In the case of SJTC with standard construction, an ac-dc difference of a few ppm is observed due to the thermoelectric effects. In the case of MJTC of PTB, the thermoelectric effect is suppressed due to the uniform temperature distribution on the heater, and contribution from the thermoelectric effect is estimated to be smaller than 0.1 ppm. Fig. 19 includes the behavior all types of these effects.



proximate component temperature distributions along the heater of a SJTC (not to scale):

(a) first-order Thomson heat component
(b) First-order Peltier heat component
(c) second-order Thomson heat component (independent of current direction)

Fig. 19: Thermoellectric Effects on the heater of the SJTVC

High-frequency characteristic:

In the frequency range above 10 kHz, the skin-effect of the conductor and the stray inductance and capacitance in the input circuit become significant. When a standard-design SJTC-element is combined with a current-limiting metal-film resistor of 1kΩ, the effect to the ac-dc difference is of the order of 0.1 ppm / 1 ppm / 100 ppm at the frequency of 10 kHz/ 100 kHz/ 1 MHz. The MJTCs generally shows larger high-frequency characteristic due to the dielectric loss in the twisted bifiler heater.

Low-frequency characteristics:

The thermal time constant of a standard-design SJTC-element is about 1 s. At frequency below 100 Hz, double-frequency thermal ripple is created due to insufficient thermal inertia. In the case of SJTC, the effect to the ac-dc difference is of the order of 0.1 ppm / 10 ppm at the frequency of 100 Hz / 10 Hz. The MJTCs generally shows smaller low-frequency characteristic due to improved linearity in the input-output characteristic. The typical frequency characteristics of an SJTC and an MJTC in the full frequency range are illustrated in figure 20. The thermoelectric effects which occur at the dc-mode give the frequency-independent offset in the ac-dc difference. Since both the low-frequency characteristic and the high-frequency characteristic reduce below 1 ppm in the frequency range between 100 Hz and 10 kHz, the ac-dc difference is dominated by the thermoelectric effect around 1 kHz.

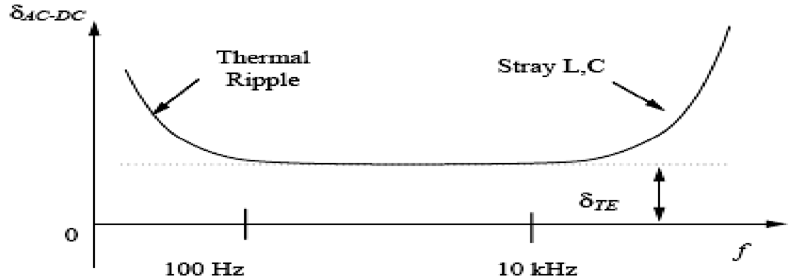


Fig. 20: The typical frequency characteristics of a thermal converter.

Uncertainty Analysis

Uncertainty of measurement is defined in the *International vocabulary of basic and general terms in metrology,* VIM (3.9) [28], however, a slightly different definition is given in the forward to BSI edition of VIM as: Uncertainty (of measurement): result of the evaluation aimed at characterizng the range within which the hue value of a measurand is estimated to lie, generally with a given confidence.

But why do we need uncertainties? Simply, the world is not a perfect place. Consequently, when measuring any quantity or effect, the results are not exact and contain an error associated with the measurement. Measurement uncertainties are calculated to evaluate and quantify the error associated with the measurement. The measurement uncertainty therefore provides a range around a measured value within which the true value lies. Measurement uncertainties are therefore a necessary feature of any measurement configuration if a complete picture is to be obtained and the results correctly evaluated.

The need for the uncertainty of measurement (U) be reported when giving the result of a measurement has long been recognized. A statement of the measurement uncertainty on certificates of calibration has been a mandatory requirement for NAMAS accredited calibration laboratories since the formation Of the British Calibration Service in 1966 and is a requirement for international accreditation standards EN45001 and IS0 Guide 25 to which NAMAS accreditation standards conform. The traceability of measurements is a key product of a national measurement system. The definition of traceability given in VIM (6.10) is: Traceability: property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken *chain* of comparisons all having stated uncertainties

The sources of uncertainty are divided into two categories, namely, Type-A and Type-B [26]. The type-A uncertainties can be evaluated from actual measurement as the standard deviation of the data as in Eq. (9), while the type-B uncertainties have to be estimated using different methods depending on the nature of the sources of uncertainty.

$$\bar{q} = \frac{1}{n}\sum_{k=1}^{n} q_k$$

$$s(q_k) = \sqrt{\frac{1}{(n-1)}\sum_{k=1}^{n}(q_k - \bar{q})^2}$$

$$u(x_i) = s(\bar{q}) = \frac{s(q_k)}{\sqrt{n}} \tag{9}$$

where:

- *n the* repeated measurements of a quantity q
- $\bar{q}$ the mean value of these measurements
- *s(q,)* the experimental standard deviation,
- q_K is any measured value of the quantity q
- $U(X_i)$ the *standard* uncertainty of the Type A.

As an example for evaluating the uncertainty, the uncertainties in this domain are calculated in accordance with NIST Technical Note 1297 [19]. The combined standard uncertainty of a measurement is the root-sum-of-squares (RSS) method of combining uncertainty components as standard deviations. These uncertainty components may be evaluated as either Type A or Type B, where the former can be evaluated using statistical means and the latter cannot. For a determination of ac-dc difference using the automated calibration system, the Type A uncertainty is the standard deviation of the points that are averaged to determine the ac-dc difference. The contributions to the uncertainty arising from the thermal converters themselves and the measurement system are evaluated as Type B components. These two uncertainty components are combined to calculate the combined standard uncertainty. The expanded uncertainty (the “final” uncertainty provided to the customer) is the combined standard uncertainty multiplied by a coverage factor (k) of 2, corresponding to a confidence level of approximately 95 %. Practically, uncertainty budgets for AC Voltage normally take into account the following contributions [29]:-

- Imported Uncertainty of ac-dc transfer
- Drift
- Applied Correction
- Flatness/ Frequency Response
- Voltage Coefficient of Frequency Response
- Temperature Coefficients
- Resolution
- Repeatability
- Connections
- DC Reversal Error
- DC Voltage

For instance, the significant sources of uncertainty in the AC-DC difference measurements of 3 V & 1 kHz at NIS-Egypt are summarized in Table 4.

Table 4: Uncertainty Budget of AC-DC Difference measurement of 3 V at 1000 Hz

Source of Uncertainty	Value, ± ppm
Short term DC source stability	0.3
Short term AC source stability	0.6
Thermal emf of the leads	0.6
Ambient temperature change	1
Effect of the T-connector	1.2
Closure of the triangle method	2
Repeatability (for 10 times)	1.2
Combined Standard, U_C	3
Expanded Uncertainty (k = 2)	6

Future Approaches

Suggested Prospects

Most developments in AC-DC transfer are driven by the need for traceability of standards used in national calibration services with uncertainties in the ppm range or less. To improve ac standards further towards the uncertainty level of dc standards, the direct use of the Josephson standard by cyclically changing the output voltage by frequency modulation of the microwave [30], by comparison of samples against Josephson steps [31] or by D/A conversion with a 14 bit arrangement of a Josephson array has been suggested [32].

Other quite new designs are proposed using radiometric sensing of the heater temperature of thin-film heaters [33]. This would allow the physical separation of the heater and the temperature sensor, providing freedom in the design of the heater for highest frequencies.

Other thermal converter designs were realized with thin-film heaters and aluminum thermoresistive temperature sensors deposited on a thin dielectric membrane. Low mass heater/sensor configuration assures minimal thermal inertia, so as to reduce settling time and speed up ac-dc transfer. An optional silicon obelisk is used as a thermal integrator to avoid low frequency ac-dc transfer differences. This design is enhanced by isothermal operation and transfers only slightly more slowly than the standard configuration without the obelisk. The thermoresistive design has an improved signal to noise ratio compared to thermal converters using thermocouples and lowers the manufacturing cost of thermal converters. But the feedback control loop necessary for the application of the TRTC raised some difficulties which stopped their wider application.

Electrometric methods comparing ac and dc via electrostatic forces, are used again after several decades during which they seemed to have been forgotten [34]. Integrated micromachined electrostatic converters are proposed in which modern technology is used to fabricate microelectromechanical systems (MEMS) in silicon [35]. This overview will updated every two years

Electrical Simulation Using

Meantime, an electrical simulation modeling by using the LT-Spice software has been achieved widely to analyze the physical structure and electrical characteristics of the TE in an effort to better understand the origin of errors in these devices. Another important purpose for using the electrical simulation is performing the building up and building down scaling for the AC-DC difference measurements. When a comparison between an accurate traceable result and an electrical simulated result for the same device at a certain frequency, the overall efficiency of this simulation will be precisely given. The electrical simulation, then, can be used easily to determine the expected AC-DC difference for that device for different values around the rated value at the same frequency. The values from 40 % to 110 % of the rated value of the device are suggested for obtaining accurate theoretical determination of the associated AC-DC differences.

For instance, through the normal use of the SJTVC (the TE itself without any multiplier resistor), the equivalent electrical circuit was imaged as shown in Fig 21. The equivalent circuit parameters of the TE were accurately measured at 55 Hz, for example, by using a very sensitive digital LCR Meter. The typical results of these parameters are listed in Table 5.

To evaluate the efficiency of the characterization and to determine the simulation error at the different frequencies, a comparison between the theoretical and practical results of the TE AC-DC Difference was performed at the rated value (5 mA). The practical results were evaluated based on the Equation No. (2). The simulation results were calculated based on the relative different between the heat power (I^2 R) on the TE heater due to the applied DC signal and the real part of the applied AC signal. The comparison results are listed in Table 6 and illustrated in

Fig. 22 at frequencies of 55 Hz, 1 kHz, 10 kHz and 20 kHz. It has been shown that the agreement between the results was good and reflects the reliability of the suggested equivalent circuit. Of course, because the electrical equivalent model of this device doesn't include all the existed parameters and effects around the device, the simulated values were, as a result, smaller than the practical results (as shown in Table 6)

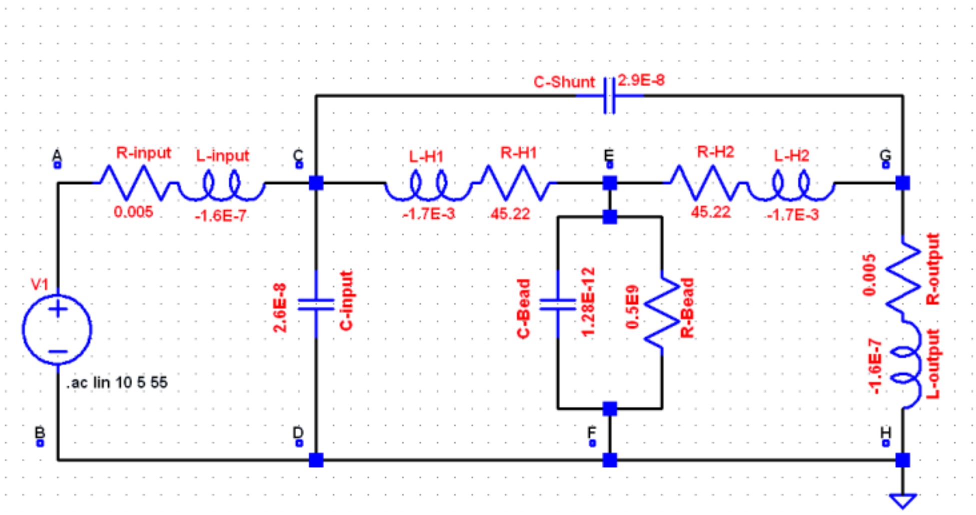


Fig. 21: The Suggested Equivalent Circuit of the SJTVC

Table 5: The Measured Parameters of the TE at 55 Hz

Symbol	Description	Values
L-input and L-output	Inductance of input and output leads	0.16 µH for each
C-input	Parasitic capacitances across the input terminals of the TE	26 nF
L-H1 and L-H2	The inductances of the two similar parts of the heater	1.7 mH for each
R-H1 and R-H2	The resistances of the two similar parts of the heater	45.22 Ω for each
C-Shunt	The parasitic capacitance across the voltage drop of the TE heater	29 nF
C-Bead	The parasitic capacitance across the insulator bead	1.28 pF
R-Bead	The high resistance of the insulator bead	0.5 GΩ

Table 6: The Comparison between the Practical and the Simulated Results

Frequency	Practical results of the AC-DC Difference, ppm	Simulation results of the AC-DC Difference, ppm	The simulation error, ppm
55 Hz	-81.2	-69	-12.2
1 kHz	-63.7	-39.5	-24.2
10 kHz	-195.5	-157.2	-38.3
20 kHz	-436.3	-389.8	-46.5

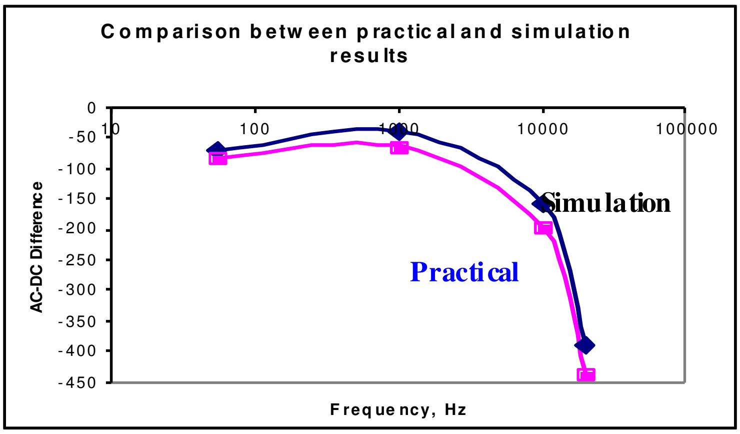


Fig. 22: Comparison between Practical and Simulated Results

In the same manner, the electrical simulation was repeated for a prototype of thin-film multijunction to investigate the effects of the heater resistance changes on the AC-DC difference of this prototype. Fig. 23 and 24 show the proposed equivalent circuit and the simulated calculations, respectively.

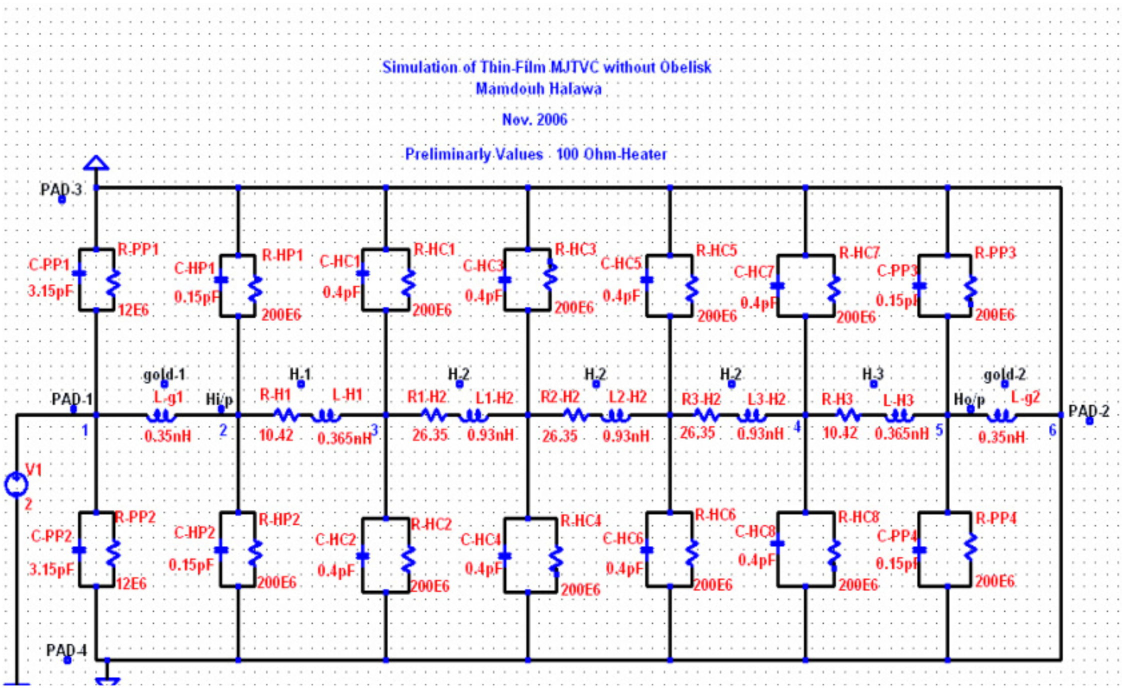


Fig. 23: The Suggested Equivalent Circuit of the MJTVC.

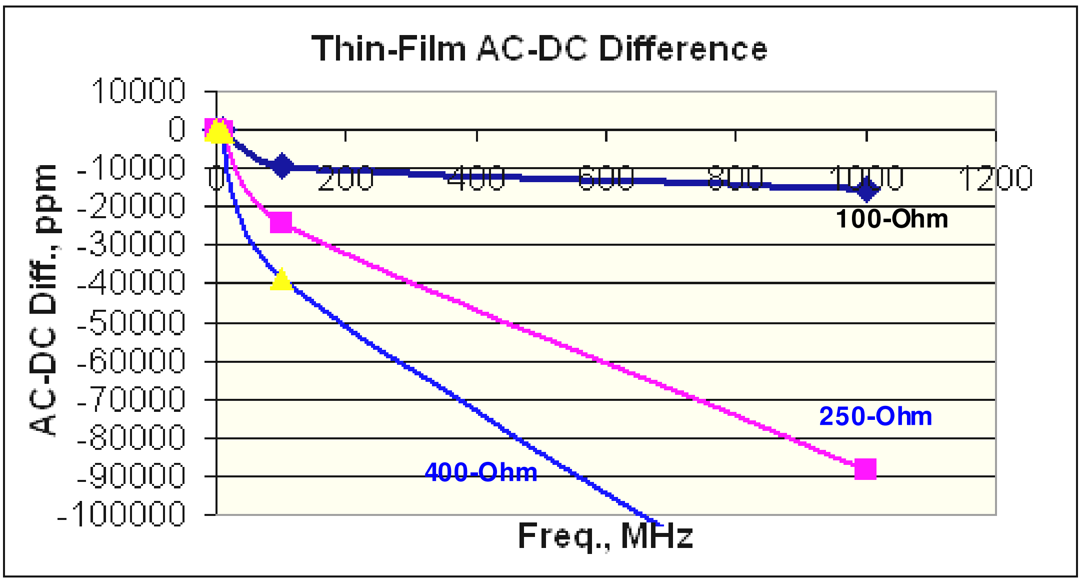


Fig. 24: The Simulated Calculations of the MJTVC.

It was found that the using of heater resistance equals 100 Ω exhibits a quite small AC-DC difference at 10 MHz (about -155 ppm). This value at this frequency represents a challenge for the-state-of-art for these thermal converters if it could be achieved practically in the future, hence the importance of using the electrical simulation.

Conclusion

In the past few years there have been several technological changes in changes affecting the AC voltage area. These have been in both commercial instruments and in the potential for new standards. The main changes are: (a) the improved stability and increased range of commercial instruments (b) the requirements for the calibration of non sinusoidal waveforms (c) the potential for improved national standards for AC voltage generation and measurement.

These changes lead to requirements for the extension in range of present calibration facilities for AC voltage as well as AC-DC transfer. There is also a requirement for the calibration of non sinusoidal waveforms. The development of new standards will initially support existing standards and ultimately provide better standards and better traceability to the primary DC standards. The Josephson array system could provide a primary standard of AC voltage. Meantime, the AC voltage standard will provide a working standard which will provide the starting point for the extension to other voltages and frequencies.

Any single voltage converter can be easily referred, with an automatic procedure, to the reference operating at the same voltage, avoiding, for single junction converters, cumulative error due to the variation of the ac/dc transfer difference as a function of the applied voltage. For frequencies outside the audio frequency band, where ratio standards are not easily known, the system mightalso be used for ac ratio calibration by means of the ac/dc converters.

An essential approach to decrease thermoelectric effects by reducing temperature gradients along the heater was the design of the MultijunctionThermal Converter (MJTC). Optimization of the materials used and a careful design resulted in the three-dimensional MJTC of PTB_Germany with an estimated ac-dc difference of less than 0.1 ppm. Moreover its low-frequency and high frequency ac-dc transfer differences have been evaluated with uncertainties of less than *0.5* ppm up to 100 kHz and 10 ppm up to 1 MHz. Today an advanced MJTC is used in the European national laboratories as a basic standard for ac-dc transfer of voltage and current. Unfortunately this device remains costly and available only for European national laboratories.

New thin-film designs of the MJTC will be used in the future. Modern technology with thin-film heaters and thermocouples on a thin dielectric membrane offer very low thermal conductance and therefore high responsivity of the device. The nearly ideal periodic structure of the thermal element optimized by computer-modeling and manufactured by a photolithographic process results in a constant temperature along the heater and negligible ac-dc transfer differences. The use of anisotropic etching and thin-film technology allows cheap mass production.

References

[1] F.L. Hermach, “Thermal Converter as ac-dc Transfer Standards for Current and Voltage Measurements at Audio Frequencies,” *J. Research NBS*, vol. 48, pp. 121-138, 1952.

[2] Luciana Scarioni, Manfred Klonz, and Torsten Funck “Quartz Planar Multijunction Thermal Converter as a New AC–DC Current Transfer Standard Up to 1 MHz”, *IEEE Trans. Instrum. Meas.*, VOL. 54, NO. 2, April 2005.

[3] Manfred Klonz, “Entwicklung von Vielfachthermokonvern zur genauen Ruckfuhrung von Wechselgrossen auf aqivalente Gleichgrossen,”*thesis Technical University Braunschweig*, 1987.

[4] T. Weimann, “Entwickling und Herstellung eines planaren Vielfachtthermokonverters fur die Prazisionsmessung von elektrischen Wechselspannungen und Wechselstromen.” *Thesis, Mathematish-*

Naturwissenschafilche Fakultat der Westfalischen Wilhelms-Universitat Munster, 1994.

[5] M. Klonz, T. Weimann, "Matching of the temperature coefficient of the output voltage of a thin film multijunction thermal converter," *Proc. Of international Metrology Congress*, Paris, pp. 153-159, 1989.

[6] U. Dillner, E. Lessler, M. Klonz, C. Thomes, "Micromachined planar ac-dc multijunction thermal converter: Aspects of design and layer materials," *Proc. Microsystems Technologies 94, Berlin,* pp. 773-782, 1994.

[7] H. M. Laiz, "Low frequency Behaviour of Thin-Film Multijunction Thermal Converters," *thesis, Technical University Braunschweig*, March 1999.

[8] M. Klonz, "Current Developments in Accurate AC-DC Transfer Measurements," *IEEE Trans. Instrum. Meas.*, VOL. 44, NO. 2, APRIL 1995.

[9] B. D. Inglis, "Standards for ac-dc transfer," *Metrdogia,* vol. 29, no. 2, pp. 191-199, May 1992.

[10] The International System of Units, *BIPM, 7th ed.*, 1998.

[11] C. F. Coombs Jr, Electronic Instrument Handbook, 2nd ed., *McGRAW-Hill, New York,* 1995.

[12] Luciana Scarioni, "High Frequency Thin-Film Thermal Converter on a Quartz Crystal Chip," *thesis, PTB-E-83Braunschweig*, September 2003.

[13] Popel R, "The Josephson effect and voltage standards," *Metrologia, vol. 29*, 1992.

[14] A. Hartland, "The quantum Hall effect and resistance standards," *Metrologia, vol. 29,* 1992.

[15] E. S. Williams, "Thermal voltage converters and comparators for very accurate ac voltage measurements," *J. Res. Nat. Bur. Stand. 75C*, pp 145-154, 1971.

[16] B. D. Inglis, c.c Franchimon, "Current independent ac-dc Transfer Error Components in Single Junction Thermal Converters,"*IEEE Trans. Instrum. Meas.,* vol. 34, pp. 294-301, 1985.

[17] L. L. Szepesi, "Recent developments on solid-state thermal voltage converters," in *Proc. 1986 Measurement Science Conference,* pp. 9-13, Irvine, CA, January 23-24, 1986.

[19] Thomas Lipe, "Operation and Reference Manual for the NIST AC-DC Calibration Systems and Software" NIST Special Publication 250-61, May 2004

[19] M. Klonz, “Entwicklung von Vielfachthermokonvertern zur genauen Ruckfuhrung von Wechselgrossen auf aqivalente Gleichgrossen,” *thesis, Technical University Braunschweig*, 1987.

[20] M. Klonz and F. J. Wilkins, “Multijunction Thermal Converter with Adjustable Output Voltage/Current Characteristics,” *IEEE Trans. Instrum. Meas., vol. IM-29, No. 4*, pp. 409-412, 1980.

[21] M. Klonz, “AC-DC Transfer Difference of the PTB Multijunction Thermal Converter in the Frequency Range from 10 Hz to 100 kHz,” *IEEE Trans. Instrum. Meas., IM-36*, pp. 320-329, 1987.

[22] M. Klonz, “Tuning of the Multijunction Thermal Converter for low temperature coefficient of the Output Voltage,” CPEM’88 Digest, pp. 217-218, 1988.

[23] M. Klonz and T. Weimann, “Accurate thin-film multijunction thermal converter on a silicon chip,” *IEEE Trans. Instrum. Meus.,* vol. 38, pp. 335-337, Apr. 1989.

[241 J. R. Kinard, D. X. Huang, and D. B. Novotny, “Performance of multilayer thin-film multijunction thermal converters,” *Dig. Con5 Prec. Electromagn. Meas.* Boulder, CO, pp. 407-408, July 1994.

[25] M. Klonz, T. Weimann, F. Volklein, H. Dinter, and A. Lerm, “ac-dc cmV transfer with highly sensitive thin-film multijunction thermal converters,” *IEEE Trans. Instr. Meas.* vol. 42, pp. 612-614, Apr., 1993

[26] “A Guide for establishing primary AC-DC transfer standard using ET2001 ADS system” *Nano-Electronics Research Institute / AIST, Japan*, (Tentative Version 2.01, Apr. 2007).

[27] Kunihiko Takahashi, Hitoshi Sasaki, Barry D. Inglis, and Manfred Klonz, “AC–DC Voltage Transfer Difference Due to Seebeck Effect in Thermal Converters,” *IEEE Trans. Instrum. Meas*, Vol. 48, NO. 2, APRIL 1999.

[28] IS0 *Intemational vocabulary of basic and general rems in metrology (VIM)* : 1994

[29] NAMAS, *The Expression of Uncertainty and Confidence in Measurements (with particular reference to Electrical Measurements).* Edition *7* May 1991. NAMAS Executive.

[30] B. D. Inglis, “Standards for ac-dc transfer,” *Metrologia,* vol. 29, pp. 191-199, May 1992.

[31] S. B. Chapman and R. B. D. Knight, “A new ac-dc transfer standard,” *Dig. Cong. Prec. Electromagn. Mecir. (CPEM ‘92).* pp. 328-329, Paris, June 9-12, 1992.

[32] C. A. Hamilton, C. J. Burroughs, and R. L. Kautz, “Josephson D/A converter with fundamental accuracy,” *Dig. Cong. Prec. Electromagn. Meas. (CPEM ‘Y41,* Boulder, CO, pp. 271-272, June 27-July l, 1994.

[33] F. L. Katzmann and M. Klonz, “A thin-film dual heater ac4c converter with infrared sensor,” *Dig. Cong. Prec. Electromagn. Meas. (CPEM ‘Y4),* Boulder, CO, pp. 413-414, June 27-July 1, 1994.

[34] U. Pogliano, “An electrometric method for precise ac/dc transfer measurements,” *Dig. Cong. Prec. Electromagn. Meas. (CPEM ‘Y4),* Boulder, CO, pp. 363-364, June 27-July I , 1994.

[35] B. P. van Drieenhuizen and R. F. Wolffenbuttel, “Integrated micromachined accurate electrostatic true rms-to-dc converter,” *Dig. Cong. Prec. Eleetromagn. Meas. (CPEM ’94),* Boulder, CO, pp. 365-366, June 27-July 1. 1994.