A Multirange Standard for AC/DC Difference Measurements

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***Abstract*—A standard for ac/dc difference measurements which incorporates an integrated circuit thermal sensor is described. The basic instrument (SL851) is intended for use in the frequency range of 100 Hz to 1 MHz and for voltage levels of 600 mV to 200 V. Coupled with an amplifier or high-voltage range resistors, the full-scale ranges can be extended down to 200 mV and up to 1000 V. This new standard is being developed to take advantage of the capabilities of the National Bureau of Standards (NBS) to give uncertainties of 10 ppm, under special conditions, in the frequency range of 100 Hz to 20 kHz, and for voltages of 5–100 V. It is expected that the SL851 will have ac/dc differences of only a few parts per million for levels up to 60 V at frequencies up to 100 kHz. Other advantages, as compared to vacuum thermoelements, are a shorter settling time and an output level of 2 V instead of a few millivolts. A power supply which can be operated on batteries was also developed.**

This paper provides a brief description of the SL851 instrument and associated high-voltage range resistors, preamp, and power supply. The factors that were considered in the physical construction are also addressed. A test configuration is described and the data obtained are presented and discussed.

I. Introduction

For many years, thermal converters using vacuum thermoelements have been used as the detector for comparing the rms voltage level of an ac signal to that of a dc signal or an ac signal at a different frequency. Based on the equivalent heating power of rms ac as compared to dc, thermoelement voltage converters have fairly well-defined ac/dc differences [1]. Typically, there is a calibration uncertainty of 20 ppm in the ac/dc difference for these converters at frequencies of 20 Hz to 20 kHz and voltages of 0.5–1000 V.

Vacuum thermoelement devices, compared to solid-state devices, have a very long thermal time constant. It may take a half-minute or longer to regain thermal equilibrium when transferring between the reference voltage and the voltage being measured. This long time delay causes an additional burden on the stability requirements for the voltage source being used. Another disadvantage of vacuum thermoelements is their low output voltage of a few millivolts. To measure ac/dc differences with a resolution of 1 ppm requires resolving a few nanovolts.

There is an obvious desire for a device with less uncertainty in the stated values of ac/dc difference, and a shorter time to stabilize. It was with these goals in mind that the SL851 rms sensor was developed.

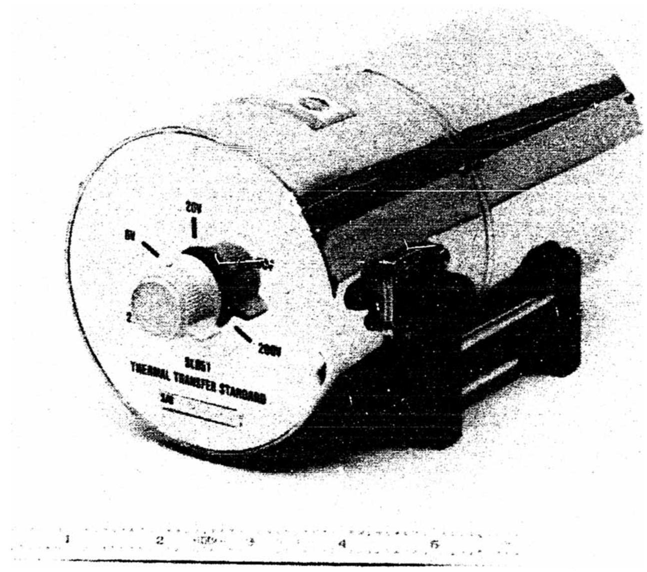

Fig. 1. SL851 ac/dc converter.

The SL851, shown in Fig. 1, contains an rms sensor, feedback amplifier, buffer output amplifier, and five switchable range resistors. A decoding section is included on the range switch which can be used in a system application to help prevent overvoltage conditions. There is also a separate power supply module and, as accessories, an amplifier and two high-voltage range resistors.

II. Circuit Description

A. Sensor

The integrated circuit thermal sensor [2] is the key to the improved performance of the SL851 as compared to previous devices. It is presently employed in the Fluke 8506A Digital Multimeter [3] in a patented ac error-correction technique described in [4], as well as in SL851. A simplified diagram of the thermal sensor is shown in Fig. 2.

The input voltage V_{in} is applied to $R1$ and resulting heat, proportional to the rms power level, is coupled to the base–emitter junction of $Q1$. The well-known relationship

$$V_{be} = (kT/q) \ln (I_c)$$

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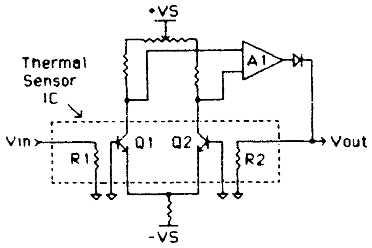

Fig. 2. Diagram of thermal sensor circuit.

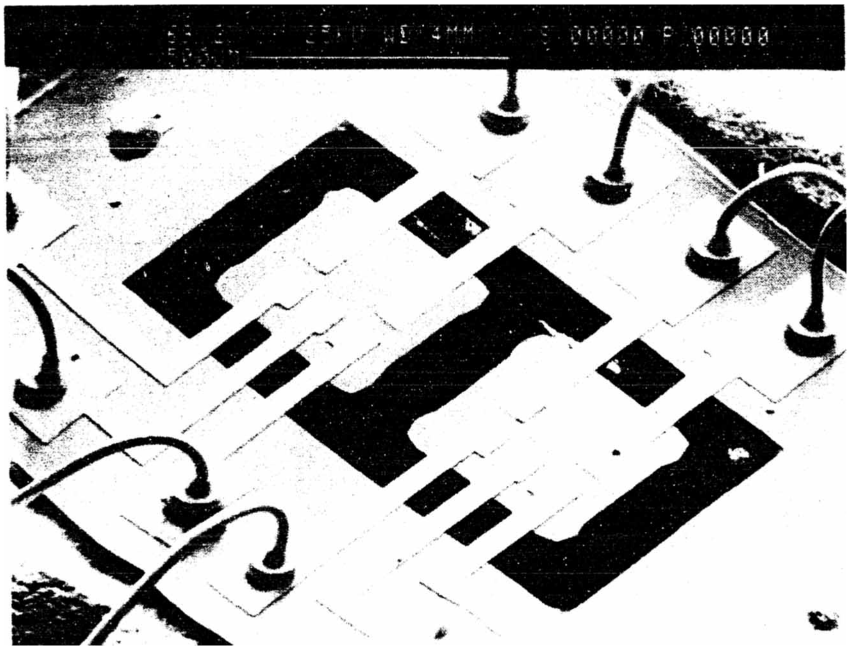

Fig. 3. Thermal sensor die (magnified).

is used in a feedback circuit

where

V_{be}	the base-emitter voltage,
k	Boltzmann's constant,
T	temperature in degrees Kelvin
q	charge on an electron (1 eV), and
I_c	collector current.

The heat generated due to the input voltage V_{in} produces a change in the base-emitter voltage of $Q1$. This error voltage is amplified by $Q1$, $Q2$, and $A1$ and applied to $R2$. The circuit drives itself into a balanced condition which results in a dc output voltage V_{out} approximately equal to the rms value of the input voltage V_{in}. Although the basic approach was developed by Ott [5], improvements in resistor technology and thermal isolation have produced improvements in the performance of these devices.

A photograph of the semiconductor die (magnified) is shown in Fig. 3. Each transistor-resistor pair is isolated on an island supported by leads that extend across the air gap between the islands and the surrounding frame. The leads are made of 304 stainless steel selected for its high electrical conductivity and low thermal conductivity. It has been determined that the thermal resistance of the device is better than 8400°C/W. The determination is based on measurements of the change in base-emitter voltage as a function of applied input power and the knowledge that the base-emitter voltage changes approximately 2.1 mV/°C.

B. Feedback Circuit

A simplified diagram of the feedback circuit is shown in Fig. 4. The rms sensor output is amplified by integrator $A1$, followed by a circuit comprised of $A2$ and its feedback circuit $H1$, and $H2$ and $A3$. The function of $A2$, $H1$, $H2$, and $A3$ is to provide improved transient response characteristics by implementing a square root function into the feedback path. $A4$ is a buffer amplifier which provides a 2-V dc output for 2-V rms at the sensor input.

C. Input Attenuator and SL853 High-Voltage Range Resistors

In front of the rms sensor circuit is an input attenuator consisting of five switchable range resistors mounted on

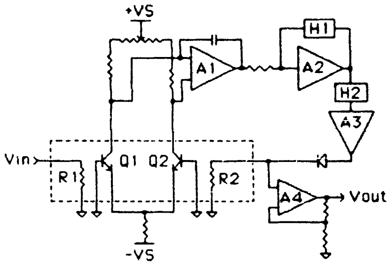

Fig. 4. Simplified diagram of feedback circuit.

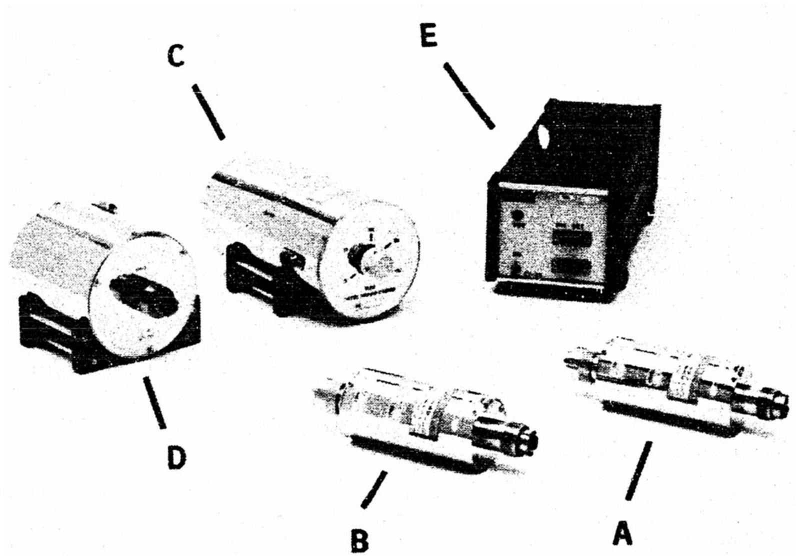

Fig. 5. SL851 and accessories.

a rotary switch selected for low thermals and repeatability of contact resistance. The thermal sensor resistor of approximately 400 Ω in conjunction with the range resistors result in full-scale ranges of 2, 6, 20, 60, and 200 V. Additional accessory high-voltage range resistors (*A* and *B* in Fig. 5) provide full-scale ranges of 600 and 1000 V. The SL851 is set to the 2-V range when using these range resistors. For comparison, the SL851 is shown as *C* in Fig. 5.

D. SL852 Preamp

An accessory preamplifier (*D* in Fig. 5) is used to provide the full-scale ranges of 200 and 600 mV. The amplifier incorporates a differential FET input stage coupled to a custom thin-film hybrid amplifier. The result is a gain of ten and a bandwidth of approximately 30 MHz. The SL851 range switch is placed in the 2- and 6-V positions when using the preamp for 200 and 600 mV, respectively.

E. SL854 Power Supply

The power supply is a differential supply of +/−15 V (*E* in Fig. 5). The supply contains batteries which will provide power for the SL851 for approximately 8 h before recharging is needed. Operation on batteries reduces the scatter (probably due to ground loops) in the measurement results.

III. Construction

The SL851, preamplifier, and high-voltage range resistors are each housed in cylindrical chrome-plated brass tubes. The tubes for the SL851 and preamplifier are 4 in in diameter and the range resistors are housed in 2-in tubes. All signal connectors are GR874. This type connector was chosen because the intended use of the SL851 is to replace thermal converters which have that type of connector. The cylindrical shape allows the tubes to be rotated on their supports in order to accommodate an arbitrary rotational position of the mating connector. GR874 connectors incorporating slip joints could have been used, but they would add an additional component to the uncertainty in the measurements.

A separate cavity in the SL851 is used to house the range switch assembly. This is done to eliminate electromagnetic coupling from the input connector and range resistors to the rms sensor and surrounding circuitry as well as to provide thermal isolation between the attenuator and rms sensor. The high-voltage range resistors are mounted coaxially in separate tubes for two reasons. The resistors must be physically distant from other components in order to make the frequency response flatter. The large physical size of the resistors makes it impractical to maintain the needed separation and house them in the same enclosure with the other range resistors. Another important consideration is that of maintaining thermal isolation between the high-power resistors (and corresponding high heat) and the thermal sensor circuit.

IV. Test Results

A typical test setup for comparison of a conventional thermal voltage converter to the SL851 is shown in Fig. 6. A stable dc voltage source is connected through a tee to a standard thermal voltage converter and the unit under test (UUT). The dc voltage is adjusted to a reference input level and the outputs of the standard and UUT are noted. The polarity of the dc voltage is reversed and the output levels noted again. The response to dc for each unit is then taken as the average of the two readings. The dc source is replaced by an ac source at the desired frequency and the level adjusted to give an input to the UUT which produces the same output as the average of the dc inputs. The output from the standard is then noted and, taking into account the ac/dc difference of the standard, the ac/dc difference of the UUT is calculated.

Table I shows the goals for uncertainties for the SL851 (a multirange device) and accessories and the present uncertainties obtainable from NBS for single-range thermoelements. The 10-ppm uncertainties are only available in special cases. Also, the calibrations at a level of 200 mV are handled on a case-by-case basis with uncertainties determined at the time of measurement.

Table II shows the results of measurements taken in the Fluke Primary Standards Laboratory, in April 1985, on two SL851 instruments, one SL852 amplifier, one SL853 and one SL153 600-V range resistor, and one SL853 and one SL153 1000-V range resistors. The SL153 range resistors are usually used with vacuum thermoelements, however, the SL851 was designed for compatibility with the SL153 resistors. The measurements were made using vacuum thermoelements as working standards. The low output voltage of the vacuum thermoelements prevented having sufficient resolution to report the data with greater than 10-ppm resolution. The uncertainties in ac/dc difference for the working standards were slightly greater than those shown in Table I for present NBS calibrations.

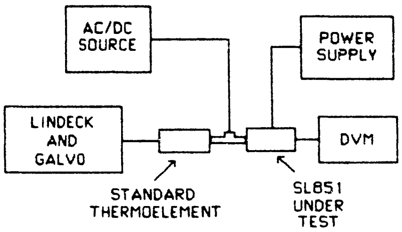

Fig. 6. Typical test setup.

TABLE I
Goals for Uncertainty Spec/Present NBS Uncertainty for Typical Single-Range TVC (at Time of Measurement) (ppm)

	100Hz-20kHz	20kHz-50kHz	50kHz-100kHz	100kHz-500kH	500kHz-1MHz
200mV	30/**	50/**	70/**	300/**	500/**
600mV	20/20	30/30	50/50	200/200	300/300
2V	10/20	15/30	25/50	100/200	150/300
6V	10/20*	15/30	25/50	100/200	150/300
20V	10/20*	15/30	25/50	100/200	150/300
60V	10/20*	15/30	25/50	100/200	150/300
200V	10/20	15/30	25/50		
600V	20/20	30/30	50/50		
1000V	20/20	50/30	100/50		

* Under special circumstances, NBS is able to give 10 ppm uncertainty for these voltages and frequencies.

** The uncertainties at 200 mV are assigned at the time of calibration.

The information in the above table was furnished by National Bureau of Standards, Gaithersburg.

TABLE II
AC/DC Differences for SL851 and SL851 in Conjunction with SL852 and in Conjunction with SL853 and SL153 Range Resistors

AC/DC Difference for SL851 S/N 002 (ppm)

RANGE	500 Hz	20 kHz	50 kHz	100 kHz	500 kHz	1 MHz
2 Volt	0	0	0	-10	+10	-30
6 Volt	0	0	0	0	+10	0
20 Volt	0	0	0	-10	-30	-80
60 Volt	0	0	0	0	+160	
200 Volt	0	-10	-10	+3		

AC/DC Difference for SL851 S/N 004 (ppm)

RANGE	500 Hz	20 kHz	50 kHz	100 kHz	500 kHz	1 MHz
2 Volt	0	0	0	-10	+20	+10
6 Volt	0	0	0	0	+20	-10
20 Volt	0	0	0	-10	-50	-210
60 Volt	0	0	0	0	+120	
200 Volt	0	-10	-10	+40		

AC/DC Difference for 200 and 600 mV into SL852 Amplifier with SL851 S/N 002 (ppm)

RANGE	500 Hz	20 kHz	50 kHz	100 kHz	500 kHz	1 MHz
200 mV	-80	-70	-60	-40	+100	0
600 mV	-70	-80	-70	-60	0	-50

AC/DC Difference for SL851 S/N 002 with 600 V SL853 and with 600 V and 1000 V SL153 Range Resistors (ppm)

	RANGE	500 Hz	20 kHz	50 kHz	100 kHz
SL853	600 V	-10	-10	+10	+140
SL853	1000 V	-20	-80	-130	-120
SL153	600 V	0	0	0	+40
SL153	1000 V	0	0	-10	0

As can be seen from the data, the ac/dc differences are very small for frequencies of 500 Hz (lowest frequency for which data were taken) to 100 kHz for voltages of 2-60 V. The differences became significantly larger for the 200-V range at a frequency of 100 kHz. The 200- and 600-mV ranges had differences of −40 to +100 ppm which are not understood at the time of this writing. More investigation is needed in order to understand and, if possible, reduce these large ac/dc differences. The 600- and 1000-V SL153 range resistors produced results consistent with previous measurements using the same range resistors with conventional vacuum thermoelements. The 600- and 1000-V SL853 range resistors produced a higher ac/dc difference due to the difference in construction. The SL153 contains a tuning sleeve which surrounds the re-

TABLE III
AC/DC DIFFERENCE (IN ppm) FOR SL851 S/N 002, MARCH 1986

RANGE	100 Hz	500 Hz	1 kHz	20 kHz
2 Volt	0	-1	2	3
20 Volt	6	7	9	6
RANGE	50 kHz	100 kHz	500 kHz	1 MHz
2 Volt	-1	1	-3	-27
20 Volt	4	2	-32	-89

sistor body and which can be adjusted to optimize the frequency response. The SL853 range resistors do not contain the adjustable sleeve. The reasons for developing the SL853 when the SL153 range resistors are available are twofold: the cost of building the SL153 is considerably higher and the SL853, due to the different construction, is much more rugged. The SL153 ac/dc difference can be affected significantly by a sharp mechanical shock to the device.

Table III contains additional data, obtained in March 1986, on SL851 S/N 002. These data were obtained using a different system from that used in the previous measurements. The system used for the data has a resolution of 1 ppm, however, there has not been a rigorous error analysis done on this system. The typical transfer uncertainty is estimated to be less than 5 ppm. The data in Table III are relative to A55 thermal voltage converters as working standards with 0-ppm ac/dc differences, however, they are different standards from those used for the measurements in April 1985.

The largest observed difference between the data taken in April 1985, and those taken in March 1986, was 13 ppm, which occurred at 500 kHz on the 2-V range. However, as mentioned, different standards were used for the two sets of data with uncertainties for the ac/dc differences of the standards much greater than 13 ppm.

Measurements were also taken on turnover (the difference in outputs for the same magnitude but opposite polarity of dc inputs), in March 1986, on SL851 S/N 002 and two typical Fluke A55 thermal voltage converters. The result was 230 and 270 ppm for the 2- and 20-V A55's and 7 and 10 ppm for the SL851 2- and 20-V ranges, respectively.

V. SUMMARY

A multirange standard for ac/dc difference measurements in the frequency range of 100 Hz to 1 MHz was described. The basic instrument contains switchable range resistors for ranges of 2–200 V, and when coupled with a preamplifier or high-voltage range resistors, will provide full-scale ranges of 200 mV to 1000 V. The rms sensor and surrounding circuitry was described as well as the construction of the supporting hardware and accessories. Preliminary measurement results were presented and briefly discussed along with goals for uncertainties for the ac/dc differences for these new standards. The 2-V output for full-scale input, short thermal time constant, and the small turnover error should enable this improved technology to advance the state of the art in ac/dc difference measurements for a wide range of levels and frequencies.

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