A Direct-Current-Comparator Bridge for Measuring Shunts up to 20000 Amperes

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Abstract—A direct-current-comparator bridge for calibrating four-terminal resistors or shunts at currents up to 20 000 amperes is described. Measurements can be made at up to full rated current of the shunts so that the effects of the load coefficient are included. The resistor under test is compared with a reference resistor of higher value by measuring the ratio of the currents through the two resistors required to produce equal voltages across them.

A comparator bridge with a range of 100 amperes and errors of less than 1 ppm has been described previously. Improvements to this bridge have been made, the main one being a reversing feature, which permits the currents through the resistors to be reversed in a few milliseconds. This makes an accurate measurement easier, particularly if there is a change of resistance due to heating. By connecting a second comparator in cascade, the range has been extended to 20 000 amperes at an overall ratio up to 2 × 10⁶:1, with only a slight loss of accuracy; the errors may be a few parts per million. Other applications of the measuring system are the accurate measurement of large currents or the calibration of transducors.

Introduction

THE RESISTANCE of a shunt is normally measured by comparing the voltages across it and across a reference resistor, when both are carrying the same current, as in Fig. 1(a). This measurement is usually done at currents much below the rating of the shunt to avoid errors due to heating of the reference, which is normally higher in resistance than the shunt. The load coefficient of the shunt must then be determined by some other method so that the actual resistance under load conditions can be calculated [1].

An accurate measurement of the resistance of the shunt under load conditions could be made and the problem of the heating of the reference resistor thus reduced if the ratio of the currents required to produce equal voltages on the shunt and on the reference resistor could be determined, as in Fig. 1(b). Furthermore, if this ratio could be made large enough, a reference of much higher resistance than the shunt could be used, and the heating in it would be negligible. The shunt could then be measured when carrying full rated current, and the effect of current on its resistance could be measured directly.

An accurate ac transformer can generate the two currents required for this measurement, but a shunt normally used for direct current should be measured when carrying dc, so a transformer capable of operating at

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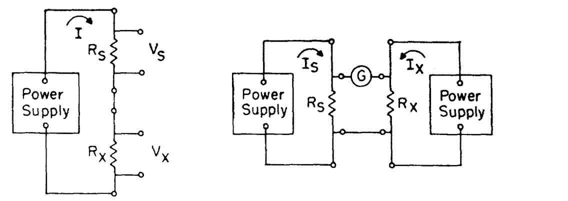

Fig. 1. Methods of comparing resistors. (a) Equal current. (b) Equal voltage.

zero frequency is required. The direct-current comparator is such an accurate, adjustable, direct-current transformer and its use for the measurement of shunts up to 20 000 amperes is the subject of this paper [2]–[4].

The Self-Balancing Direct-Current Comparator

A direct-current comparator consists of a pair of toroidal cores of high-premeability magnetic material, surrounded by a magnetic shield, over which are ratio windings, which carry the currents to be compared. The operation of the comparator is based on the detection of balance in the ampere-turns imposed on the magnetic cores. An oscillator applies an alternating voltage to windings on the cores, driving them into saturation in opposite directions twice each cycle. Direct current in the ratio windings generates even harmonics of the applied voltage, which are detected by a demodulator. When the dc flux in the cores is zero, the ratio of the currents in the ratio windings is equal to the inverse of the turns ratio, with a high degree of accuracy. In the self-balancing comparator, if a current flows through one ratio winding, a dc power supply, controlled by a signal from the demodulator, supplies to a second winding the current required to keep the core flux at zero. Thus the comparator acts like a current transformer that operates down to zero frequency.

The Direct-Current-Comparator Ratio Bridge

The use of a nonreversing bridge based on the direct-current comparator for the comparison of four-terminal resistors, as shown in Fig. 2, has been described previously [5]. The current from the master power supply, which flows through the resistor R_x, is set by adjusting R_1'. The current from the slave power supply, which flows through the resistor R_s, is set by adjusting R_1, so that the net ampere-turns are close to zero as indicated by the ampere-turn detector. The signal from the ampere-turn detector also controls the slave power supply, and tends to keep the

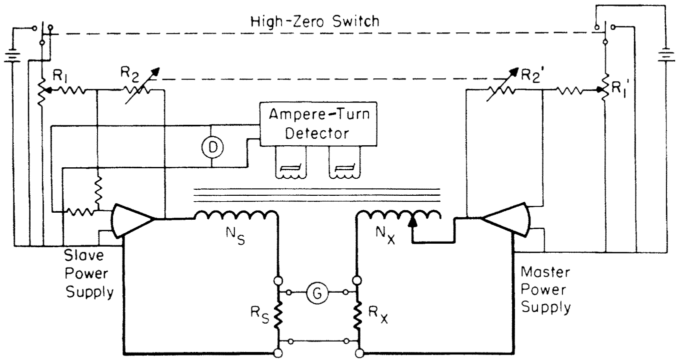

Fig. 2. Basic direct-current-comparator bridge (nonreversing).

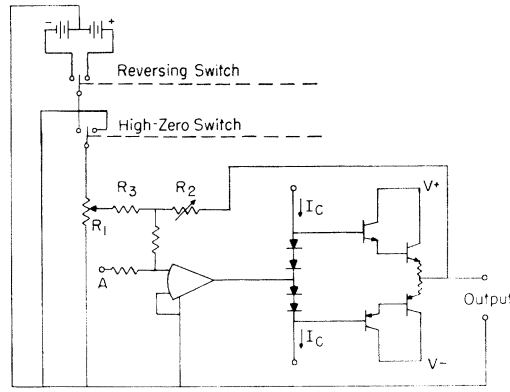

Fig. 3. Reversing power supply.

net ampere-turns zero. Since most of the control voltage to the slave supply is provided by the setting of R_1, and only a small part by the ampere-turn detector, part-per-million accuracy can be obtained without the necessity of very high gain in the feedback loop, and the problems of stability are reduced considerably. The number of turns are adjusted so that the voltages across R_s and R_x are equal, as measured by a sensitive galvanometer. When the voltage measured by the galvanometer and the net ampere-turns are zero, the ratio of the currents, and therefore of the resistors, is indicated by the turns ratio. A synchronized tracking control, consisting of R_2 and R_2', which are ganged together on one shaft, permits the current level of both the master and slave supplies to be adjusted without upsetting the ampere-turn balance. The range of the bridge using internal supplies is from a few milliamperes to 1 ampere, and windings are available for using external supplies up to 150 amperes. A modified and improved version of this bridge and a range-extension unit with a rating of 20 000 amperes are described in this paper.

In order to ensure that a measurement is not affected by thermal voltages, which may be present in the potential circuit, the bridge is balanced at two different values of current. The correct bridge balance is obtained if both the ampere-turn balance, indicated by the detector D, and the voltage balance, indicated by the galvanometer G, are unaffected when the current is switched between the two different values. The bridge described previously used conventional nonreversible dc supplies as the sources of the currents in both resistors. The outputs of the supplies were switched simultaneously between the assigned current levels and zero by operating a high-zero switch in their control circuits. When measuring resistors at current levels where the heating effects are not negligible, the currents are allowed to flow until the thermal conditions have stabilized before the high-current balance is taken. The currents are then switched to zero, and the zero-current balance must be taken quickly before the thermal conditions change.

If the currents in the resistors could be reversed between successive bridge balances, the thermal conditions would remain essentially constant so that more accurate measurements could be made and, in addition, the voltage sensitivity would be doubled. Three methods have been considered for reversing the currents: the use of synchronized switches to reverse the currents of conventional nonreversible supplies; the use of reversing power supplies; and a combination of both. The problems and advantages of the different systems are as follows.

If nonreversible power supplies are connected to the windings and resistors through reversing switches, the polarity of the feedback from the ampere-turn detector to the slave supply is reversed, so this connection cannot be used.

The resistors alone can be connected by reversing switches, with the windings connected directly to the supplies. However, the switches on the master and slave sides must be operated in perfect synchronism so that a current imbalance does not occur during reversal. Since the ampere-turn feedback to the slave power supply, whose current maintains zero flux in the cores, is open while the switch is reversing, a transient during this time can introduce a shift in the zero of the comparator and thus an error in the measurement, so the current must be zero while switching. In addition to the normal balances with the forward and reverse directions of current, balances are required at zero current, with the switches set in the forward and reverse directions, to detect any offset current from the comparator. Offset current must be set to zero because it is reversed in the resistor being measured but not in the winding, and therefore introduces an error in the measurement.

Both the extra balances and the necessity of reversing at zero current can be avoided by using a reversible slave power supply. The master supply may be a similar reversible supply or, since there is no feedback from the comparator to the master, it may be a nonreversible supply connected to the winding and the resistor through a reversing switch, which is operated in synchronism with the reversal of the slave supply.

The circuit of the reversible power supplies is shown in Fig. 3. The input from the ampere-turn detector to the operational amplifier is at point A. The output stage has a current rating of 1 ampere in either direction. In series with the high-zero switch is a reversing switch, which connects the supply to either a positive or a negative control voltage. The reversing switches of the master

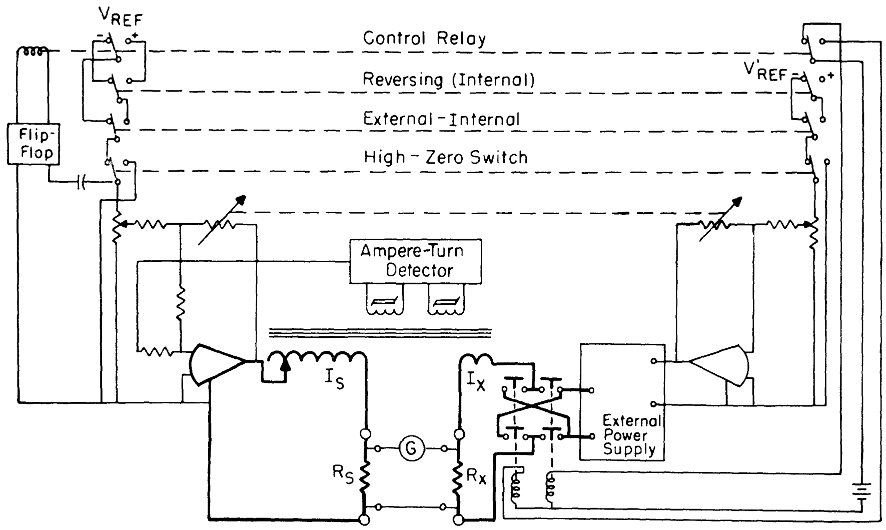

Fig. 4. Dc-comparator bridge with external power supply and synchronous tracking.

and slave supplies are ganged together in the same manner as the high-zero switches, so that both supplies can be switched together. The response times of both supplies must be short and approximately equal so that the comparator, acting as an ac transformer, can reduce the effect of switching transients to negligible proportions.

The bridge can be used with an external supply at currents up to 1000 amperes, as shown in Fig. 4. The external supply can be a commercially available nonreversible regulated supply, operated in its remote-voltage constant-current mode. It is controlled by the voltage generated by the internal master supply, which is not reversed when used to control the external supply. In this way, the current is controlled from the front panel of the bridge in the same manner as when using internal supplies.

A reversing relay at the output terminals of the external supply is used to reverse the master current. Setting the high-zero switch to zero drops the voltage of both the master and slave supplies to zero, and at the same time actuates a flip-flop, which in turn reverses a control relay, which reverses the master-current relay and the control voltage to the slave power supply. When the switch is returned to "high," the flip-flop continues to hold the control relay in its new position and the currents come up to their assigned values, but reversed from their previous directions. If the response time of the supplies is short, the currents drop to zero before the main relay can operate so that the reversal is made at zero current.

It was found that the synchronized tracking control, in which the slave and master supplies are driven by synchronized signals, is not satisfactory if the response time of the external supply is much longer than that of the slave supply, because a large ampere-turn imbalance is produced on switching. For this reason the circuit was changed so that only the master supply is controlled by the operator. The voltage across the winding and resistor on the master side, which may be the output of an ex-

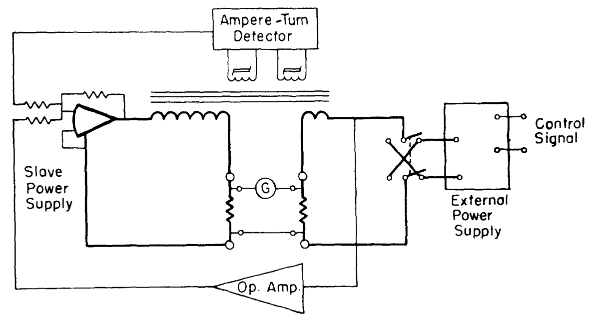

Fig 5. Comparator bridge with automatic current tracking.

ternal or of the internal supply, is used as the control voltage for the slave supply. In order to prevent the resistance of the potential leads of the resistors being compared from affecting a measurement, the current through these leads is kept negligibly small by using an operational amplifier with the high-input impedance of an FET to transfer the control voltage from the master to the slave side, as in Fig. 5. This "auto-tracking" eliminates the need for a fast transient response of the master supply, but does require that the response time of the slave supply be not more than that of any master supply that may be used with it. It also permits the operator to reverse the current or change the current level by adjusting the master supply only.

Extension of Range to 20 000 Amperes

If measurements are to be made at currents larger than 1000 amperes, it is necessary to use a second comparator in cascade with the comparator bridge. A comparator with a rating of 20 000 amperes, but with a limited number of turns ratios, has been used. The prototype of this comparator has been described previously [6]. It was designed primarily for *in situ* calibrations in industry of measuring devices for large currents such as are encountered in aluminum production [7], [8]. It is of the feed-through type, so that the primary consists of

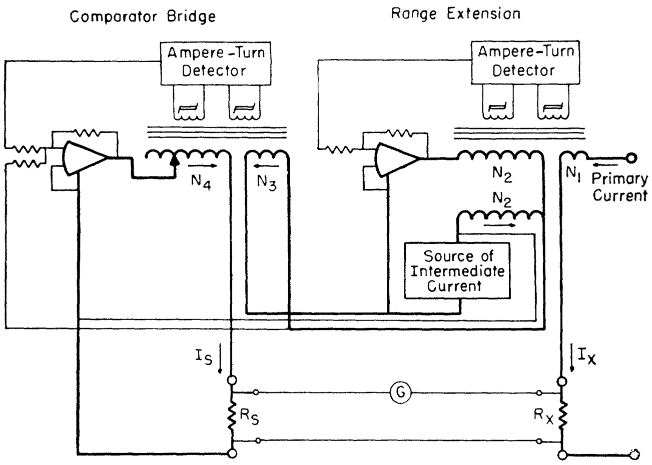

Fig. 6. Comparator bridge with range-extension unit.

the high-current bus. Secondaries of 2000, 1750, or 1500 turns are available, which are capable of carrying currents up to 10 amperes.

The range-extension unit is shown with the comparator bridge in Fig. 6. At balance on the two comparators

$$I_x N_1 = I_2 N_2$$

$$I_2 N_3 = I_s N_4$$

where I_2 is the intermediate current that flows through the secondary windings of the range-extension unit and through the primary windings of the bridge. The overall ratio is

$$I_x/I_s = (N_2/N_1)\cdot(N_4/N_3).$$

The maximum ratio is 2×10^6:1, adjustable in parts-per-million steps.

The range-extension unit has two secondary windings with equal numbers of turns so that the currents from two separate supplies can be added. A reversible slave power supply, similar to the one used in the bridge and controlled by the ampere-turn detector in the same manner, is connected to one winding. A second source, which should supply as much of the secondary current as possible, is connected to the other winding. In this way, the current rating of the slave supply is much less than the full secondary current, and since it provides only the difference between the primary and the coarse secondary ampere-turns, the necessity for a loop gain of 10^6 (for parts-per-million accuracy) is avoided in the range-extension unit as in the bridge.

The current-reversal feature of the bridge can be retained because the source of most of the intermediate current, if it is nonreversible, can be connected to the winding through a reversing switch. The reversible slave power supply remains connected with the correct polarity to maintain ampere-turn balance. The automatic current-tracking feature of the bridge can also be retained. Connections can be made as shown to obtain the control voltage for the slave supply of the bridge from the voltage across the winding that carries most of the intermediate current. Because the secondary circuit of the range-extension unit is isolated from both the primary current circuit and from the secondary circuit of the bridge, a coupling unit with a high-input impedance is not required.

Three methods of supplying most of the intermediate current can be used.

1) A manually controlled 10-ampere regulated dc power supply has been used with the 20 000-ampere comparator. This is quite satisfactory if the primary current is known and steady. If the power supply is adjusted so that the current controlled by the detector is close to zero, the error due to the finite gain of the detector feedback loop is essentially zero. If the primary current is varying, it is difficult to keep the regulated supply at the currect value. If the current range of the balance detector is exceeded, the magnetic cores saturate and all feedback control is lost. However, the system can be reset by adjusting the supply.

2) A transductor, which is a "dc transformer" accurate within about 1 percent, can be used. The current required to correct this error must be obtained from the slave power supply, driven by the ampere-turn balance detector. The use of the transductor is most suitable where the primary current varies, or is not under the control of the operator. The secondary current of the transductor is approximately correct at all values of the primary current so an output capacity of 1 ampere is more than adequate for the slave power supply.

3) An automatically controlled 10-ampere regulated dc power supply can be used. A signal proportional to the primary current can be obtained across R_x, the shunt being measured, or across the shunt and the winding as in Fig. 5 since there is no need for either high accuracy or long-term stability in this signal generator. To limit current flow through the potential terminals of the shunt or of the reference resistor, the control signal should be coupled from the primary current circuit to the power supply through an operational amplifier with a high-input impedance.

Design and Performance of the Transductor

A suitable type of transductor is shown in Fig. 7 [9], [10]. Its operation is as follows. During any half-cycle of the ac supply, one of the cores is unsaturated and the current flowing through the secondary winding on that core, and through the load, is

$$I_2 = I_x/N + I_m$$

where

I_x is the primary current
N is the turns ratio, which is the same as the turns ratio of the comparator
I_m is the magnetizing current of the transductor.

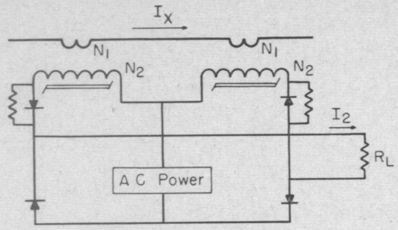

Fig. 7. Transductor.

During the next half-cycle the other core is unsaturated and the same current flows through its winding and the load. During the period in each cycle when the supply voltage is below the value necessary to drive the current, the inductance due to the unsaturated core is sufficient to cause the current to continue to flow through both windings and the load. In this way, the ripple in the secondary current due to the ac supply is very small. The resistors that bypass a rectifier on each side permit the voltage of the source to reset the core flux during the half-cycle when it is not being used to regulate the current. The value of these resistors should be sufficiently small so that the cores are reset if the primary current is zero. However, they should be no smaller than necessary because they load the ac supply if the primary current is large enough to saturate the cores before the end of a half-cycle.

Over a large range of primary currents, most of the error of the transductor is due to the magnetizing current. The error is larger when the primary current is near the maximum or near zero. The ac supply voltage must be high enough to ensure that at the largest primary current the error is not excessive, and the cross-sectional area of the cores must be sufficient so that at this voltage the cores do not saturate at zero primary current. The error of a transductor used with the 20 000-ampere comparator, which determines the required current rating of the slave power supply, is shown in Fig. 8.

A transductor is used only when the ratio N_2/N_1 is large because voltage from the ac power source is coupled into the primary current circuit by transformer action, but at large ratios the induced voltage is small.

The current is directed through the windings by rectifiers, so the transductor can be used with primary current in one direction only. If this current were reversed, the rectifiers would block the secondary current flow and the cores would saturate. However, the primary current can be reversed if at the same time the secondary windings are reversed by relays. Operating the relays can induce transient voltages at the output of the slave power supply of sufficient amplitude to damage the transistors. A "crowbar" protection is added consisting of a silicon-controlled rectifier, which is fired to bypass the transistor if a transient exceeds the breakdown voltage of a Zener diode set at 12 volts. The design of a transductor that can be used with the 20 000-ampere comparator is given in the Appendix.

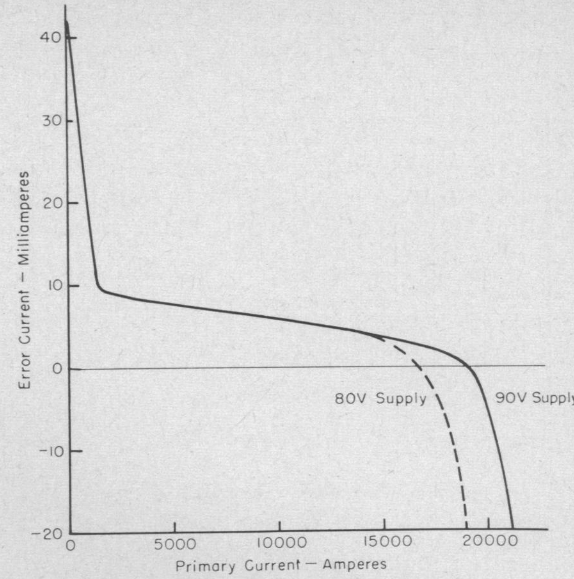

Fig. 8. Error of transductor at 2000:1 ratio.

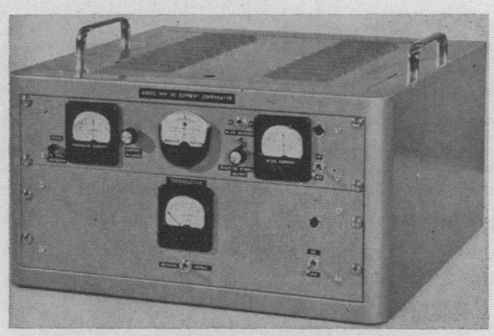
Fig. 9. Circuit cabinet for 20 000-ampere comparator and transductor.

The cabinet containing the circuits for the 20 000-ampere comparator and for the transductor is shown in Fig. 9. The circuits for the comparator are in the upper panel with the transductor circuits below.

Performance of the Bridge and the Range-Extension Unit

The noise level of the comparator used in the bridge is less than 10-μA turns, and the current ratio differs from the turns ratio by less than 1 ppm. To make measurements with parts-per-million accuracy, the bridge should be operated at a sufficiently high ampere-turn level, e.g., a current of 5 mA flowing in a winding of 1000 turns, so that the sensitivity is not limited by the noise. The errors of the range-extension unit under laboratory conditions are approximately 1 ppm, and it is estimated that under industrial conditions they are less than 10 ppm. The noise level of the range-extension unit is about 1000 times larger than that of the bridge, but if the system is connected to obtain the maximum overall ratio of 2×10^6:1 the operating ampere-turn level of the range-extension unit is 2000 times that of the bridge, and the contributions of each unit to the total effective noise level of the system are about equal. If the overall ratio is smaller, the system noise level is due almost entirely to the range-extension unit.

Conclusions

A system for calibrating and measuring four-terminal resistors and shunts at currents up to 20 000 amperes has been described. It consists of a reversible direct-current-comparator bridge, which can be used up to 1 ampere. The addition of a commercial power supply extends the range to 100 or 1000 amperes, while the addition of a range-extension unit extends the range to 20 000 amperes. At all current levels the system is reversible so that the effects of thermal electromotive forces on the potential circuit of the resistors may be minimized. In addition, an automatic tracking control permits the primary current level to be changed or reversed without the need for readjusting the ampere-turn balance.

Appendix

Construction Details of Transductor

Cores: Material—80 percent Ni–Fe alloy, in Al cases; 14¾-inch ID, 15¾-inch OD, ¾-inch high × 2.

Windings: Two windings on each core, in parallel, covering 180° each; 2000 turns, tapped at 1750 and 1500 turns, no. 16 wire, Formex covered, two in parallel.

Resistors: 70 ohms, 100 watts each.

Supply: 90 volts, 60 Hz.

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Detection of Shifts in the Values of Saturated Standard Cells Used as References

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***Abstract*—A method of analyzing data taken in routine comparisons of a test group of saturated cells to a reference group, so that shifts in the electromotive forces of individual reference cells may be detected, is explained. Limitations on the minimum number of reference cells adequate for close tracking of cells under text become apparent from examination of data, as do the advantages of knowing precisely the electromotive force of each reference cell at the time of use. The technique is suggested as a convenient means of augmenting surveillance of the stability of individual reference cells with respect to the average of a larger group.**

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Introduction

A METHOD of detecting and correcting for shifts in the terminal electromotive forces (EMF) of individual saturated cells used as references in routine comparisons for assigning values of EMF to other cells, by analyzing the test data normally taken, has been devised by the Primary Standards Laboratory of Sandia Laboratories.[1] Corrections determined by this method are substantiated when the group of cells in routine use as a reference is compared to other references for the purpose of checking the stability of its group mean.

[1] Operated for the Atomic Energy Commission by Sandia Laboratories.