An Automated AC-DC Transfer Calibration System

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Abstract

The paper describes recent improvements in the NRC ac-dc transfer capabilities. They were achieved through full automation of the ac-dc transfer comparator, extensive redesign of the control software, and modification of the voltage buildup procedure. Hardware additions to the comparator design include several stepping motor driven switches and a range changer of the highest accuracy commercial electronic transfer standard. Redesigned Visual Basic software is very flexible, and can be easily modified to accept new instruments and new procedures. The NRC buildup procedure has been modified at the 500 V and 1000 V levels. The expanded uncertainty assigned to the NRC working standard is given and its components are briefly discussed.

1. Introduction

Ac-dc transfer standards and comparators are maintained by the National Metrology Institutes (NMI's) to provide a primary link between the active ac and dc quantities. The paper describes a fully automated ac-dc transfer system, developed at the National Research Council of Canada (NRC) and the voltage buildup procedure adopted at NRC. It concentrates on the recent hardware and software improvements as well as on the differences from similar systems maintained at other NMI's, [1], [2] and [3].

Traditionally the most accurate ac-dc transfer comparators were designed for the comparison of vacuum junction thermal converters only. In recent years, these simple but inconvenient to use devices are being replaced by electronic instruments. The new electronic instruments are built with different levels of design complexity, either as complete IEEE488-bus instruments or containing only input and output amplifiers, thus requiring an external dc voltmeter. The NRC ac-dc transfer comparator has been designed for testing of all these instruments and devices, as well as for ac calibration of voltmeters and calibrators of the highest accuracy.

2. AC-DC transfer comparator hardware

The simplified circuit diagram of the comparator, Fig. 1, shows comparison between a vacuum junction thermal voltage converter (TVC) and an Electronic Transfer Standard (ETS). During the comparison, the outputs of the two devices are measured while the voltage applied to the input of the Tee alternates between *ac*, *dc_normal* and *dc_reverse*. When two separate test signal sources are used, AC V Source and DC V Source, then they are sequentially connected to the input of the Tee by a mechanical relay switch. However, when an ac/dc calibrator, which can generate both ac and dc test signals, is available, as in most calibration laboratories, there is no need for two separate supplies. In this case, shown in Fig. 1, the test signal is switched internally, inside the AC/DC IV Source. The disadvantage of this approach is that the timing of the internal switching of the calibrator varies from a fraction of a second to several seconds, depending on the voltage level. This non-uniform switching time can be a source of a relatively large error in ac-dc difference determination, reaching several μV/V when the time constants of the two compared converters differ significantly. This error was eliminated by introduction of an Auxiliary DC Source [3], adjusted to the same value as the dc voltage of the ac/dc calibrator. Before the internal switching is initiated, the tested devices are switched to this auxiliary dc source by an external fast relay. In this way the thermal state of the tested converters is not disrupted during internal switching and a uniform switching time is maintained. The auxiliary dc source can be of lower resolution and stability than the test source and is required mainly for the highest accuracy tests.

The output of the ETS, 0.5 V–2 V range, is measured by a voltmeter; the low-level output of the TVC, typically 1 mV–7 mV, is measured by a millivoltmeter. The accuracy and linearity of this latter measurement is increased by applying a back-off voltage in series with the output of the TVC. The back-off voltage is computer adjusted to a value close to the TVC output. During the test the millivoltmeter operates at its lowest range, usually less than 10 μV. The back-off voltage source was custom

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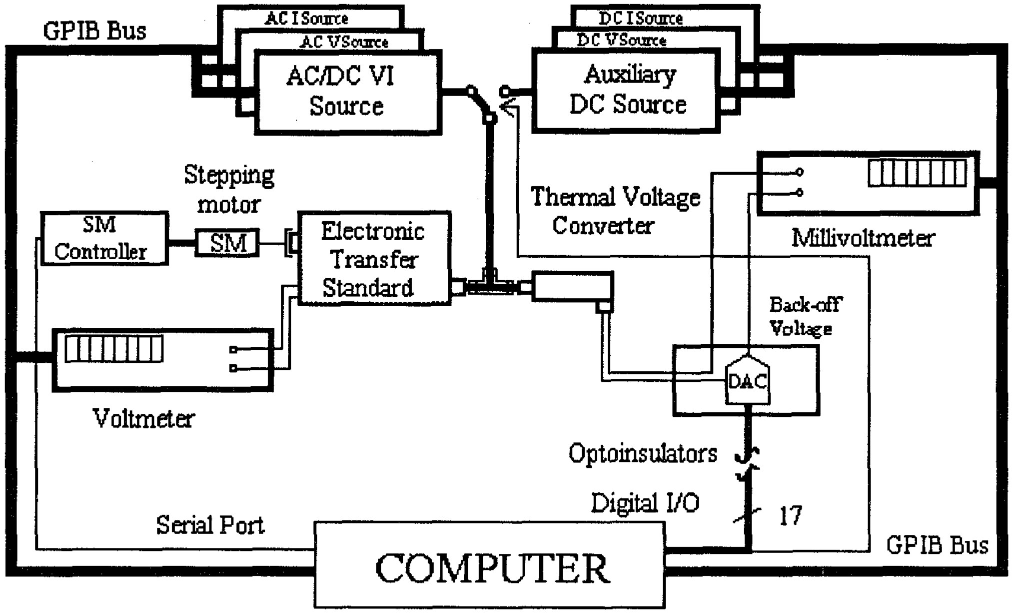

Fig. 1. Simplified circuit diagram of ac-dc transfer comparator.

designed using a 16 bit DAC, selected for low linearity error, 0.25 LSB, and low temperature coefficient of the drift, less than 1 (μV/V)/°C. The output of the back-off voltage source is not grounded and the power frequency noise current, flowing through the inter-winding capacitance of the DAC power supply transformer, may corrupt the very low measured signal. This noise was eliminated using a custom designed triple-shielded power supply transformer.

A mechanical switch sets the measured range of the ETS. To speed up calibration of this instrument its range changing has been automated and is now computer controlled. This automation is important when a calibrated ETS is compared to a working standard ETS. The testing procedure, 300 points on 7 voltage ranges, 22 mV – 220 V, can be performed without interruption for manual range switching. Only the 1000 V range test, requiring different test sources, demands operator intervention. Fig. 2 shows two electronic transfer standards during comparison. The stepping motors are linked to the knob grips by torque amplifying speed reducers and flexible shaft couplers.

3. AC-DC transfer comparator software

The flexibility of the comparator design is achieved by the test software, written in Visual Basic. The selected configuration of the calibrator is entered into the program via screen shown in Fig. 3a. In the section Transfer Standard Description the reference and test converters are identified. In the section Equipment the operator selects, from the drop-down menus, test voltage and current sources, the auxiliary source (different for low and high voltage tests), reference and test voltmeters or millivoltmeters, and the switch. This last menu, AC/DC Switch, selects one of eight switching devices, such as a low voltage mercury wetted relay switch, a high voltage vacuum relay or a stepper motor controlled current switch.

The selections available in the switch menu are determined by the Voltage or Current setting in the Measurement section of the screen. Depending on this setting the tested devices should be connected either in parallel, as in Fig. 1, or in series. The remaining three selection buttons: Multiple Sources, Single Source and 4920 determine the test sequence. When the Single Source is selected then the test voltages are applied in a sequence *ac-dc_normal-dc_reverse-ac*, or, more precisely, *ac-aux_dc-dc_normal-aux_dc-dc_reverse-aux_dc-ac*. The Multiple Sources sequence is *ac-*

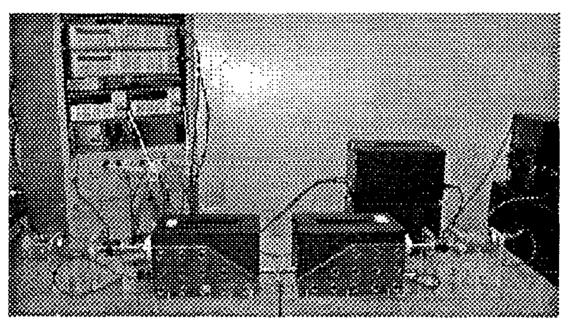

Fig. 2. An automated setup for comparing two electronic transfer standards.

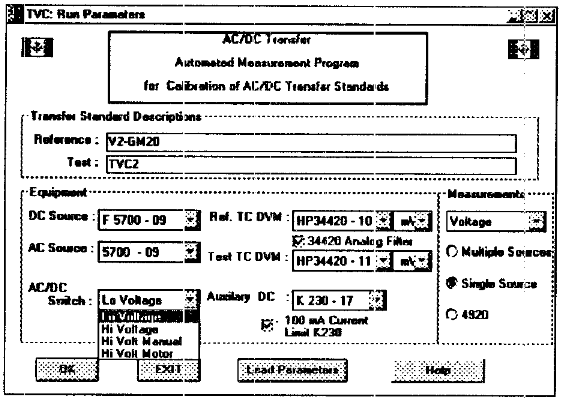

Fig. 3a. Ac-dc transfer program hardware selection screen.

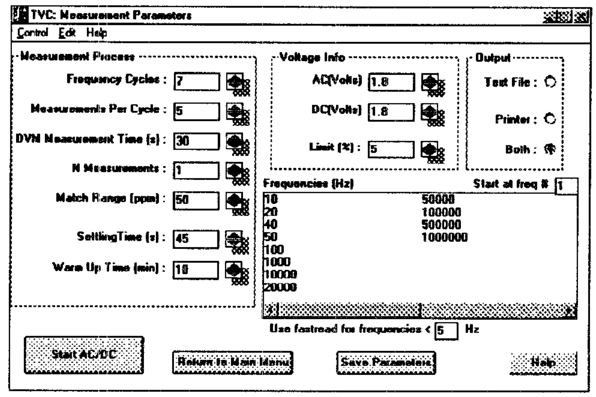

Fig. 3b. Ad-dc transfer program test parameters selection screen.

dc_normal-ac-dc_reverse-ac. No auxiliary source is required in this case; the dc source is switched from normal to reverse when the tested devices are connected to the ac source. In the selection designated 4920 the sequence is *dc_normal-dc_reverse-ac*. This last sequence is specific for one of the commercial Electronic Transfer Standards calibrated using this software.

Fig. 3b shows the test parameter selection screen. Most of the entries in this screen are self-explanatory. The test frequencies are shown and entered in the Frequencies section. The nominal test voltage (current) is entered in the Voltage (Current) Info section. Usually the ac and dc test voltages are identical. However, when the loading of the ac and dc test sources differs significantly, because of the different output impedances, then these two settings can also differ. The Limit [%] setting shows how much the computer-set test voltages, adjusted as described below, can differ from the nominal settings, before the test is aborted. This is a safety feature. Prior to the beginning of the actual measurement sequence the normal and reverse dc voltages are adjusted for the output of the reference instrument to be the same at ac and both dc voltages. Ideally the output of the reference should not vary with the applied input, in practice, however, only a limited match is possible. The maximum allowable mismatch is set by the operator as the Match Range [ppm] entry in the Measurement Process section. When matching cannot be achieved after 5 attempts the test is aborted.

At the beginning of the test the program determines, for both devices, the exponent n, from the equation $E \propto i^n$ linking the tested device input current i and dc output E. For thermal converters E is the output of a thermocouple measuring temperature of the heater and n is close to 2. For electronic instruments n is close to 1. The value of the exponent n is level dependent and is measured by measuring the change in E when the *dc_normal* input is varied by ±1%. In the setting N Measurements the operator sets the number of times exponent n is measured. Usually one measurement is sufficient.

The remaining entries of the Measurement Process set the devices warm up time, number of Measurements per Cycle i.e. test sequences used in the determination of the ac-dc difference, number of repetitions of Frequency Cycles and the averaging time of the output millivoltmeters.

The test results are printed and/or saved on disk.

Three stations configured for different tasks use the described software. Computers running these stations are connected to the Internet via the Local Area Network. The software is stored in one place, facilitating its maintenance, upgrading and data sharing. Thanks to the network connection, tests can be remotely monitored using, for example, Microsoft NetMeeting. During a recent demonstration of the NetMeeting videoconference, calibration results of a client's instrument were discussed with the client, while sharing with him the screen of the computer running the test.

It should be noted that the program has been written for the instrumentation typical and readily available in the calibration laboratories. It is sufficiently flexible to transform an ac/dc calibrator, with the addition of two millivoltmeters and a computer controlled switch, into an accurate ac-dc transfer comparator. Its design is very flexible and new hardware additions and new test procedures can be easily incorporated. The control program runs under Windows 3.1 or Windows 95 and accepts IEEE-488 boards from two different manufacturers.

4. Voltage build-up

The NRC primary reference standard of the ac-dc transfer is a group of four 20 mA Multijunction Thermal

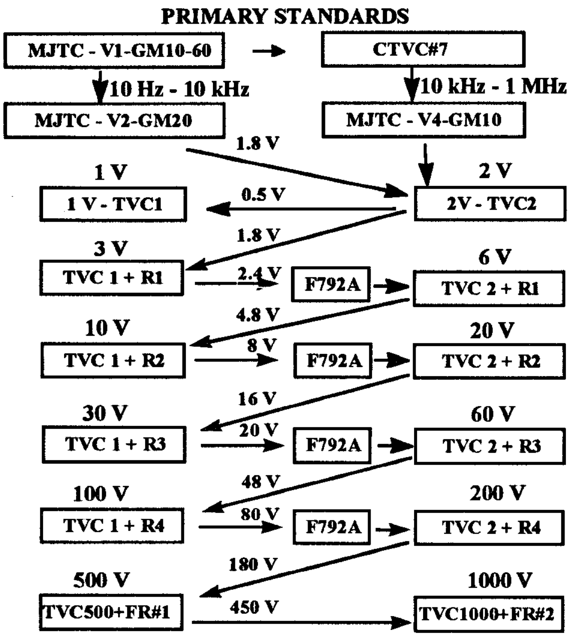

Fig. 4. Schematic of the voltage buildup.

Converters (MJTC). The average value of the group is assumed to be zero in the frequency range 10 Hz – 10 kHz. This frequency range is extended up to 100 MHz by use of a Calorimetric Thermal Voltage Converter (CTVC) developed at NRC, [4] and [5]. In 1995 NRC primary standards were compared with those of other NMI's, showing very good worldwide agreement in the range of frequencies 1 kHz – 1 MHz [6].

The primary references operate at 1 V – 2 V. Extension of this range to higher voltages, step-up, and lower voltages, step-down, is performed using a so-called voltage buildup procedure, [1]. The NRC step-down procedure has been described previously, [7]. The NRC step-up procedure is shown schematically in Fig. 4. For voltages up to 200 volts, two TVC's, TVC1: 2.5 mA, 1 V, TVC2: 5 mA, 2 V, and four range extending resistors, R1 to R4, are employed. For higher voltages, two additional TVC's, V500 and V1000, in combination with two commercial highly stable high voltage resistors, are used.

The voltage build-up procedure starts with a member of the primary standards group, V1-GM10-60, which is used to calibrate a 2 V MJTC, V2-GM20, and the high frequency standard, CTVC#7. The ac-dc difference of the two working standards, TVC1 and TVC2, are now determined by comparison with two MJTC's, V2-GM20 and V4-GM10. The latter MJTC, high-output, high-stability converter, was introduced into the comparison chain for convenience. The 3 V range is obtained by extending the range of the TVC1 using a series range resistor R1 and comparing it to the previously calibrated TVC2. The 6 V range is obtained by calibrating the TVC2 and R1 combination using TVC1 and R1 as the reference. This last comparison cannot be performed directly, thus a highly stable working standard, Fluke 792A (F792A), [8], is used as a transfer. It is assumed that the ac-dc difference of the TVC does not change significantly with the voltage level, thus TVC1 and R1 are calibrated at a lower voltage, 1.8 V, and used at a higher voltage, 2.4 V. This assumption introduces a small uncertainty, less than 1 μV/V, taken into account in the uncertainty budget. The ac-dc difference of F792A is level dependent and both comparisons are performed at exactly the same voltage level.

4.1 High voltage range extension

The buildup procedure is modified at the two highest voltage ranges, 500 V and 1000 V. The low voltage resistors, R1 - R4, are manufactured in-house, by mounting commercial resistors in tubular enclosures, with GR-874 connectors on both ends. The high voltage resistors manufactured in-house using the same technology, were not sufficiently stable. An extensive investigation of different high voltage resistors, custom designed and available commercially, was carried out. In the final buildup, the resistor used as a high voltage range extender of the F792A was adopted. Two such resistors were available, FR#1 and FR#2. These resistors are mounted with type-N rather than GR-874 connectors. Additionally, they are capacitively compensated and adjusted for a specific F792A unit. For this reason two additional TVC's, marked in Fig. 3 as TVC500 and TVC1000, were mounted in enclosures with type-N input connectors, and matched to the two resistors by capacitive compensation of the input.

Stability of the ac-dc difference of the TVC-resistor set

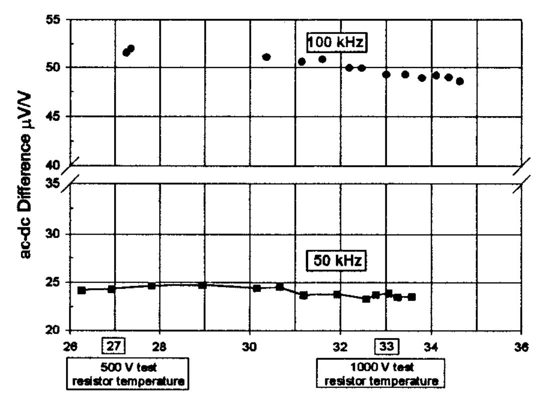

Fig. 5. Temperature dependence of the ac-dc difference of V1000 and FR#2; test voltage 1000 V.

with temperature and in time was investigated during the resistor selection. The high voltage resistor, physically relatively large, dissipates comparatively large power, 5 W at 1000 V. Its temperature changes with the applied voltage and so does its ac-dc difference. Fig. 5 shows the temperature dependence of the ac-dc difference of TVC1000 and FR#2 at 1000 V input voltage and two test frequencies. The change of the resistor temperature was obtained by forcing or restricting airflow around the resistor. Even at 100 kHz, the highest frequency of interest, the change in the resistor ac-dc difference is less that 2 μV/V, when its temperature changes from the temperature it reaches at 500 V test to the temperature of 1000 V test. For comparison, in a similar test, a resistor manufactured by another company changed its ac-dc difference value by more than 16 μV/V.

The experiments indicated that the change of the ac-dc difference with temperature originates mostly in small changes of mechanical dimensions of the housing, thus small changes in residual leakage capacitances. Resistors whose ac-dc difference change with temperature, even after cleaning and aging, [9], are also unstable, probably due to the mechanical hysteresis of the housing. It was assumed that the resistors used have negligible voltage level dependence, even at highest frequencies of interest. Test, such as described in [10], would be required to experimentally confirm this assumption. However, it was confirmed indirectly by an observation that the level change of the ac-dc difference of an F792A on 1000 V range closely matches level change of its ac-dc difference at the lower voltage ranges, using lower value range extenders. This indicates that the high voltage resistor does not contribute a significant level dependent component.

For alternating current, the high voltage resistor, TVC heater resistor, and the input to ground capacitance of the TVC, form a frequency dependent voltage divider. When the input voltage level changes, the temperature and the resistance of the heater change and the ac voltage division ratio, thus the ac-dc difference, change. This source of level dependence of the TVC-resistor assembly can be neglected for lower voltages, i.e. lower value resistors. However, at the highest range, the high value of the resistor and the increased input capacitance of the TVC, caused the ac-dc difference change between 500 V and 1000 V levels to be as high as 10 μV/V at 100 kHz. This error is considered in the error budget.

4.2 Low frequency range extension

The lowest test frequency included in the buildup was 10 Hz. Below this frequency application of TVC's and MJTC's is no longer practical. Their thermal averaging becomes ineffective, the temperature of the heater starts to follow the ac input signal and a large second harmonic component appears at the dc output. This noise becomes significant even at 10 Hz, previously restricting use of NRC primary standard MJTC's to 20 Hz. However, the new integrating millivoltmeters can average out this output noise if their sampling parameters are selected to effectively integrate during an integer number of second harmonic cycles. Only after following this procedure, use of MJTC's was extended to 10 Hz.

The test frequency range can be extended below 10 Hz by sampling the test voltage and calculating the ac value. The Swerlein sampling algorithm [11] developed for the HP3458A voltmeter was adopted for this purpose. The sampling voltmeter approach was compared with the CTVC in the 1 kHz – 0.5 Hz frequency range. The advantage in using the CTVC at very low frequencies is its long time constant, 16 s, as compared to a fraction of a second of TVC's or MJTC's. Preliminary test results from comparison of sampling voltmeter performance with the CTVC are given in [5]. Full results will be discussed in a future contribution.

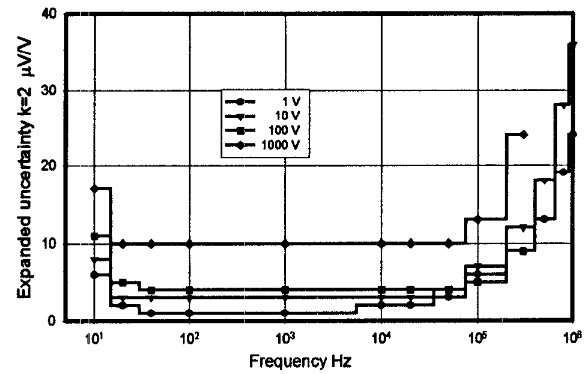

Fig. 6. Expanded uncertainty assigned to the NRC working standard, k=2, 95% confidence level.

5. Uncertainty

The expanded uncertainty, (k=2, 95% confidence level), assigned to the NRC F792A working standard is shown in Fig. 6. At the 1 V level it was calculated as a root-sum-square of three components: uncertainty of the primary standard (type B), statistical uncertainty of comparison (type A), and the uncertainty proportional to the magnitude of the measured ac/dc difference (type B). The comparison uncertainty reflects the noise inherent in the comparison process. It is due to such causes as the short-term instability of the sources, output voltage measurement noise, and small variations in the ambient conditions. It is often less than 1 μV/V for ten consecutive ac-dc difference determinations. The uncertainty component proportional to the magnitude of the measured ac-dc difference reflects several magnitude dependent errors: the uncertainty of n determination, output voltmeter nonlinearity, and back-off voltage uncertainty. This uncertainty component was assumed to be less than 0.1% of the measured ac-dc difference.

The comparison and magnitude dependent uncertainties are associated with every step of the buildup. The third uncertainty component, also associated with every step, is the previously discussed TVC level dependent uncertainty, assumed for both TVC's, TVC1 and TVC2, as type B. This uncertainty was bound by ±1 μV/V at lower frequencies and ±4 μV/V at 1 MHz.

At the test frequencies approaching 1 MHz, the test source grounding configuration, and even length of the cable leads, influence measurement results. Identical tests performed at different test stations, using different sources and different cabling can produce slightly different results. The type B uncertainty assigned to this uncontrollable effect, was bound by ±1 μV/V at 100 kHz and ±10 μV/V at 1 MHz.

At the high voltage range extension, two different sets of converters were used in the buildup. At the highest frequency of interest, 100 kHz, the values obtained for the working standard, using two different buildup paths, exceeded the uncertainty from the known sources. A type B uncertainty, bound by ±10 μV/V at 1000 V and 100 kHz, was incorporated in the uncertainty budget to reflect this lack of closure. Work is continuing to identify the source of this uncertainty.

The voltage buildup and uncertainty assignment was repeated three times, over more than three years. In the process, the voltage and frequency calibration ranges were extended and test uncertainties significantly reduced, at some test points even tenfold.

6. Summary

The paper describes NRC work on improving its ac-dc transfer calibration capabilities: improvement in the design of the ac-dc transfer comparator and its control software, modification in the voltage buildup procedure and redetermination of the working standard uncertainty budget. Hardware additions include stepper motor controlled mechanical switches and complete automation of the F792A test. The design of the ac-dc transfer comparator program is very flexible, new hardware additions and new test procedures can be easily incorporated. The program takes advantage of the Internet. The adopted buildup procedure differs from that used by other NMI's at the highest voltage levels and takes advantage of the commercially available high voltage resistors. The discussed improvements extended NRC calibration capabilities in voltage and frequency. The resulting uncertainties were significantly decreased from the previous values, at some test points even tenfold.

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