An Intercomparison of AC Voltage Using a Digitally Synthesized Source

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Abstract—An ac voltage intercomparison was conducted by the National Institute of Standards and Technology (NIST) to determine the consistency of ac voltage measurements made at various standards laboratories. The transport standard used for this purpose was an NIST-developed digitally synthesized sinusoidal voltage source whose rms value was calculated by measuring the dc level of each of the steps used to synthesize the sine wave. The uncertainty of the calculated voltage at approximately 7-V rms is typically within ±10 parts per million (ppm) from 15 Hz to 7.8 kHz. This approach incorporates a technique of determining ac voltage with reference to a measured standard dc voltage, which is independent of the traditional thermal voltage converter approach. Preliminary measurements made at each of the participating laboratories agree with the calculated value to within ±20 ppm. These results indicate that at 7 V, in the low audio-frequency range, the ac voltage measurement techniques implemented at these laboratories are near the state-of-the-art.

I. Introduction

THE MOST accurate ac voltage measurements are normally made, at the standards laboratory level, by comparing the unknown ac voltage to a known dc voltage using a thermal voltage converter (TVC). Techniques for measuring the ac–dc difference of TVC's have been well documented [1] and state-of-the-art uncertainties for ac-dc difference are less than ±1 part per million (ppm) in the audio-frequency range. Automatic systems which make use of thermal converters to measure ac voltage have also been described [2], [3]. The performance of these systems depends not only on the TVC's but also on other system components, and it is estimated that the state-of-the-art uncertainty for audio-frequency ac voltage measurements is between ±2 and ±10 ppm.

Until recently there has been no way to verify the accuracy of these ac voltage measurement systems other than by estimating the errors contributed by each component in the system. Even comparisons between systems were not feasible because a sufficiently stable voltage source capable of being transported between systems did not exist. In 1988, a calculable digitally synthesized source (DSS) [4], developed at the National Institute of Standards and Technology (NIST), was tested as a transportable standard to verify the accuracy of ac voltage measurement systems. The results of measurements made at NIST, and standards laboratories at Hewlett Packard Company, Lockheed Missiles and Space Company, and the Naval Air Test Center (NATC) are reported in this paper.

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II. Transport Standard

The DSS output voltage waveform is actually a "staircase" approximation of a sine wave consisting of steps generated when digitally stored sine values are applied to a digital-to-analog converter (DAC). This approximation approaches a pure sinusoidal waveform as the number of steps per period is increased. The rms value of an ideal staircase-type waveform can be calculated by measuring the static voltage of each step. If the steps were perfect, the rms value would be the same at all frequencies; however, transient energy at the step transitions (often referred to as "glitch" energy) alters the step shape as the frequency is increased, making it difficult to accurately predict the rms value.

Switching glitches in the waveform may be reduced by toggling between two DAC's that are updated at different times [5]. A block diagram of the DSS, which employs this dual-DAC deglitching scheme, is shown in Fig. 1. Digital sine values, stored in a read-only-memory (ROM) are sequentially latched into multiplying DAC's, MDAC1 and MDAC2, by a two-phase clock. Fast CMOS switches ($S_1 - S_4$) steer the output current from each MDAC to ground until the current step has settled, and then into the summing node of a wide-band operational amplifier. While one DAC is settling, the other DAC supplies the output step and, thus most of the transient energy is dissipated in the ground plane. This technique does not eliminate charge injection from the switch, or amplifier errors. Other sources of error include feedthrough from the clock and short-term instability of the MDAC and its dc reference.

The DSS uses two high-resolution 18-bit MDAC's; however, to simplify the circuit, only the most significant 8 bits are used to synthesize the sine wave, which is constructed of 128 steps per period. While 8-bit quantization may pose a problem if a pure sinusoidal waveform is required, the contribution to the rms value due to quantization noise is negligible [4]. Similarly, the "sampling" harmonics introduced by the waveform synthesis process contribute only about 100 ppm to the rms value of the

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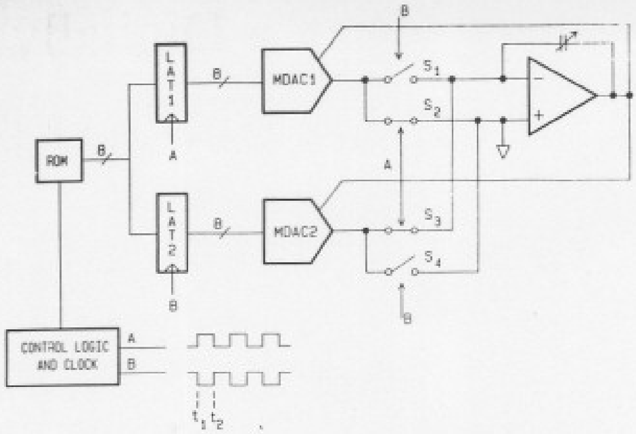

Fig. 1. A block diagram of the DSS.

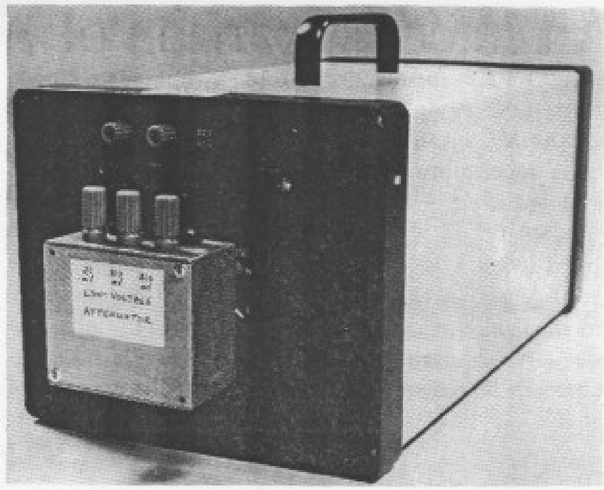

Fig. 2. The DSS and associated low-voltage attenuator.

signal. This condition does require a wide-band system to measure the synthesized waveform accurately to the ppm level. The DSS has an internal clock that is switch-adjustable in powers of two, between 244 Hz and 2 MHz (the maximum usable clock frequency), resulting in sine wave frequencies between 1.9 Hz and 15.6 kHz. For higher resolution, an external clock may be used to generate sine waves from near dc to 15 kHz (the dual-DAC deglitching scheme does not impose a minimum clock-frequency limit).

With a 10-V dc reference, the generated sine wave has a peak value of 10 V and an rms value of approximately 7.07 V. The amplitude of each step of the waveform is measured "off line" with a precision dc digital voltmeter (DVM), and the rms value of the generated waveform is determined by computing the square root of the mean value of the square of each of the measured step voltages:

$$V_{\text{rms}} = \left(\sum_{i=1}^{N} \left[v_i (1 + C) \right]^2 / N \right)^{1/2}$$

where

- v_i voltage of the ith step,
- N number of steps in one period,
- C DVM correction.

The DSS output amplitude may be reduced by lowering the dc reference voltage. The MDAC's used to generate the waveform can operate with a dc reference voltage between 0 and 10 V to produce 0 to 7.07-V rms sine waves. However, the best performance is achieved with reference voltages between 5 and 10 V and, to accurately generate low voltage signals, an external attenuator is employed. For the measurements reported in Table II, the 7-V signal was scaled to 100 mV using a passive resistive divider. Fig. 2 shows the DSS (front view) with the external attenuator plugged into the 7-V output terminals.

III. Thermal Measurement Systems

A. At NIST and NATC

The NIST and NATC ac voltage calibration systems [3] are semiautomatic TVC-based systems used to calibrate

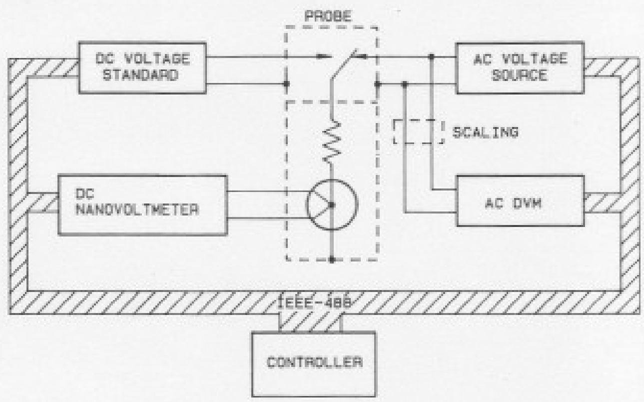

Fig. 3. Block diagram of the TVC-based voltage measuring systems at NIST and NATC.

ac sources and ac voltmeters. As shown in Fig. 3, each system consists of a controller, a programmable dc voltage standard, a measurement probe (housing a programmable ac/dc switch and an NIST-calibrated TVC), a digital nanovoltmeter to read the TVC output, and the unit-under-test (an ac voltage source). In normal operation, the value of the dc voltage and the nanovoltmeter readings (with the TVC connected alternately to the ac source and the dc standard) are used to compute the rms value of the ac source. Using these systems, at 7 V in the 30-Hz to 7.8-kHz range, the estimated uncertainty of measurements made on the DSS was ± 10 ppm for the NIST system and ± 15 ppm for the NATC system.

Tests were also performed at 100 mV, considerably below the normal operating range of TVC systems. At this voltage level, NIST calibrations were made using two different scaling techniques.

1) The ac source was characterized at 1 V (using the TVC system) and then scaled to 100 mV with a binary inductive voltage divider (BIVD). This voltage was used to calibrate a stable ac DVM which was then used to calibrate the 100-mV output of the DSS.

2) The ac source was characterized at 700 mV using a 7:1 micropot (a coaxial resistive divider consisting of a

thermoelement heater and a terminating resistor). The voltage across the terminating resistor (100 mV) was calibrated by measuring the current in the heater on ac and reversed dc. A stable ac DVM was used to transfer from the 100-mV output of the micropot to the DSS.

The uncertainty of the 100-mV DVM calibrations was estimated to be ±40 ppm in the 30-Hz to 7.8-kHz range.

At NATC, a similar step-down procedure was employed using a 20-dB RF attenuator to scale a characterized 1-V signal to 100 mV. The actual attenuator ratio was measured at dc and at 1 kHz (using an inductive divider). It was assumed that the attenuator had negligible frequency response errors. Again, a DVM was used as a transfer standard to calibrate the DSS output. The uncertainty of this calibration was estimated to be ±100 ppm in the 30-Hz to 7.8-kHz range.

B. At Hewlett Packard

At Hewlett Packard, an NIST-calibrated set of primary standard TVC's is used to determine the errors of a commercially available ac–dc thermal transfer standard. Several modifications are made to the transfer standard and special algorithms are implemented in the control software to enhance its performance. The measured errors of the transfer standard are stored in a file and used to correct its readings when it is used to measure an unknown ac voltage. It is necessary to generate error data for each voltage and most frequencies to be used. These error data represent the difference between the response of the automatic transfer standard and the actual rms input voltage. The node at which the voltage is actually determined is the center of the "tee" connector which joins the automatic transfer standard and the primary standard TVC. The process for generating the error data is automated and described in [7].

Since the automatic transfer standard compares the unknown ac voltage to a single polarity of dc voltage, and its dc turnover error is generally a function of the applied voltage, interpolation of data between amplitudes will lead to unknown errors. However, limited interpolation between frequencies can be used. The unknown ac voltage can be either from a source or applied to a measuring instrument. In the latter case, a source is used to drive the measuring instrument and the automatic transfer standard in parallel. Measurement of the DSS output was accomplished by connecting it to the transfer standard input using remote sensing. Since the transfer standard draws appreciable current, changes in the tee connector resistance are a potential source of error which must be monitored.

The data on the 100-mV DSS output were taken by comparing the output of a specially built resistive divider to the DSS low-voltage output using an ac DVM as a transfer standard. The special divider was calibrated using both dc and ac ratio techniques.

The estimated uncertainty at the time of measuring the DSS output was ±50 ppm at 7 V and ±70 ppm at 100 mV in the frequency range from 30 Hz to 7.8 kHz.

C. At Lockheed

A semiautomatic, TVC-based ac measurement system is used at Lockheed. Instead of physically matching the output from the dc source with that of the ac source, "computational matching" (CM) is performed to determine the matching dc voltage. The measurement technique and software were basically adopted from the TVC calibration system described in [6]; however, there have been some hardware modifications. A double-pole, double-throw relay mounted in a metal enclosure is inserted directly between the unknown ac source terminals and the TVC. An IEEE-488 controlled switch provides remote control. The switch is similar to that described in [8] with the exception that the relay allows the external sense lines of the dc source to be switched through the measurement plane of the TVC. The TVC used for measurement of the DSS output was specially constructed to have a full-scale input of 7.07 V and was mounted in a shielded enclosure. The ac–dc difference of this TVC was compared to an NIST calibrated 10-V TVC.

Verification of the measurement results were obtained in two ways. First, the same hardware configuration was used and the physical matching was performed manually. Second, a commercial ac source was measured at 7.07 V at each test frequency. An ac-DVM was then used as a transfer device to compare the output of the ac source to that of the DSS. The results of the three methods agreed to within ±3 ppm at 7.07 V. The total uncertainty at this voltage level was between ±30 and ±40 ppm in the 30-Hz to 7.8-kHz frequency range.

At present, high accuracy calibration facilities at Lockheed are limited to 500 mV. There are plans to extend the calibration capability down to the 100-mV level using one or more of the techniques described above.

IV. Results

For the intercomparison, the DSS was calibrated at NIST and then shipped (in a special shipping container) to each of the three laboratories. It was returned to NIST for an additional calibration before being sent to the next laboratory. The differences between the calculated DSS voltage and the thermally-measured voltage for each laboratory are given in Tables I and II. The corrections (in ppm) are added to the calculated voltage to give the measured output voltage of the DSS (a negative correction indicates that the calculated voltage is higher than the thermally-measured voltage).

The Lockheed results are averages of measurements made manually early in the intercomparison and measurements made nearly one year later on the automatic system described in [6]. Results at 3.9 and 7.8 kHz were obtained by manual measurements only.

The data from the various NIST calibrations, performed during the intercomparison, agreed to within the uncertainty of the NIST voltage measurement system, indicating that there was no significant drift in the DSS. Thus for simplicity, only the average NIST results are reported. Results at 15 Hz are included to emphasize that the measurement systems used have low-frequency errors

TABLE I
7-V DSS CORRECTIONS (PPM)

Frequency (Hz):	15	30	61	122	244	488	976	1.95k	3.9k	7.8k
NIST:	-10	1	-1	1	0	0	0	-3	-4	-1
Hewlett Packard:	-20	0	1	-1	0	0	1	-4	-4	-2
Lockheed:	2	-1	1	4	6	4	2	-4	4	4
NATC:	-2	-7	-5	-5	-5	0	4	3	4	3

TABLE II
100-mV DSS CORRECTIONS (PPM)

Frequency (Hz):	15	30	61	122	244	488	976	1.95k	3.9k	7.8k
NIST:	-22	-25	-31	-37	-21	-18	-19	-26	-23	+10
Hewlett Packard:	-46	-23	-31	-32	-2	-15	3	-37	-37	-8
NATC:	-60	-63	-12	-16	-16	-16	-16	-4	-27	-80

that depend on system components (there is no reason to suspect that the DSS frequency degrades at low frequencies). It should be noted that the DVM used in the step calibration was calibrated with the same dc voltage standard used in the thermal calibration; thus only the instability and nonlinearity of the dc voltage standard and DVM contributed to dc errors in each measurement system.

V. CONCLUSIONS

The calculable DSS described in this paper represents a limited means for evaluating wide-band ac voltage measurement systems at the ± 5 to ± 10-ppm level. The four standards laboratories that participated in this intercomparison have sophisticated TVC-based ac voltage measurement systems with claimed uncertainties ranging from ± 10 to ± 100 ppm in the 30-Hz to 7.8-kHz frequency range. The NIST and NATC systems, while similar, are not identical, and the Hewlett Packard and Lockheed systems were developed independently. The common tie is that system uncertainties are all based on NIST calibrations of the ac–dc difference of TVC standards.

Agreement between the digital-synthesis and TVC-based measurement techniques, which is within ± 20 ppm at 7 V and ± 100 ppm at 100 mV at all four laboratories, is a result of extensive measurements made on each system. Most importantly, this agreement reinforces the 7-V and 100-mV uncertainty claims of each system.

An important feature of the DSS is that it can be calibrated *in situ* using local dc standards; this step calibration was performed before and after each thermal measurement. Therefore, the predicted rms value was known ahead of time and this knowledge could have biased the thermal measurements. The possible effects of this bias are somewhat reduced by the fact that the thermal measurements at each of the laboratories were performed on automatic systems with little or no operator interaction. In addition, there was a relatively large spread of errors at 15 Hz. This is probably due to the tracking (low frequency) errors of different TVC's.

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