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Broadband Ac-dc Difference Calibrations of Current Shunts up to 100 A at NIST

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Abstract:
NIST is now offering broadband, ac-dc difference calibrations of current shunts from 3 A to 100 A, and at frequencies up to 30 kHz, as special tests. We present an overview of this new service including the design and construction of the NIST standard, high-current shunts. We describe the build-up procedure and two-stage current transformers being used to characterize the NIST standards, as well as the uncertainty analysis for these calibrations. Future plans, such as the extension of the frequency range up to 100 kHz, are also discussed.

Introduction

In response to requests from clients, NIST is now offering broadband, ac-dc difference calibrations of ac-dc transfer shunts from 30 A to 100 A. Frequencies range from 30 kHz at 30 A to 10 kHz at 100 A. These services expand on the presently offered 20 A service for frequencies up to 100 kHz. Industrial needs are beginning to require high-current/high-frequency traceability for such applications as high-frequency welding techniques, harmonic power measurement by the utilities, and power supply manufacturers needing accurate measurements of current in high-current switching supplies. The decision to extend the NIST calibration service for current shunts is also driven in part by the requirement for NIST traceability of current shunts to support a new 100 A, 100 kHz transconductance amplifier coming into use in the US Air Force's calibration system. This new amplifier is a commercial version of a previously reported NIST development [1].

To support this new service, we have constructed new high-current transfer shunts using a three-terminal, coaxial design, and also wide-band, two-stage current transformers. Characterization of the reference standards is underway based on a current shunt build-up process and on ac-ac comparisons with the current transformers.

Three-Terminal, Coaxial Transfer Shunts

Traditionally, ac-dc difference calibrations of current shunts at NIST has relied on comparison to artifact standard thermoelements whose heaters carry the full signal current. The standard thermoelements are characterized by extensive study including a current build-up process [2, 3]. The existing NIST standard thermoelements are limited to 20 A. Although some work has been done on the construction of high-current multimodules containing multiple thermoelements [4], it was decided early in this project that reference shunts would be best suited as standards for these very high currents.

In order to appreciate the difficulty in achieving low ac-dc differences of high current shunts one must recognize the design tradeoffs of a high- current, wide-band shunt. The power dissipated in a shunt is directly proportional to the resistance, so a lower resistance reduces the power dissipated and hence the temperature rise, but if the resistance is reduced too much, the voltage drop becomes too small to be suitable for measurement. In addition, lowering the resistance exacerbates the problem of maintaining low reactance and skin-effect. Thus, the tradeoff becomes one of manageable power dissipation, sufficient voltage drop, and acceptable ac-dc difference. As an example, consider a shunt with a resistance of 1 mΩ. It will develop 10 W of dissipation at 100 A and 0.1 V across the potential terminal. This is a very manageable dissipation; however, even tolerating a change in impedance of 10^{-3} and neglecting skin-effect, these parameters require an inductance in the resistance element of less than 70 pH at 100 kHz. A further requirement in any practical shunt is maintaining a reasonably low impedance at the current terminals in order to minimize the drive or compliance voltage. Clearly such requirements dictate some kind of coaxial structure.

Candidate, prototype devices from commercial sources were evaluated. Most of the designs submitted where found to exhibit very large ac-dc differences of the order of 30,000 μA/A at 100 kHz. Such large ac-dc differences can be measured, albeit with some difficulty; however, the measurement uncertainty would become quite large. As might be expected from shunts with such large frequency coefficients, these sample shunts generally exhibited poor stability, making them unsuitable as reference standards.

Early work at NIST in the development of wide-band transconductance amplifiers identified the need for stable, wide-band, high-current shunts with reasonably flat frequency response. It was found that a surprisingly high quality four-terminal shunt could be obtained by paralleling a large quantity of low-power metal film resistors between two copper plates and connecting the potential terminal at the center of the resistor matrix [5]. This led to other general-purpose shunts used at NIST that consisted of a matrix of film resistors soldered between two double-sided circuit boards. This approach has become the preferred technique of the shunts used in the commercial 100 A transconductance amplifier [6].

Fig. 1 shows an exploded view of one such NIST 100 A shunt. Two hundred-fifty, 1 Ω, 2 W, axial-leaded metal film resistors soldered between double-sided printed circuit plates in a circular array provide a nominal 4 mΩ resistance. The resistors are arranged in three concentric circles near the outer perimeter of the boards. Separate potential leads connected to the inside copper layer of the array provide the potential connection that is terminated at an isolated BNC type connector. Type LC male and female connectors provide the input and output current terminals. LC type connectors were chosen to be compatible with the commercial transconductance amplifier and to provide a good coaxial environment that can handle 100 A. Their center conductors are attached to the center point of the resistor array. The entire resistive element is housed inside an aluminum cylinder and end plates.

Unlike line terminating, or two terminal shunts, this in-line configuration allows an unknown to be inserted in the current circuit while maintaining a coaxial environment. As such, this configuration is ideal for comparing other current measuring devices such as shunts and current transformers. If the shunt is used only by itself, then a low-inductance shorting cap is screwed to the female connector. This coaxial structure reduces the total inductance of the shunt so that less than 3.5 V rms compliance voltage is required to drive 100 A rms and 100 kHz.

The resistor array is potted inside the coaxial enclosure with a room temperature curing silicone rubber, exhibiting very high thermal conductivity with good insulating qualities. This compound displaces all the air inside the structure and provides a low thermal resistance from the resistor elements to the finned outer case. In addition, forced-air cooling results in thermal equilibrium after about 60 minutes warm-up with 40 watts of dissipation. While it is not within the scope of this paper, several experiments indicate that the pick-off location of the potential leads from the resistor array is critical and can cause sign reversals of ac-dc differences below 10 kHz. Potential lead location was optimized for maximum flat response.

Wide-Band, Two-Stage Current Transformers

Current transformers provide a useful means of scaling high levels of current to lower levels of current that can be measured by monitoring the voltage drop across a secondary burden resistance. They also have the inherent advantage of providing good isolation and rejection of common-mode voltages developed across multiple current sensing devices. Most ordinary current transformers exhibit relatively large errors, which are critical functions of the operating current, secondary burden, and frequency. However, the work done by Souders [7] showed that amplifier-aided multistage current transformers can achieve very high accuracies over the frequency range of 50 Hz to 10 kHz.

Fig 2. shows the schematic diagram of an amplifier-aided, two-stage transformer. Basically, the amplifier serves two purposes: to provide a very low burden voltage to the tertiary winding, and to sum the currents of the tertiary winding into the burden of the secondary winding. The supply voltages are best provided by a battery so that signal currents do not have to travel in and out of a mains-connected supply. The battery-powered system allows the secondary burden voltage to float, and so prevent unwanted ground loops.

This design was implemented to form a 100 A two-stage, amplifier-aided current transformer. The tertiary portion of the transformer was constructed by winding 100 turns of #18 awg magnet wire equally distributed around a high permeability, laminated core. A second high permeability, laminated core is stacked on top of the tertiary wound core. The secondary winding is formed by winding 100 turns of #18 awg magnet wire equally distributed around the stacked core assembly. The entire core assembly is held in place with glass type insulating tape. The core assembly is housed in an aluminum cylinder with end plates that have male and female type LC connectors that act as the input and output terminals. A rod from the center pin of each of the connectors through the center opening of the cores acts as a one-turn primary circuit. As in the shunt, the return current is conducted back through the housing to the shell of the connector. This transformer is also a through device allowing another current sensing device (shunt or transformer) to be placed in series.

Fig. 3 shows a drawing of the transformer assembly. A box on top of the housing contains the battery, burden resistor, and amplifier. The burden resistor is a 1 Ω resistor made up of ten 10 Ω resistors in a circular array. The ac-dc difference of the equivalent 1 Ω burden is under 75 μA/A up to 100 kHz. Thus, with the 100:1 turns ratio and 1 Ω burden across the secondary, the device gives a nominal sensitivity or trans-resistance of 10 mV/A.

Shunt Characterization

Ac current shunts of good electrical and thermal design can be expected to exhibit small changes in ac-dc difference as a function of current level. The shunts of the NIST design have small inductance and low skin effect due to their inherent design. Their large, distributed structure allows good thermal contact to heat sinks. These characteristics make it possible to calibrate the shunt at low current against existing standards and then use the device at higher currents to some level of uncertainty.

To provide greater confidence, two specific additional processes are used to calibrate the new high-current shunts. The first is characterization of the reference standard shunts by a current build-up process, and the second is an ac-ac comparison with the two-stage, amplifier-aided current transformer.

The current build-up process begins with characterization of one or more shunts at the 20 A level using a NIST reference standard thermoelement. Two shunts, with different current ratings, are connected in series. The signal applied is equal to or less than the rating of the lower shunt. If the instrumentation used to monitor the voltage drops across the potential terminals has small level dependence, then the higher rated shunt can be characterized in terms of the lower rated one. In order to add redundancy to the process, shunts rated at 30 A, 50 A, and 80 A were used in addition to the 100 A device. The diagram in Fig. 4 shows the shunt build-up process.

The second method used to characterize the high-current shunts involves the comparison of the frequency coefficient of a shunt to the frequency coefficient of an amplifier-aided, two-stage transformer. Since dc current may not be passed through the transformer, the process involves a high frequency ac to low frequency ac comparison. A frequency of 50 Hz is low enough where most shunts exhibit very low ac-dc differences and the transformer has very low error. The diagram in Fig. 5 shows the ac-ac comparison against the frequency coefficient of the transformer. As with the shunt build-up process, all characterizations begin with the 20 A reference standard thermal converter.

Table 1 lists the ac-dc difference values determined for the NIST constructed 100 A shunt against the reference thermal converter at 20 A.

Table 1. Ac-dc Difference of NIST 100 A Shunt in μA/A.							
	100 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
20 A	-40	-683	-1107	-1310	-1501	-2306	-3967

Table 2 lists the results of the ac-ac comparisons between the NIST constructed 100 A shunt and amplifier-aided, two-stage transformer.

Table 2. Ac-ac Comparison of NIST 100 A Shunt vs. Transformer in μA/A.								
	100 Hz	500 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	90 kHz
20 A	-1	-408	-671	-1101	-1271	-1466	-2213	-3492
50 A	-22	-421	-690	-1119	-1207	-1387	-2276	-3505
90 A	-13	-437	-689	-1115	-1216	-1447	-2040	-3183

Uncertainties

The results of a preliminary uncertainty analysis are given in Table 3. The elements in the analysis include:

- uncertainties of the reference standards
- Type A contributions from the measurement process
- run-to-run variations in measured values
- longer term drifts in measured values
- failures of trilateral comparisons to close.

Table 3. Preliminary Uncertainties in μA/A. (k=2)				
Current Level	1 kHz	10 kHz	20 kHz	30 kHz
30 A	202	251	266	314
50 A	251	329	361	442
80 A	310	428	488	
100 A	373	499		

Future Plans

Future plans include the continued study of the build-up process to improve the characterization of the NIST working standards. Further comparisons will be made between shunts of difference values and against current transformers. Tests will be made to investigate the possible extension to higher frequencies.

References

[1] Laug, Owen B., "A 100 A, 100 kHz Transconductance Amplifier," *IEEE Trans. Instrum. Meas.*, Vol. 45, June 1996, pp. 440-444.

[2] Kinard, J.R., Hastings, J.R., Lipe, T.E., Childers, C.B., "Ac-dc Difference Calibrations," NIST Special Pub. 250-27, May 1989.

[3] Kinard, J.R., Lipe, T.E., Childers, C.B., "Extension of the NIST Ac-dc Difference Calibration Service for Current to 100 kHz," *NIST J. Res.*, Vol. 102, No. 1, Jan-Feb 1997, pp. 75-83.

[4] Kinard, J.R., Lipe, T.E., Childers, C.B., Novotny, D.B., Huang, D.X., "High-Current Thin-Film Multijunction Thermal Converters and Multiconverter Modules," *IEEE Trans. Instrum. Meas.*, Vol. 46, No. 2, April 1997, pp. 391-394.

[5] Laug, Owen B., "A Wide-Band Transconductance Amplifier for Current Calibrations," *IEEE Trans. Instrum. Meas.*, IM-34, No. 4, Dec. 1985, pp. 639-643.

[6] Hess, D.T., et al., "Evaluation of 100 A. 100 kHz Transconductance Amplifiers," *IEEE Trans. Instrum. Meas.*, Vol. 48, No. 2, pp. 447-449, April 1999.

[7] Souders, T.M., "Wide-Band Two-Stage Current Transformers of High Accuracy," *IEEE Trans. Instrum. Meas.*, Vol. IM.21 , No. 4, Nov. 1972, pp. 340-345.

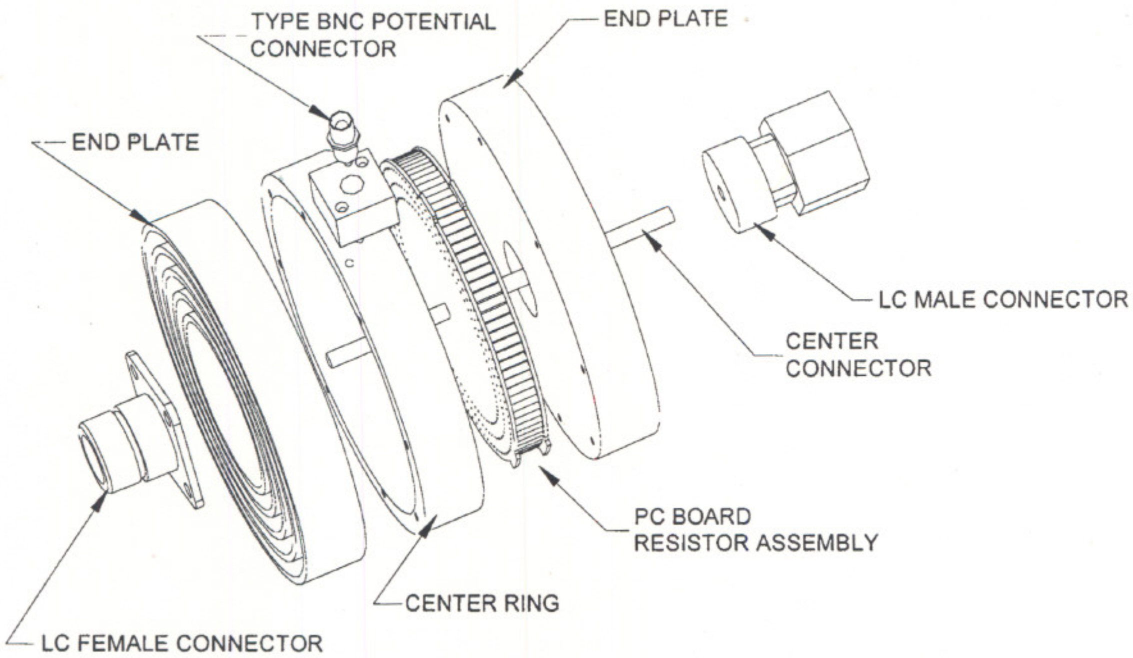

Fig. 1. An exploded view of a NIST 100 A shunt.

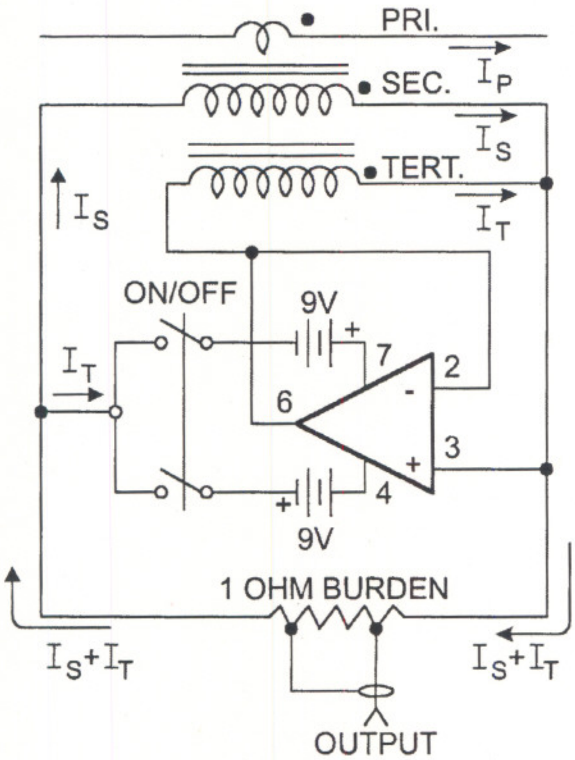

Fig 2. Schematic diagram of an amplifier-aided, two-stage transformer.

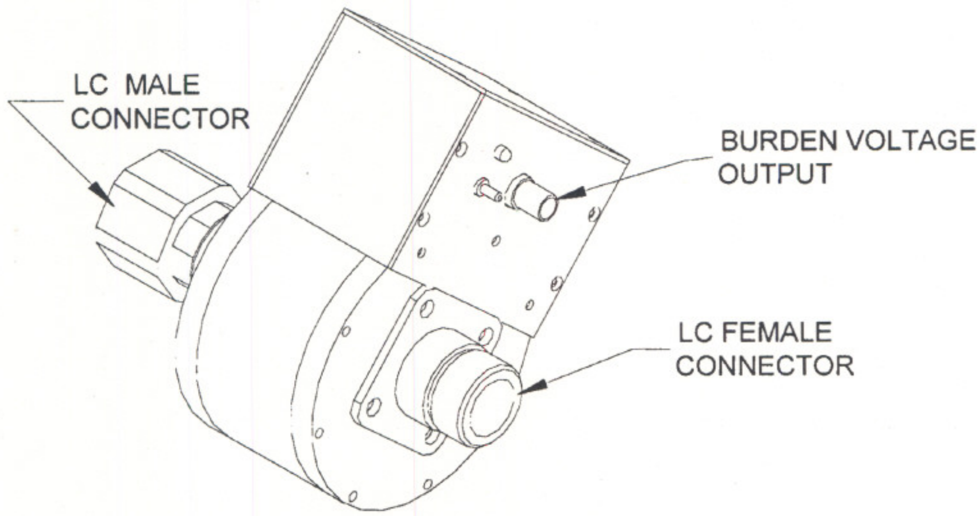

Fig. 3. Drawing of the amplifier-aided, two-stage transformer.

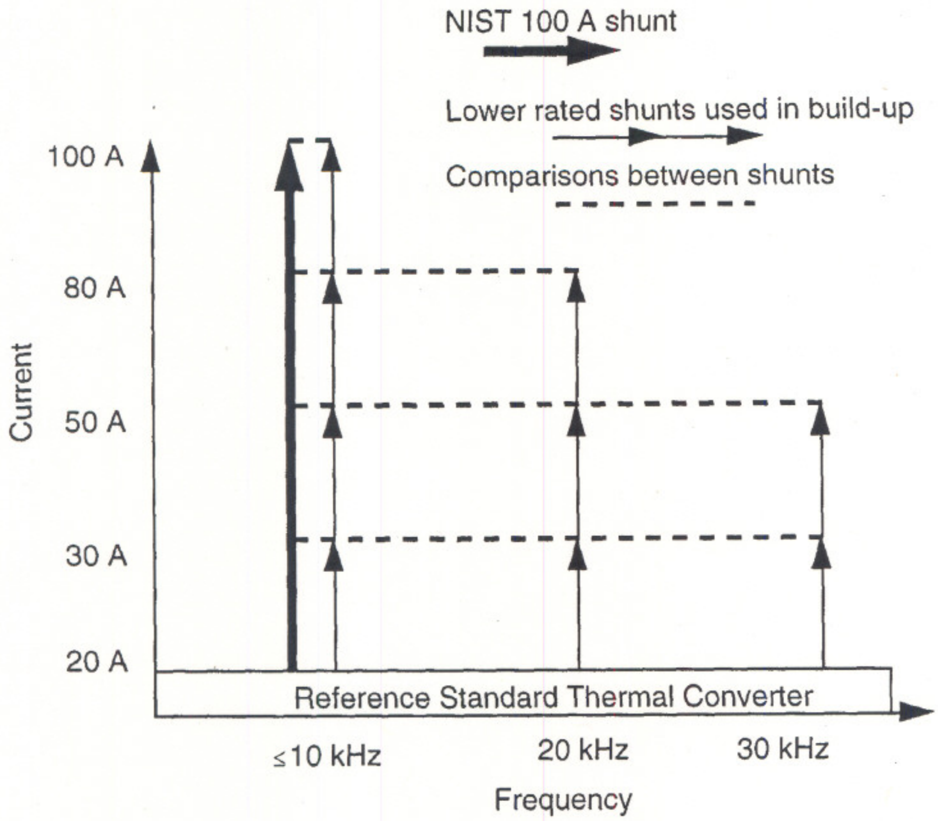

Fig 4. Diagram of the shunt build-up process.

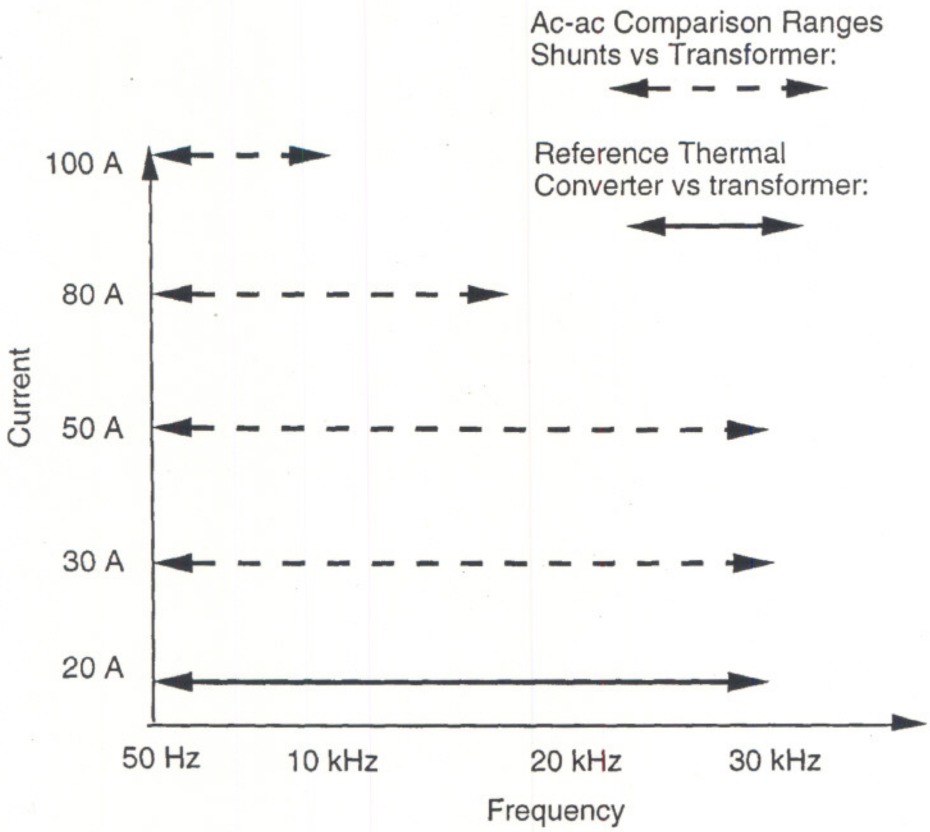

Fig 5. Diagram of the ac-ac comparison against the frequency coefficient of the transformer.