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Technical Note 172

PRACTICAL METHODS FOR CALIBRATION OF POTENTIOMETERS

DAVID RAMALEY

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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David Ramaley
Radio Standards Laboratory
National Bureau of Standards
Boulder, Colorado

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Practical Methods for Calibration of Potentiometers

David Ramaley

Potentiometer circuitry, particularly as related to calibration, is discussed with the primary consideration given to the required circuit measurements. The more feasible means of calibrating potentiometers are described in considerable detail. Emphasis is placed upon the use of the Universal Ratio Set as the basic implement for accomplishing the major portion of potentiometer calibrations.

1. Introduction

This paper is concerned primarily with calibration of potentiometers of precision quality, including both the multipurpose types and somewhat specialized types. A presentation of the methods involved and enough detailed descriptive material are included to enable the reader to grasp the fundamentals. Minutely detailed instructions are omitted. It is anticipated that this manner of presentation will fulfill the requirements of one who wishes to understand the principles without the necessity of becoming involved in procedural details. Calibration procedures or instructions of the "cook book" type also are needed. This latter need now is becoming more nearly fulfilled by manufacturers' instructions and recently available procedures written up by various standardizing laboratories. For example, the Division of Electricity of the National Bureau of Standards is compiling calibration procedures for several types of potentiometers. These procedures are available to other standards laboratories upon request to the Resistance and Reactance Section of the Division of Electricity, NBS.

Examples of potentiometer circuits given in this paper are chosen to demonstrate the diversity of circuit arrangements and in several cases are not taken from actual existing instruments. Good explanations of principles involved in the circuitry of various types of manufactured potentiometers can be found in texts on electrical measurements such as that of Harris [1][1]. In this paper the more complicated calibration methods are not discussed where simpler methods are available. Generally, instead of calibrating potentiometers by means of potential differences, the appropriate resistors in the instrument are compared or measured by means of Wheatstone net circuits incorporating the Universal Ratio Set [2, 3, 4]. A brief review of the Universal Ratio Set follows.

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[1] Figures in brackets indicate the literature references at the end of this paper.

2. Universal Ratio Sets

2.1. Circuitry of Ratio Sets

Practically all ratio sets and resistive voltage dividers contain a resistance circuit terminated on each end by a binding post connector. A simple slide-wire represents the most readily visualized ratio set or voltage divider. The sliding contact is free to travel from one end of the wire to the other. The ratio of the resistance of the wire on one side of the sliding contact to the resistance on the other side can be varied continuously as the slider is moved along the resistance wire. These two resistances, one on either side of the slider, can be used to form two arms of a Wheatstone net or bridge circuit. It is such a circuit that is used to calibrate potentiometers. At least one and commonly two of the other bridge arms consist of selected portions of the potentiometer under calibration. We may also think of the slide-wire as a ratio set giving the ratio of resistance of either arm of the slide-wire to the total slide-wire resistance. Likewise, the slide-wire may be considered as a voltage divider. A fraction of the voltage impressed between the two slide-wire ends appears between the slider and one end, while the remainder appears between the slider and the other end. These concepts facilitate the visualizing of the operation of a ratio set.

It is not practical, physically, to construct a very long, accurately graduated slide-wire of extremely uniform cross section such that the resistance per unit length is sufficiently constant. Such a slide-wire would offer an infinite number of ratios of resistance, limited only by the fineness of adjustment possible with the slider. The resolution of such a slide-wire would be exceptional. As an approach to this ideal, substitute circuits containing many intermediate steps have been developed. In the case of commercial voltage dividers, the well known Kelvin-Varley circuit [1] usually is utilized. Such a circuit makes possible a large number of ratios and can be used to calibrate potentiometers. However, the overall resistance of most commercial voltage dividers is usually somewhat excessive for many potentiometer calibrations.

Universal Ratio Sets are designed for calibrating most types of potentiometers. In function, the six-dial URS is actually the equivalent of a calibrated slide-wire potentiometer with an extremely high resolution. It is identical in operation to a slide-wire of total resistance 2111.110 ohms graduated in equal divisions of 0.001 ohm. Actually, the URS utilizes separate resistance coils, and the position of the adjustable contact is varied by means of dial switches. The first dial is associated with 20 equal 100-ohm steps, and the other dials control decade resistances ranging from 10 ohms per step to 0.001 ohm per step in the case of a six-dial ratio set. A schematic diagram of a URS is shown in figure 1. All of the ten-step dials are of the same type construction. One switch handle operates both the switches to the upper and to the lower resistance sections simultaneously. If resistance is added by the upper switch, an equivalent resistance is removed from the circuit by the lower switch. (This technique will be referred to as "compensation" of the device.) The use of this type of decade enables one to establish a potential difference in the resistance network corresponding to any of the various step points. Furthermore, when several decades of this type are connected together as is done in the URS or in the Feussner potentiometer [5], the potential connections can be made corresponding to any step on the interconnected dials. The total overall resistance of the ratio set is held constant by means of these compensating switching dials. The resistance between A and C increases from 0.000 to 2111.110 ohms as the dials are advanced from their minimum to their maximum readings. At the same time the resistance between B and C decreases from 2111.110 ohms to 0.000 as the dials are advanced. The URS can thus be represented schematically by a simple, graduated slide-wire.

2.2. Operation of the Universal Ratio Set as a Calibrating Instrument

To illustrate determination of ratios of resistances by means of a Universal Ratio Set, variable resistive voltage divider, or a uniformly graduated slide-wire, the resistances for comparison are all connected in series and the whole series then shunted by the Universal Ratio Set, divider, or slide-wire as shown in figure 2.

With currents I_1 and I_2 as shown, balances are made on the calibrated slide-wire corresponding to connections to the resistance elements a, b, and c. Therefore, R_1 is at the same potential as P_1, the terminal at the left end of a, and R_2 is at the same potential as P_2, the terminal at the right end of a. The potential drop across these two resistance segments is equal.

$$(R_2 - R_1)\, I_1 = aI_2. \tag{1}$$

Likewise,

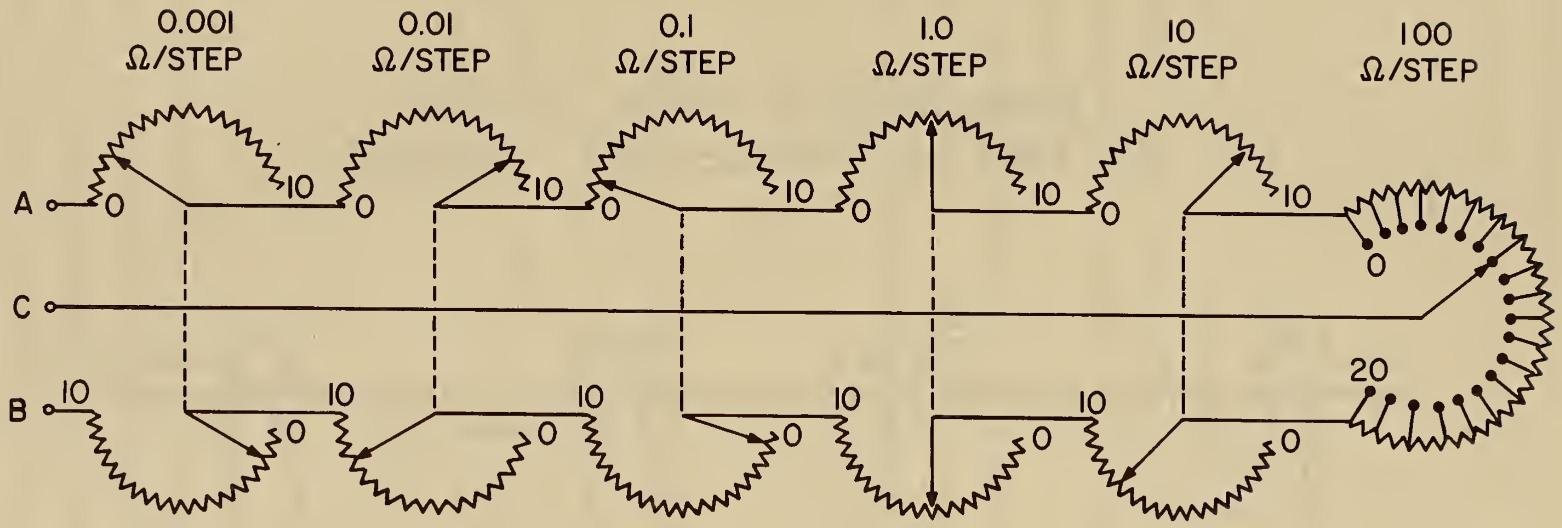
$$(R_4 - R_3)\, I_1 = bI_2. \tag{2}$$

Dividing (1) by (2),

$$\frac{R_2 - R_1}{R_4 - R_3} = \frac{a}{b}. \tag{3}$$

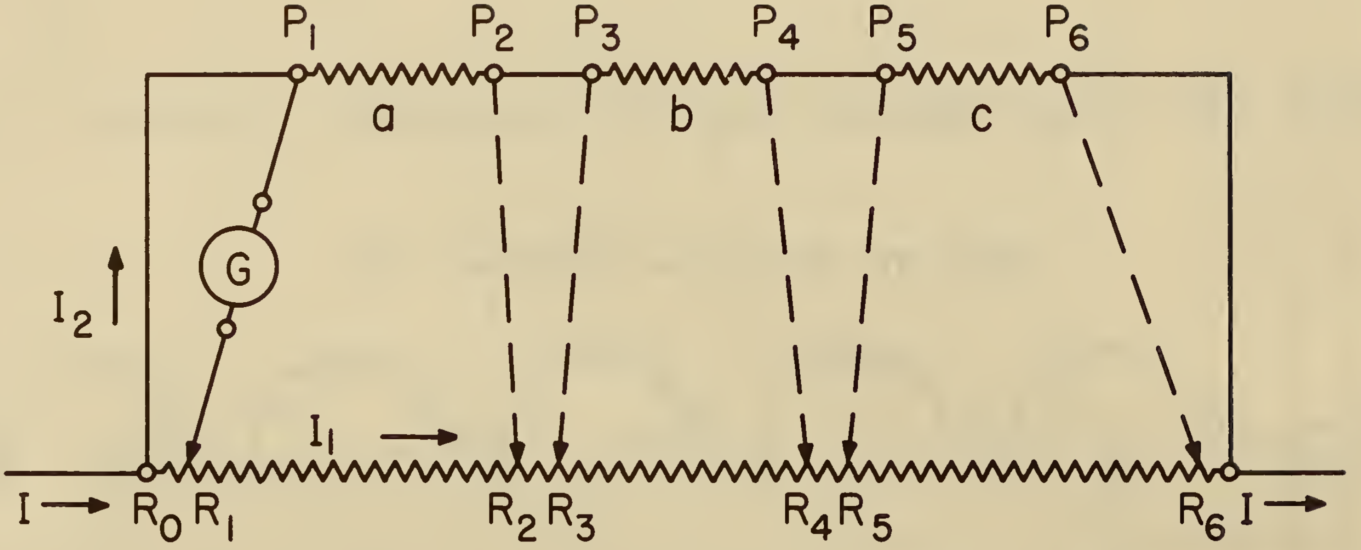
Likewise,

$$\frac{R_2 - R_1}{R_6 - R_5} = \frac{a}{c}, \text{ etc.} \tag{4}$$



DIAL SWITCHES ARE GANGED AS SHOWN

FIG. I SCHEMATIC DIAGRAM OF SIX DIAL UNIVERSAL RATIO SET (URS)



OVERALL RESISTANCE OF URS OR
SLIDE-WIRE IS CONSTANT

FIG. 2 SCHEMATIC DIAGRAM SHOWING ARRANGEMENT FOR COMPARING RESISTANCES BY MEANS OF A URS, A SLIDE-WIRE, OR A RESISTIVE DIVIDER

Because each balance point R_1, R_2, R_3, etc., is made in a Wheatstone bridge circuit, the positions R_1, R_2, R_3, etc., are not dependent upon the constancy of current in the circuit. Furthermore, the connections to the power source and galvanometer can be interchanged without affecting the balance points R_1, R_2, R_3, etc. Under some conditions this interchange is advantageous from the standpoints of power dissipation in the circuit and suitable galvanometer damping. It is desirable to use a source of power which is reversible in polarity, thus affording increased sensitivity and reduction of effects of thermoelectromotive forces.

Most Universal Ratio Sets are closely adjusted to the design specifications. However, a URS should be calibrated to determine any corrections which should be applied when the instrument is used. Hereafter in this paper when we refer to URS readings, we are referring to corrected URS readings.

3. Constant Current Multipurpose Potentiometers

3.1. The Basic Potentiometer Concept

A simplified schematic diagram demonstrating the principles of a constant current potentiometer is shown in figure 3. In this figure, BA is a supply battery which furnishes a current that is controlled by the variable resistor R. R_1 is a uniform or linear graduated slide-wire which may be adjusted over the entire graduated scale. With this arrangement, two sources of emf, E_x and E_s, can be compared, with no appreciable current being drawn from either source. The actual current drawn causes only slight deflections of the galvanometer as the operator is adjusting for a null condition. With the standard source E_s (e.g., a standard cell) in the circuit, the adjustable slider is set to a reference position R_s such that the scale will be direct reading in terms of the voltage of the standard cell. The current through the potentiometer is adjusted by means of R until the galvanometer indicates a null. The potentiometer is then said to be standardized. The unknown emf E_x can then be measured by connecting the unknown source in place of the standard and adjusting the slider on R_1 to the position R_x such that a null is indicated by the galvanometer. If the scale of the slide-wire is calibrated in units of potential difference, the value of E_x can be read directly in the same units. Otherwise E_x can be determined relative to E_s by the ratio of resistance of that portion of R_1 to the left of R_x to that portion of R_1 to the left of R_s.

Obviously, the only calibration needed for such a simple instrument would be a determination of the linearity of the resistor R_1 corresponding to various settings of the adjustable slider.

3. 2. Modifications to the Basic Idea

Potentiometers are rarely as simple as the one described above. The modifications are usually either for the purpose of adding to the convenience of operation or for extending the range of measurements, for example, measurements in the microvolt region.

In order to facilitate more rapid measurements and easier standardization, the circuit employed in standardizing the instrument commonly is terminated by specially designated SC terminals. The SC circuit may or may not be a part of the measuring or EMF circuit with terminals marked EMF. In many potentiometers the two circuits may employ certain resistance portions of the same circuit jointly. Potentiometers are generally so constructed that, by means of switches, a single galvanometer and a single set of keys for several degrees of

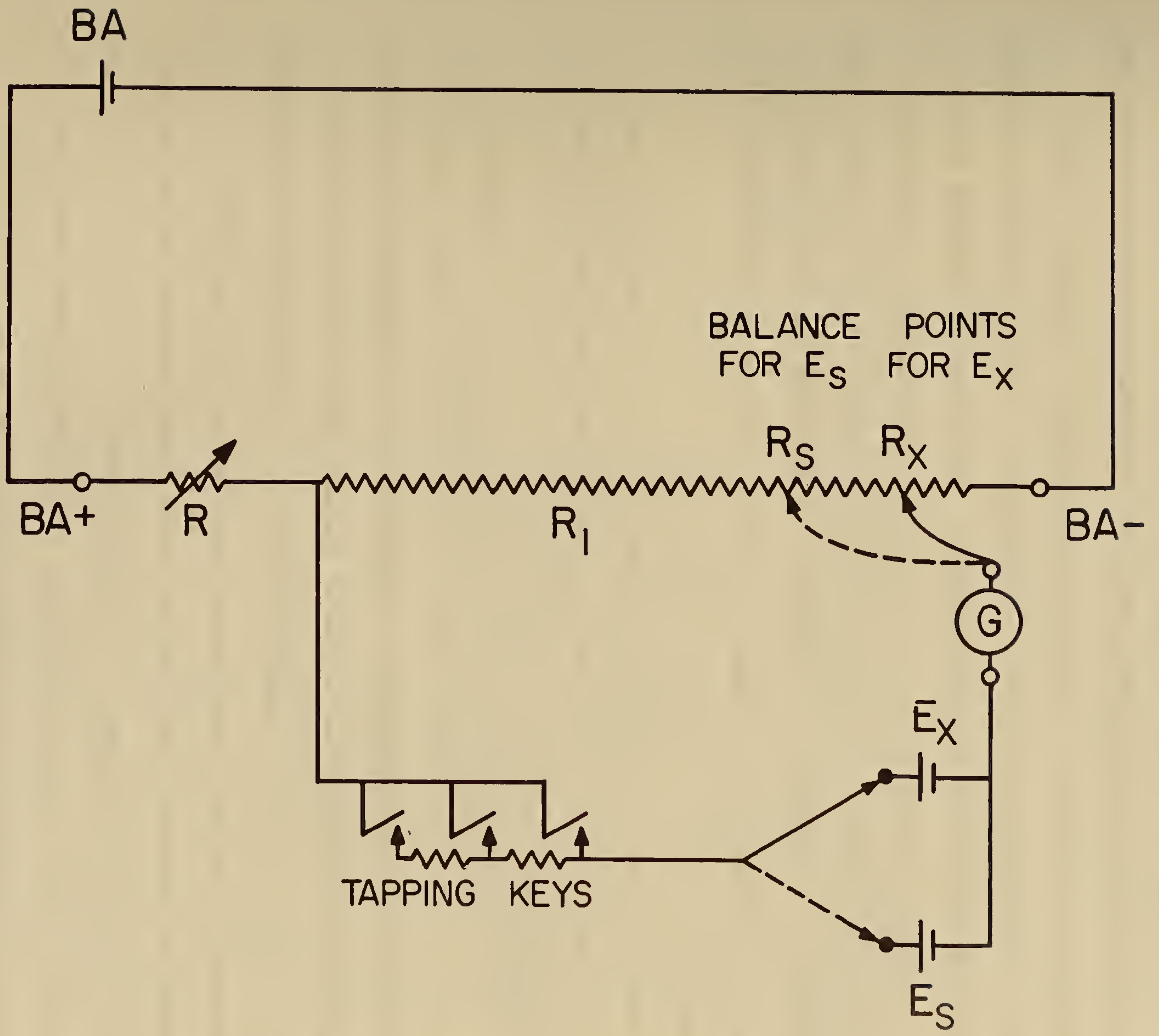


FIG. 3 SIMPLIFIED SCHEMATIC DIAGRAM TO INDICATE PRINCIPLES OF A CONSTANT CURRENT POTENTIOMETER

sensitivity can be switched conveniently from the standardizing circuit to the measuring circuit, thereby eliminating the need for duplicate galvanometers and keys.

The incorporation of a separate standard cell dial or dials apart from the EMF or measuring circuit, although adding to the convenience, detracts somewhat from the accuracy of operation. The use of a dial and slide-wire instead of the single slide-wire adds to convenience of taking readings. Calibration of a potentiometer of this type requires additional measurements. Both the measuring and the standard cell circuits need to be checked for linearity. The ratio of resistance of the EMF circuit to the resistance of the SC circuit must be established. As before, no absolute standards of resistance are required for calibration because only the ratios of resistances need be determined.

Instruments with additional ranges will be considered next; however, these utilize compensating resistors, and a brief consideration of compensated circuits is appropriate.

3.3. Compensation Considerations

The term compensation as applied to potentiometers refers to the adjustment of circuit resistances for various settings of dial switches, range switches, and EMF-SC circuit switches in respect to the constancy of overall resistance between the BA+ and BA- terminals. If the overall resistance is constant for all such switch settings, the instrument is said to be perfectly compensated.

In case the overall resistance of the instrument when the instrument is standardized is slightly different from the overall resistance of the instrument when the unknown E_x is being measured, the current drawn from the supply battery will be different for the two conditions. This circumstance is not encountered in single-range potentiometers but may occur in multiple-range instruments as demonstrated later. In the discussion that follows we shall assume that the power supply has negligible internal resistance and a constant electromotive force.

The following equations represent the relationships existing at the time of measurement and the time of standardization:

$$E_x = R_x I_x \, , \tag{5}$$

$$E_s = R_s I_s \, . \tag{6}$$

I_x is the current drawn when the emf E_x is being measured and I_s is the current when the standardization occurs. Dividing (5) by (6), gives

$$\frac{E_x}{E_s} = \left(\frac{R_x}{R_s}\right) \left(\frac{I_x}{I_s}\right) \, . \tag{7}$$

In well compensated potentiometers the current through the potentiometer will be practically independent of the positions of the EMF dials when making measurements and independent of the settings of the standard cell dials when the SC-EMF switch is set to SC. Consequently, the ratio I_x/I_s usually will be a constant and needs to be measured only once for any given range.

However, this ratio may be variable in a potentiometer having double decade-switching dials of the Feussner variety exemplified by the ten-step dials of a URS in figure 1. Here the resistance between points A and B is the same for various settings of the ten-step switches, provided the various sections of the double decades are completely compensating. If the sections are sufficiently different in resistance, the current will depend upon the switch positioning.

For the situation where I_s and I_x are independent of standard cell dial positioning and EMF dial positioning, for a given factor or range,

$$\frac{E_x}{E_s} = \left(\frac{R_x}{R_s}\right)\left(\frac{I_x}{I_s}\right) = \left(\frac{R_x}{R_s}\right)\left(\frac{T_s}{T_x}\right) . \qquad (8)$$

T_s is the total overall potentiometer resistance when the instrument is being standardized, and T_x is the total overall potentiometer resistance when measurements are being made.

3. 4. Range or Factor Arrangements

Extra ranges in potentiometers are usually 0. 1 and 0. 01 of the primary range. Switching arrangements in the circuits usually change the ranges by changing the ratios of resistance of the EMF circuit to the SC circuit by the appropriate amounts.

Figure 4 illustrates a potentiometer circuit in which the range change is accomplished by changing the resistance of the EMF or measuring circuit. When the plug is placed in the 0. 1-range position, a shunt reduces the resistance of the EMF circuit by a factor of ten. At the same time, the removal of the plug from the 1-range position inserts a series resistor of proper magnitude to maintain a constant overall resistance for the potentiometer.

For an arrangement such as this, where the instrument can be standardized on both ranges and where the standard cell circuit resistance is identical for both ranges, the currents I_s and I_x will be equal, and there is no need to make measurements of the overall resistance.

If the standardizing circuit is combined with the measuring circuit as in figure 5, it will be impossible to standardize the instrument on more than one range since the standard cell circuit is shunted

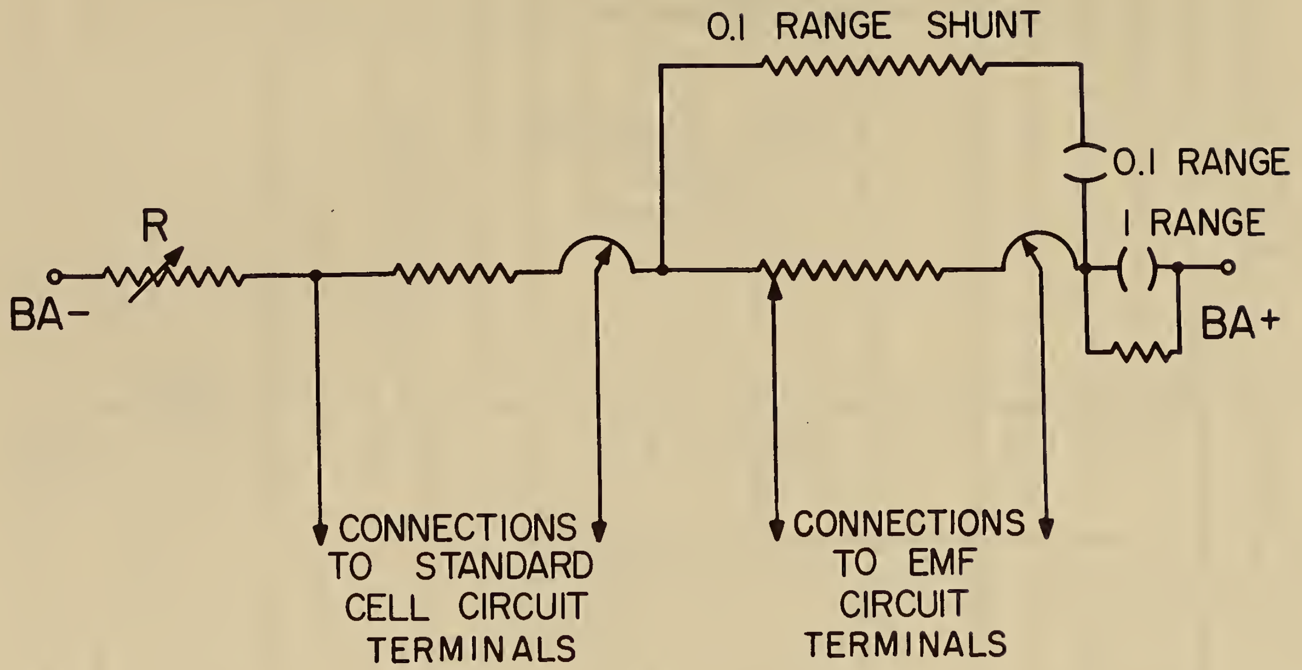


FIG. 4 SCHEMATIC DIAGRAM OF A DOUBLE RANGE POTENTIOMETER INCORPORATING STANDARDIZATION ON BOTH RANGES

along with the EMF circuit when the range is changed. Therefore if the range resistors are not perfectly compensating, I_x for the 0.1 range will differ slightly from I_s which is determined on the 1.0-range. Consequently, a calibration of the potentiometer for the 0.1-range must take into consideration the ratio of I_s on the 1.0-range to I_x on the 0.1-range or T_x to T_s.

In order to calculate the factor or range correction, it is necessary to determine the factor compensation of the instrument. The factor compensation refers to the ratio of currents through the potentiometer corresponding to the various factor or range switch positions. In turn, the current ratios are determined by the ratios of the overall resistances between supply battery terminals of the potentiometer for the various ranges.

Some of the potentiometers in which the balance for the standard cell circuit is made on a single range include the Rubicon Type B, and Leeds and Northrup Type K-1 [6] , and the Wenner Standardizing Leeds and Northrup potentiometers. The Rubicon Type B is so arranged that whenever the SC-EMF selector switch is set to the SC position, the highest voltage range is in the circuit. If potentiometers of these several types are inadequately compensated, the correction to the factor or range multiplier may vary with the emf of the supply battery when batteries furnishing voltages of different magnitudes are used. The overall resistance of such a potentiometer is different for different factor positions and results in a current difference in the instrument when the factor is changed. If another supply battery of twice the voltage were to be substituted, and additional amount of resistance equal to that of the overall resistance for the first condition would be required in the adjusting rheostat R. For this modified situation, when the factor is changed the total change in current is only about one-half as

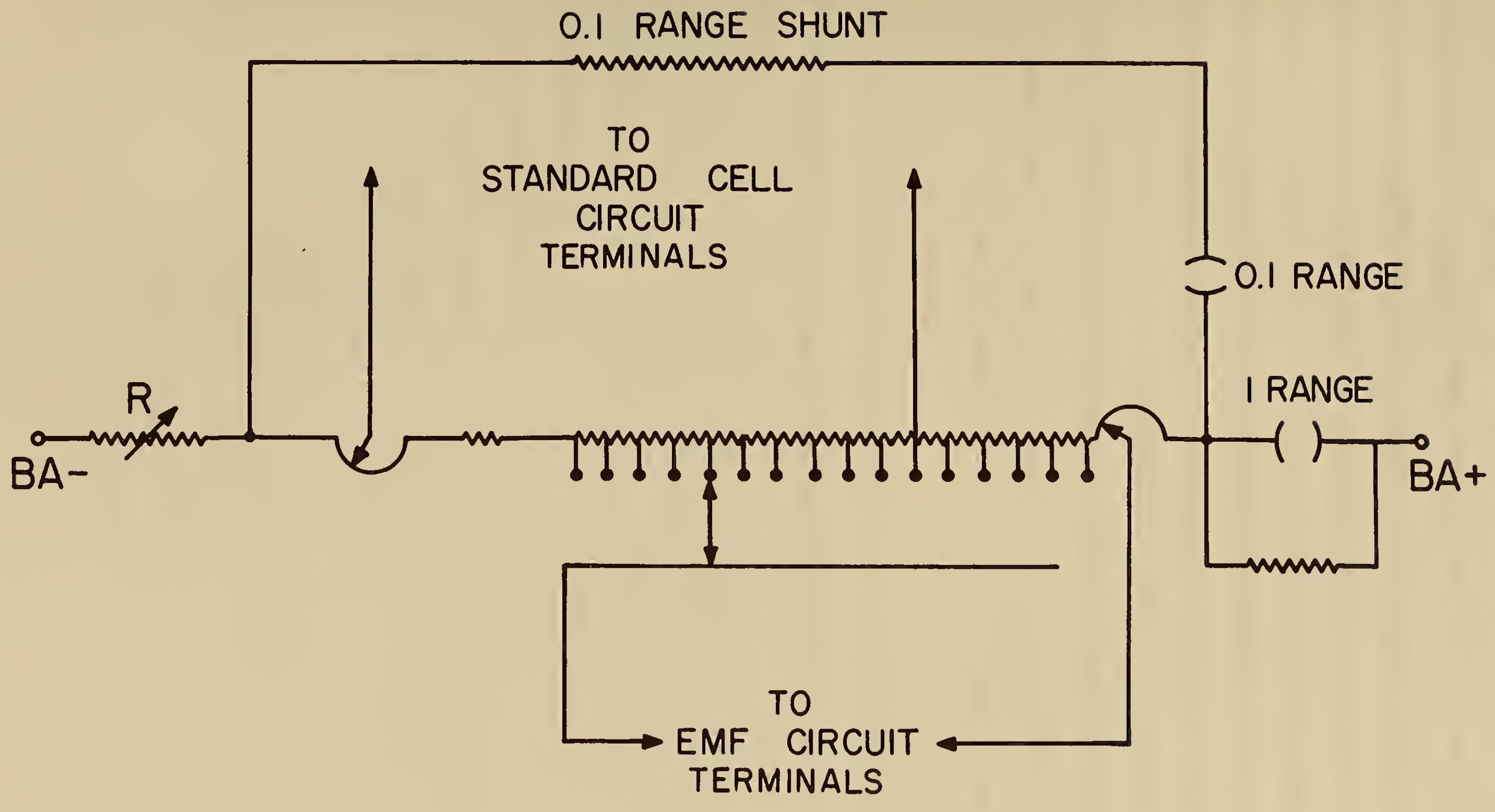


FIG. 5 SCHEMATIC DIAGRAM OF A DOUBLE RANGE POTENTIOMETER INCORPORATING STANDARDIZATION ON ONE RANGE ONLY

much as for the original situation. Therefore the factor value can be seen to be a function of the supply battery voltage. Most multipurpose potentiometers are constructed to permit standardization on all ranges, and for this type of instrument the current can be properly readjusted when a change in range is made.

The factor calibration for the circuit of figure 4 is determined as a ratio of the resistances of the two EMF circuit arrangements considered as four-terminal resistors.

The calibration of ranges or factors will be considered in some detail later. For the more complicated circuit arrangements, range or factor determinations may be somewhat intricate.

4. Calibration of Constant-Current Potentiometers

4. 1. Necessary Calibrations and Corrections

In general, the calibration of a multirange constant-current type potentiometer will require measurements on the standard cell circuit to determine its linearity. Perfect linearity implies that the standard cell circuit resistance varies directly with the setting of the standard cell dial or dials. Calibrations are needed for the individual dials in the EMF circuit and also for the ranges or factors for instruments with multiple ranges. The ratio of resistance of the EMF circuit to the SC circuit is established for the appropriate range at the time the EMF dials are calibrated by the manner in which this calibration is performed. The calibration data on a simple potentiometer in which the standard cell circuit is linear, usually can be applied to a convenient equation similar in form to the following:

$$E = F\,(1 + f)\,(D_1 + d_1 + D_2 + d_2 + D_3 + d_3, \text{ etc.}). \qquad (9)$$

In this equation E is the EMF or potential difference being measured expressed in the same unit as the emf of the standard cell used in standardizing the instrument. F is the multiplying factor for the range in use, and D_1, D_2, D_3, etc., are the readings of the several EMF dials obtained by the observer after he has positioned the dials so that a null is indicated by the galvanometer when the potential difference is being measured. The terms f, d_1, d_2, d_3, etc., are calibration corrections to be applied to F, D_1, D_2, D_3, etc. If the SC circuit is not adequately linear, a table can be prepared giving corrected settings for the standard cell dials for various standard cell voltages. The corrections f, d_1, d_2, etc., can be arranged conveniently in tabular form.

The correction to the high range or factor 1 is normally given as zero because the calibration of the instrument is performed for this range. The factor corrections for the other ranges will not be zero if the instrument is not in perfect adjustment in respect to factor switching resistors. Usually in the case of universal or multipurpose type of potentiometers, the correction for the 0.1 factor is given to 0.001 percent and for the 0.01 factor to 0.01 percent on documents issued by the National Bureau of Standards.

Some manufacturers have provided their instruments with so-called self-checking facilities. Switching arrangements may be provided to intercompare the various steps and ranges in order to determine circuit linearity and correctness of adjustment. Instruction sheets or booklets should be consulted to check the instrument in this manner.

4.2. Calibration of the Maximum Range with the Universal Ratio Set and Calibration of the Standard Cell Circuit

Normally, multipurpose potentiometers can be calibrated most simply with a Universal Ratio Set. These include the following: Leeds and Northrup Type K varieties and Wenner Standardizing model, Rubicon Type B and Bonn Five-Dial type, Otto Wolff Feussner varieties, and counterparts made by other manufacturers. A detailed set of instructions for calibrating a potentiometer of the Crompton type is available [7] .

We shall consider the calibration of the potentiometer shown in figure 6 as an example of the method of calibrating a single-range potentiometer or the maximum range of a multirange instrument. The potentiometer circuit is a hypothetical single-range potentiometer consisting of an EMF circuit with two associated dials. Each step of the first dial is 0.1 volt. The second dial is a slide-wire with a total range of 0.11 volt which is graduated in finer steps. The standard cell circuit consists of a fixed resistance including part of the EMF circuit (steps 2 to 12) and an adjustable SC slide-wire. Standardization is accomplished by adjusting the battery rheostat, R.

In this circuit the measurements to be made for a complete calibration include (1) a comparison of the resistances of all steps on the first dial, (2) a determination of the linearity of the second dial at frequent intervals such as 0.01-volt steps, (3) a determination of the linearity of the standard cell circuit, and (4) the ratio of the resistance of the SC circuit to the EMF circuit. If we take these measurements, the corrections designated as d_1 and d_2 in (9) will be determined. Because this is a single-range potentiometer there is no factor correction f.

The left terminal of the URS is connected to the BA+ terminal of the potentiometer. The right URS terminal is connected to the BA-# terminal. Leads from the URS to the BA+ and BA-# terminals of the potentiometer may be reversed if desired. If so, readings on the URS will be symmetrically arranged in respect to the first set of readings about the midpoint of the URS. If a second calibration of a potentiometer is desired, a good procedure is to perform the second calibration with reversed leads. The galvanometer or null detector is across the URS also. Power is supplied at the center terminal of the URS and to the selected one of four connecting paths to the potentiometer circuit, namely the SC+, SC-, EMF+, and EMF-# binding posts.

Balance is obtained for each connection selected by adjusting the dials of the URS until a position is obtained such that there is a minimum of galvanometer deflection upon reversal of the current from the power source.

The differences between URS readings for selected positions of the SC and EMF dials and slide-wires serve to indicate the linearity of the SC and EMF circuits and also the ratio of resistance in the EMF circuit to the resistance of the SC circuit. Differences between balance-point readings on the Universal Ratio Set are directly proportional to the resistances of the respective portions of the circuits involved when these balances are made as previously described. The comparisons of the various portions of the circuits are thus computed by ratio and proportion.

A convenient method of making the computations is to assume that a standard cell of 1.01900 volts is to be used with the instrument. Then the difference between the URS readings for the SC+ and SC-# connections would correspond to 1.01900 volts. The differences between SC+ and SC-# readings for other settings of the standard cell

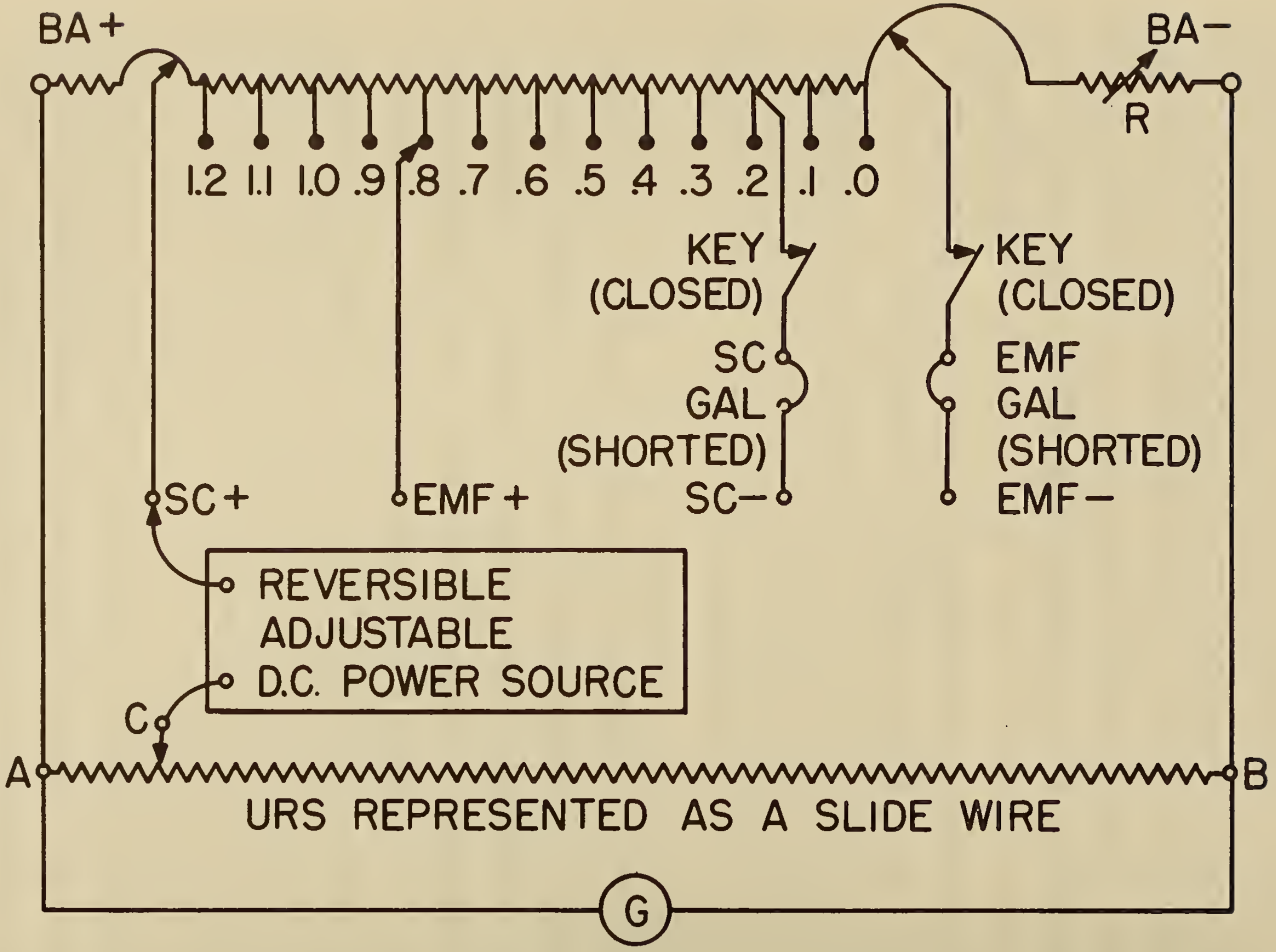


FIG. 6 SCHEMATIC DIAGRAM SHOWING ARRANGEMENT OF UNIVERSAL RATIO SET (URS) FOR CALIBRATING A POTENTIOMETER

dial would then yield figures expressable as voltages, which would determine just how linear the standard cell dial actually might be. The differences between the URS readings for EMF+ and EMF- connections will yield the voltages which will appear across these terminals when a standard cell of 1.01900 volts is used with the potentiometer. With the actual voltages corresponding to the various settings of the EMF dials thus determined, the corrections d_1 and d_2 for the various dial positions are obtained by simple inspection. If a standard cell of other voltage is to be used we can use the same computation procedure based on the other standard cell voltages. This calibration procedure actually gives the calibration of the EMF dials in terms of the SC dial and establishes the relationship between the two circuits.

A method of reducing the computations to a minimum is afforded by making the URS direct reading in terms of a desired portion of the circuit under calibration. Usually the portion of the circuit selected is that part of the standard cell circuit corresponding to a voltage typical of the majority of standard cells. If the potentiometer is to be used with unsaturated cells at room temperatures, a setting of standard cell dial or dials at 1.01900 volts would be convenient. To make the ratio set direct reading in terms of this selection, the difference in readings for balances of the URS when connected to SC+ and SC- terminals respectively should be 1019.000 ohms, if the ratio set is calibrated in ohms. To achieve this difference the first time a new type instrument is calibrated, a system of trial and error is necessary using different settings of the battery adjusting rheostat R. In achieving the correct setting of R for other instruments of the same type, the SC+ and SC- readings will usually be found to be in the same general range on the URS. Thus, previous experience with a given type of potentiometer helps to shorten the time used in setting the battery circuit rheostats.

Let us assume that the URS has been made direct reading for the SC circuit and that the readings for the circuit in figure 6 are as shown in table 1. By taking the series of SC+ readings, we have determined the uniformity or linearity of the standard cell circuit for points 1.01800, 1.01850, and 1.01950. The uniformity at other points could be determined similarly. The resistance of the standard cell circuit at 1.01800 setting is about 6 parts in a million lower than it should be. The resistance of the standard cell circuit at point 1.01850 is low by 3 parts per million and at point 1.01950 is high by about 30 parts per million. If we wish to achieve the maximum accuracy with a 1.01950-volt cell, we should set the standard cell circuit dial at point 1.019469 instead of 1.019500.

The EMF circuit is calibrated in a similar manner. Let it be assumed we obtain the URS readings at balance for various settings of the potentiometer as shown in table 2. In following this procedure again we have actually established the relationship between the EMF circuit and the SC circuit because the EMF circuit measurements were taken after the circuit was adjusted to correspond to a specified standard cell potential.

The corrections are computed on the assumption that the potential of the EMF+ terminal is zero when the 0.1-volt-per-step dial is set on zero. The EMF-# terminal could have been chosen just as conveniently for the reference terminal.

In the course of performing such a calibration, any instability in the potentiometer circuit will be evident as non-reproducibility of URS readings. Consequently, the URS readings for the SC+ and SC- connections should be checked as often as necessary to insure that the arrangement remains sufficiently stable. Changes of a few parts per million would not be excessive for normally expected precision of

Table 1

Typical Calibration Data for the Standard Cell Dial Circuit of Figure 6

Power Applied to Terminal Indicated	Potentiometer Setting, Volts	URS Reading, Ohms	Reading Difference
SC-	1.0190	1023.363	1019.000
SC+	1.0190	4.363	
SC+	1.01800	5.369	1017.994
SC+	1.01850	4.866	1018.497
SC+	1.01900	4.363	1019.000
SC+	1.01950	3.832	1019.531

Table 2

Calibration Data and Computed Corrections for a Simplified Two-Dial Potentiometer

Power Applied to Terminal Indicated	Positons of Potentiometer Dials (Volts)	URS Reading	URS Reading Differences	Corrections to be Applied to the Potentiometer in Volts
	First Dial			
EMF+	1.2	23.397	1199.972	-0.000028
	1.1	123.394	1099.975	-0.000025
	1.0	223.381	999.988	-0.000012
	0.9	323.375	899.994	-0.000006
	0.8	423.359	800.010	+0.000010
	0.7	523.345	700.024	+0.000024
	0.6	623.338	600.031	+0.000031
	0.5	723.336	500.033	+0.000033
	0.4	823.342	400.027	+0.000027
	0.3	923.354	300.015	+0.000015
	0.2	1023.363	200.006	+0.000006
	0.1	1123.365	100.004	+0.000004
	0.0	1223.369	0.000	0.000000
	Second Dial			
EMF-	0.00	1223.373	0.004	+0.000004
	0.01	1233.373	10.004	+0.000004
	0.02	1243.370	20.001	+0.000001
	0.03	1253.367	29.998	-0.000002
	0.04	1263.362	39.993	-0.000007
	0.05	1273.351	49.982	-0.000018
	0.06	1283.359	59.990	-0.000010
	0.07	1293.366	69.997	-0.000003
	0.08	1303.372	80.003	+0.000003
	0.09	1313.379	90.010	+0.000010
	0.10	1323.382	100.013	+0.000013
	0.11	1333.391	110.022	+0.000022

measurement. Instability, when present, usually results from poor contacts in the battery rheostat. It is advisable to clean these as well as possible.

Another but more precise method of calibrating this potentiometer with a URS would be to set the EMF dials at the voltage of the standard cell to be used with the instrument. The potentiometer battery rheostats are then adjusted so that the URS reading difference at balance points between EMF+ and EMF- terminals corresponds to the voltage of the standard cell. The URS would then be direct reading for calibrating the EMF dials at all desired points.

By switching the URS connection to the standard cell circuit, the correct setting could be obtained that would correspond to the potential of the standard cell. After this correct setting is known, the user can standardize the instrument with the usual standard cell circuit if the standard cell dial is set to this point. This same point can be obtained by the user without a URS, simply by first standardizing the instrument with the standard cell connected to the EMF circuit and quickly switching the standard cell to the standard cell circuit and obtaining a balance by adjusting the standard cell dial. A repetition may be necessary to assure the user of the correctness of the setting.

This same technique can be used for spot checking the adjustment of any potentiometer having an emf range covering that of the standard cell dial.

The URS can be connected so that readings are spread out over the range of the set more effectively in many situations. Let us assume that we have a potentiometer with considerable resistance in one end and no measurements to be taken on this portion of the circuit. If we connect the variable resistance box, H, in series with the URS as shown in figure 7, the readings on the portion of the circuit in which we are interested can be spread out more effectively and thereby provide better resolution.

This arrangement, shown in figure 7, is the equivalent of adding an extra range, H, to the URS although no readings can be taken over the range H. This imposes no restrictions, however, if there are no readings to be taken corresponding to resistors K, L, and M which would be those that would fall on the added range H. Consequently, we have been able to spread out the EMF and SC readings so that more of the URS range is utilized.

4.3. Calibration of Additional Ranges or Factors with the Universal Ratio Set

The procedure for calibration of factors depends upon the circuitry of the potentiometer. It is best for the person performing the calibration to be familiar with the circuit and to derive his own expressions for the factor determination in terms of resistance ratios of the various circuit components.

Methods described here for calibration of factors of multipurpose potentiometers are the simpler ones but not necessarily the most precise. If we choose to solder special connecting leads into the circuits and in some instances use calibrated standard resistors, usually it is possible to attain better precision and accuracy on factor measurements.

Let us now consider the factor for some range, Y, other than the 1 range and designate this factor as F_Y. This generalized expression can be used to represent either the 0.1 range or the 0.01 range. We shall designate the potential difference developed at the EMF terminals corresponding to the Y range as V_Y and the potential difference

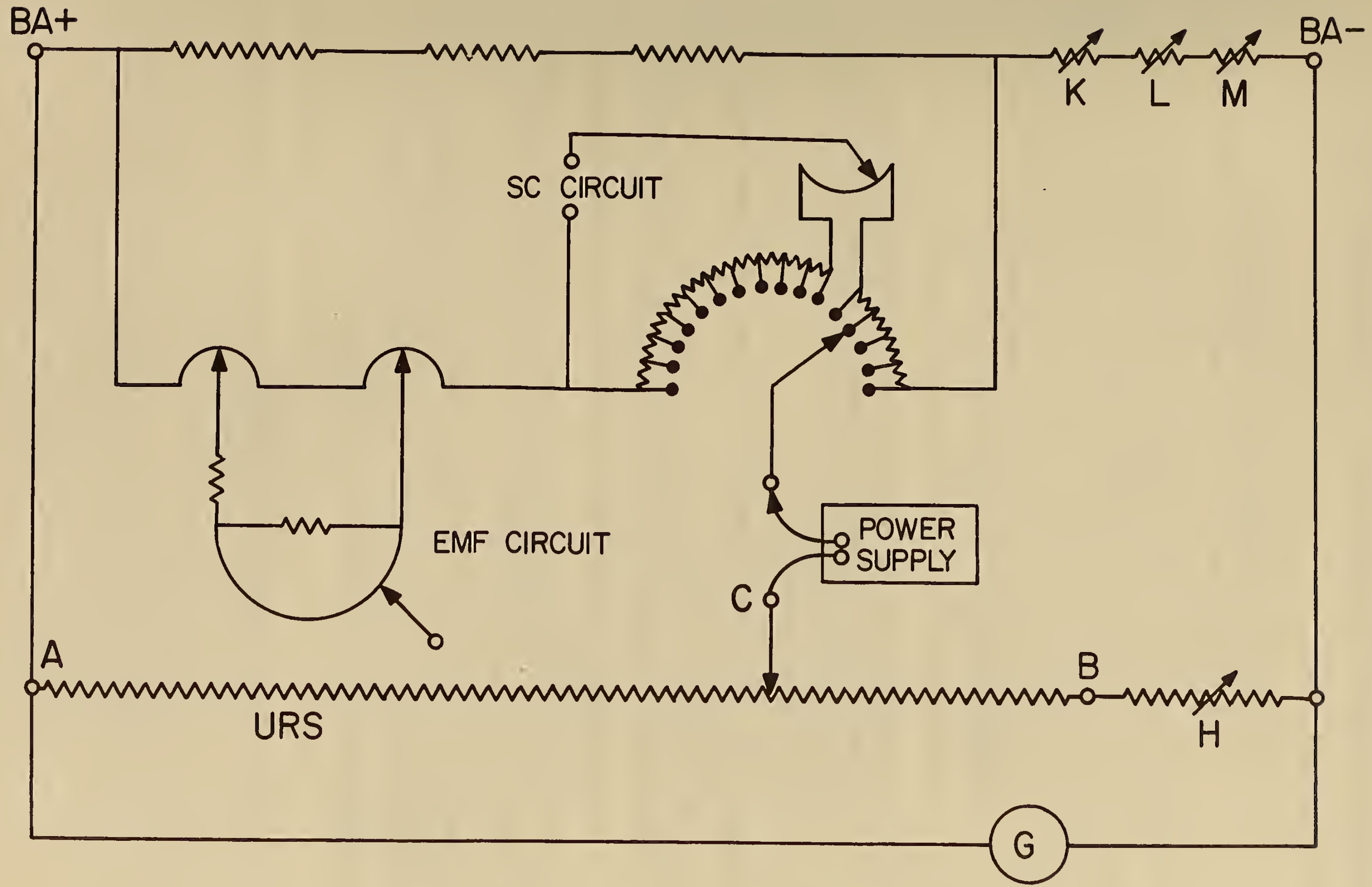


FIG. 7 DIAGRAM INDICATING METHOD OF SPREADING OUT UNIVERSAL RATIO SET READINGS

at the EMF terminals for the 1 range as V_1. In both situations the potentiometer is assumed to have been properly standardized. F_Y is thus the ratio of V_Y to V_1.

a. Factors for Potentiometers Designed for Standardization on All Ranges

For potentiometers which actually standardize on all ranges regardless of circuit details, we can develop a factor expression. We shall use the following terminology:

I_1	is the current supplied to the potentiometer by the battery when the factor is set at 1.
I_Y	is the current when the factor is set at Y.
R_{E1}	is the four-terminal resistance of the EMF circuit considering the EMF terminals as potential terminals with the EMF dials set to a maximum position and the factor set on 1.
R_{EY}	is the corresponding four-terminal resistance with the factor set on Y.
R_{S1}	is the four-terminal resistance of the standard cell circuit considering the SC terminals as potential terminals and the standard cell dial set to a convenient position.
R_{SY}	is the corresponding four-terminal resistance with the factor set on Y.

It should be noted that figure 4 is a special case of the following derivation in which $R_{S1} = R_{SY}$ and $I_1 = I_Y$. The factor F_Y for the Y range is obtained from the following expression:

$$F_Y = \frac{V_Y}{V_1} = \frac{R_{EY} I_Y}{R_{E1} I_1} . \qquad (10)$$

For the corresponding standardization for each range, the potential difference developed across the standard cell circuit is the same and is

$$R_{S1}I_1 = R_{SY}I_Y \; . \tag{11}$$

Consequently,

$$\frac{I_Y}{I_1} = \frac{R_{S1}}{R_{SY}} \; . \tag{12}$$

Substituting (12) into (10), gives

$$F_Y = \left(\frac{R_{EY}}{R_{E1}}\right)\left(\frac{R_{S1}}{R_{SY}}\right) = \left(\frac{R_{EY}}{R_{SY}}\right)\left(\frac{R_{S1}}{R_{E1}}\right) . \tag{13}$$

The ratio R_{EY}/R_{SY} is readily measured on the URS by connecting one end of the URS to BA+ and the other end to BA-# terminals of the potentiometer. The battery-adjusting rheostat should be set to its minimum and the factor switch set on Y. The ratio R_{S1}/R_{E1} is obtained in a similar manner with the factor switch set on 1.

F_Y can be obtained from (13) by actually measuring, as four-terminal resistances, the four resistances on the right of the equation. These can be measured in terms of known standards using the URS, by means of a Kelvin or Thomson double bridge or any other convenient and acceptable method. The factor F_Y can be expressed as $F(1 + f)$ where F is the nominal factor and f the correction. For example, a factor of 0.100006 would represent the nominal 0.1 factor with a correction of +0.006 percent.

b. Factors for Potentiometers Standardizing on a Single Range

For the potentiometer which standardizes on the highest range only, such as shown in figure 5, the method will be somewhat modified. The current I_Y may differ from I_1 because the overall resistance of the potentiometer T_Y for the Y factor differs from the overall resistance for the 1 factor T_1.

$$\frac{I_Y}{I_1} = \frac{T_1}{T_Y} . \qquad (14)$$

Substituting (14) into (10), gives

$$F_Y = \left(\frac{R_{EY}}{R_{E1}}\right)\left(\frac{T_1}{T_Y}\right) . \qquad (15)$$

It should be emphasized that T_1/T_Y is the ratio of total resistances for the potentiometer when in use with a battery of a specified voltage. If a battery of a different voltage is used with the potentiometer, a corresponding change in the battery rheostat must be made in which case T_1/T_Y may be appreciably different if T_1 and T_Y are not close to equality (the condition of poor factor compensation). For this situation the factor for range Y will be a function of the supply battery voltage and will have to be calculated for whatever voltage is furnished by the supply battery.

The expression R_{EY}/R_{E1} can be measured readily by connecting a URS across the BA+ and BA- terminals. After EMF and SC dials have been calibrated, the EMF dials are set to a maximum and readings at balance taken on the URS for potential connections EMF+ and EMF-. The same procedure is repeated with the factor switch in the Y position. The URS reading differences ΔE_1 for the 1 factor and ΔE_Y for the Y factor are given by the following equations:

$$\frac{\Delta E_1}{2111.11} = \frac{R_{E1}}{T_{1C}} , \qquad (16)$$

$$\frac{\Delta E_Y}{2111.11} = \frac{R_{EY}}{T_{YC}} . \qquad (17)$$

The term 2111.11 represents the overall resistance, in ohms, of conventional Universal Ratio Sets. The term T_{1C} is the total resistance of the potentiometer on the 1 factor as the instrument is being calibrated, and T_{YC} is the total resistance of the potentiometer on the Y factor as the instrument is being calibrated.

Combining (16) and (17) and rearranging terms gives

$$\frac{R_{EY}}{R_{E1}} = \left(\frac{\Delta E_Y}{\Delta E_1}\right)\left(\frac{T_{YC}}{T_{1C}}\right). \tag{18}$$

Substituting (18) in (15) gives

$$F_Y = \left(\frac{\Delta E_Y}{\Delta E_1}\right)\left(\frac{T_{YC}}{T_{1C}}\right)\left(\frac{T_1}{T_Y}\right). \tag{19}$$

Equation (19) is used to compute the factor. The term $\Delta E_Y/\Delta E_1$ is obtained directly from differences of URS readings. The term T_{YC}/T_{1C} is obtained by comparing the total resistances with the factor set at 1 and at Y with the battery rheostat in the position used when the EMF dials are calibrated. This comparison can be made with a precise Wheatstone bridge but is obtained more conveniently with a Direct Reading Ratio Set (Wenner Ratio Set) [2, 4] . The term T_1/T_Y is obtained in similar fashion except that the total resistance in the potentiometer is that in the circuit when the potentiometer is in use.

If the potentiometer is to be used with a battery such that the overall potentiometer resistance is close to that at which calibration is performed, the expression

$$\left(\frac{T_{YC}}{T_{1C}}\right)\left(\frac{T_1}{T_Y}\right)$$

reduces to unity for practical purposes. This is frequently the situation. One manufacturer, however, provides for choice of either three or six-volt supply by providing the instrument with an added resistor to be inserted in series with the battery-adjusting rheostat. The factor corrections for instruments of this type frequently are different for use with three and six-volt batteries. If an extremely high voltage supply were used with the correspondingly high dropping resistance, the term T_1/T_Y practically would be unity. If the term T_{YC}/T_{1C} is unity, so also is T_1/T_Y unity.

c. Other Factor Circuits

Other factor arrangements for constant current potentiometers can be treated in a similar manner to determine just what measurements are necessary and to what precision. The examples given are illustrative of the type of measurement capabilities of the URS. These methods may be extended with slight modifications to such specialized varieties as microvolt potentiometers and others where the range of potential measured differs considerably from that of a standard cell.

4. 4. Examples of Factor Measurement

a. Measurements on an Instrument that Standardizes on All Ranges

Typical data are shown in table 3 for factor determiniation on a potentiometer that standardizes on all ranges.

We have shown that the ratios of URS reading differences are proportional to the ratios of the corresponding resistances. Equation (13) may be restated in terms of URS reading differences. For the 0. 1 factor,

$$F_Y = \left(\frac{R_{EY}}{R_{SY}}\right)\left(\frac{R_{S1}}{R_{E1}}\right) = \left(\frac{\Delta E_{0.1}}{\Delta SC_{0.1}}\right)\left(\frac{\Delta SC_1}{\Delta E_1}\right), \qquad (20)$$

$$F_Y = \left(\frac{197.518}{1251.246}\right)\left(\frac{1251.248}{1975.317}\right) = 0.099993. \qquad (21)$$

This can be expressed in terms of the nominal factor ratio 0.1 and a correction. Using the same reasoning for the 0.01 factor,

$$F_Y = \left(\frac{\Delta E_{0.01}}{\Delta SC_{0.01}}\right)\left(\frac{\Delta SC_1}{\Delta E_1}\right) = \left(\frac{19.751}{1251.239}\right)\left(\frac{1251.248}{1975.317}\right)$$

$$= 0.009999 = 0.01(1 - 0.0001). \qquad (22)$$

b. Measurements on an Instrument that Standardizes on a Single Range

Typical data are shown in table 4 for factor determination on one type of potentiometer that standardizes on a single range. Potentiometer dials are set at 1.600 volts. When the instrument is calibrated by the URS and also when it is used as a potentiometer with a 3-volt battery, the overall resistance is about 272 ohms. When the instrument is used as a potentiometer with a 6-volt battery, the overall resistance is about 545 ohms.

The following measurements were taken with a high-resolution Wheatstone bridge on overall resistances for use in (19). The circuit was adjusted for calibration or for use with a 3-volt power supply.

For 1 factor, $T_{1C} = T_1 = 271.990$ ohms.
For 0.1 factor, $T_{YC} = T_Y = 271.984$ ohms.
For 0.01 factor, $T_{YC} = T_Y = 271.996$ ohms.

The following terms were computed for a 6-volt power source requiring an added resistance of about 273 ohms.

For 1 factor, $T_1 = 544.990$ ohms.
For 0.1 factor, $T_Y = 544.984$ ohms.
For 0.01 factor, $T_Y = 544.996$ ohms.

Table 3

Typical Factor Measurement Data for an Instrument That Standardizes on All Ranges

Potential Connection to Potentiometer	Factor or Range	URS Reading	Reading Differences
SC+	1	859.452	1251.248 = ΔSC_1
SC-	1	2110.700	
EMF-	1	1976.472	1975.317 = ΔE_1
EMF+	1	1.155	
SC+	0.1	859.454	1251.246 = $\Delta SC_{0.1}$
SC-	0.1	2110.700	
EMF-	0.1	2037.891	197.518 = $\Delta E_{0.1}$
EMF+	0.1	1840.373	
SC+	0.01	859.461	1251.239 = $\Delta SC_{0.01}$
SC-	0.01	2110.700	
EMF-	0.01	2044.032	19.751 = $\Delta E_{0.01}$
EMF+	0.01	2024.281	

Table 4

Typical Factor Measurement Data For an Instrument
that Standardizes on a Single Range

Potential Connection to Potentiometer	Factor or Range	URS Reading	Reading Differences
EMF+	1	71.228	1600.002 = ΔE_{1}
EMF-	1	1671.230	
EMF+	0.1	1511.139	160.005 = $\Delta E_{0.1}$
EMF-	0.1	1671.144	
EMF+	0.01	1655.005	16.002 = $\Delta E_{0.01}$
EMF-	0.01	1671.007	

When these values are substituted in (19), the following results are obtained.

For 0.1 factor and a 3-volt battery,

$$F_Y = \left(\frac{160.005}{1600.002}\right)\left(\frac{271.984}{271.990}\right)\left(\frac{271.990}{271.984}\right) = 0.100003.$$

For 0.1 factor and a 6-volt battery,

$$F_Y = \left(\frac{160.005}{1600.002}\right)\left(\frac{271.984}{271.990}\right)\left(\frac{544.990}{544.984}\right) = 0.100002.$$

For 0.01 factor and a 3-volt battery.

$$F_Y = \left(\frac{16.002}{1600.002}\right)\left(\frac{271.996}{271.990}\right)\left(\frac{271.990}{271.996}\right) = 0.010001.$$

For 0.01 factor and a 6-volt battery,

$$F_Y = \left(\frac{16.002}{1600.002}\right)\left(\frac{271.996}{271.990}\right)\left(\frac{544.990}{544.996}\right) = 0.010001.$$

Because the 0.01 factor ordinarily is computed with no more precision than 0.01 percent, the 0.01 factor would be the same for either a 3-volt or a 6-volt power source.

4.5. Working Test for Factors

In addition to the spot check mentioned on page 25 for checking the EMF range corresponding to the SC range, a simple working test for three factors can be arranged. The test requires three accurately known resistors in ratios 1 to 10 to 100. The lowest resistor can be of any value from 1 to 100 ohms. These resistors are connected in series to a suitable battery of constant voltage and thus provide three stable sources of potential difference with nominal ratios of 0.01 and 0.1. The actual ratios of potential are the same as the accurately known ratios of the three resistors. A suitable, stable current is established in the resistors so that the potential difference across the highest resistor falls near the upper limit of the highest range of the potentiometer. The potential differences across the three resistors are measured on the three respective ranges of the potentiometer. The factors can be checked by comparing the measured potential ratios against the actual potential ratios. This same technique is applicable to other types of potentiometers also.

4.6. Comparison with Another Potentiometer as a Method of Calibration

Perhaps the most straightforward method of calibrating a potentiometer is to compare it directly with a potentiometer of similar range which previously has been calibrated accurately. However, this method usually is not as accurate as the bridge circuit URS methods. It has the advantage of calibration under actual operating conditions and is suitable for portable instruments of moderate accuracy.

In comparing a potentiometer with another calibrated one, the instrument under calibration can be used to furnish potential differences at desired calibration points. These potential differences are measured by the calibrated potentiometer. The functions of the two instruments may be interchanged. It is essential that the currents in both potentiometers be held as constant as possible. This requirement demands the utmost in stability of power sources. Furthermore, the presence of thermal electromotive forces constitutes possible sources of calibration errors. If two observers work together and standardize the instruments as frequently as required, the errors due to drift with time may be minimized. A single standard cell with appropriate switching arrangements may be used to standardize both instruments. If separate standard cells are used, emf's of both must be known accurately or the difference known accurately.

If standard cell circuits are compared with each other for linearity, a switching arrangement should be used that avoids the possibility of accidently discharging the standard cells. During this comparison, the standard cell terminals of both instruments will be connected to each other, and the standard cells must not be connected to either potentiometer while the potentiometers are interconnected. The standard cell circuit linearity can be evaluated by using the EMF circuit of a calibrated potentiometer, if switching arrangements are provided to protect the standard cell from accidental discharge.

To determine the factor corrections of a potentiometer by comparison, it is not necessary to make measurements on all positions of the dials. A check on two or three of the highest settings of the first dial should be adequate to furnish the ratios of the factors.

4.7. Calibration of Constant-Current Potentiometers Designed to Measure Small EMF's and of Modified Constant-Current Potentiometers

Typical of the group are such types as the Diesselhorst potentiometer, the Wenner Low-Range potentiometer, the White Double potentiometer, and the Rubicon Six-Dial Thermofree potentiometer. Most of these are described by Harris [8] . Specialized circuits are incorporated in these instruments necessitating individual circuit analysis for each variety before a definite calibration procedure can be established. Some of these varieties can be calibrated by a number of methods. Details of the calibration by means of another potentiometer, outlined previously, are applicable here. The URS is useful in calibrating all of these instruments. However, because of the extensive range in magnitude of component circuit resistors, resultant high or low resistance ratios cannot be obtained with the required measurement accuracy by direct comparison of URS reading differences. In these circumstances the comparison of the components with calibrated standard resistors of approximately the same magnitude as the components usually is required. Thus, an added step is introduced in determination of resistance ratios.

5. Potentiometers of the Constant-Resistance or Lindeck Variety and Combination Types

5.1. Principles of Circuitry

Figure 8 is a schematic diagram of a simple potentiometer illustrating this principle. The source of unknown potential difference is connected in series with a galvanometer G and a tapping key, all connected across a calibrated resistance R_E. R_E may be a single resistor, a multiple resistor, or a combination of resistors. Current is supplied to this resistor by a battery, and its magnitude is controlled by the adjustable rheostat R. A meter, M, usually a milliammeter or microammeter, is inserted in this circuit.

When the tapping key is closed and the galvanometer indicates a null condition, the EMF or potential difference at the EMF terminals equals the four-terminal resistance of R_E times the current in this resistor. The current is indicated by the meter. The meter scale usually is graduated to read the potential difference present across the EMF terminals of the instrument.

Several types of potentiometers in use incorporate in their circuits a combination of a constant-current potentiometer and a constant-resistance potentiometer. Each unit measures a portion of the unknown emf. Figure 9 is the schematic diagram of such a combination.

This instrument has two ranges, and both the constant-current portion of the circuit and the Lindeck portion of the circuit have separate factor plug switches to accomplish this change in range. That portion of the unknown EMF measured by the constant-current method is equal to the potential drop across resistors $S_1 + S_2$; the portion measured by the Lindeck potentiometer is equal to the drop across S_3.

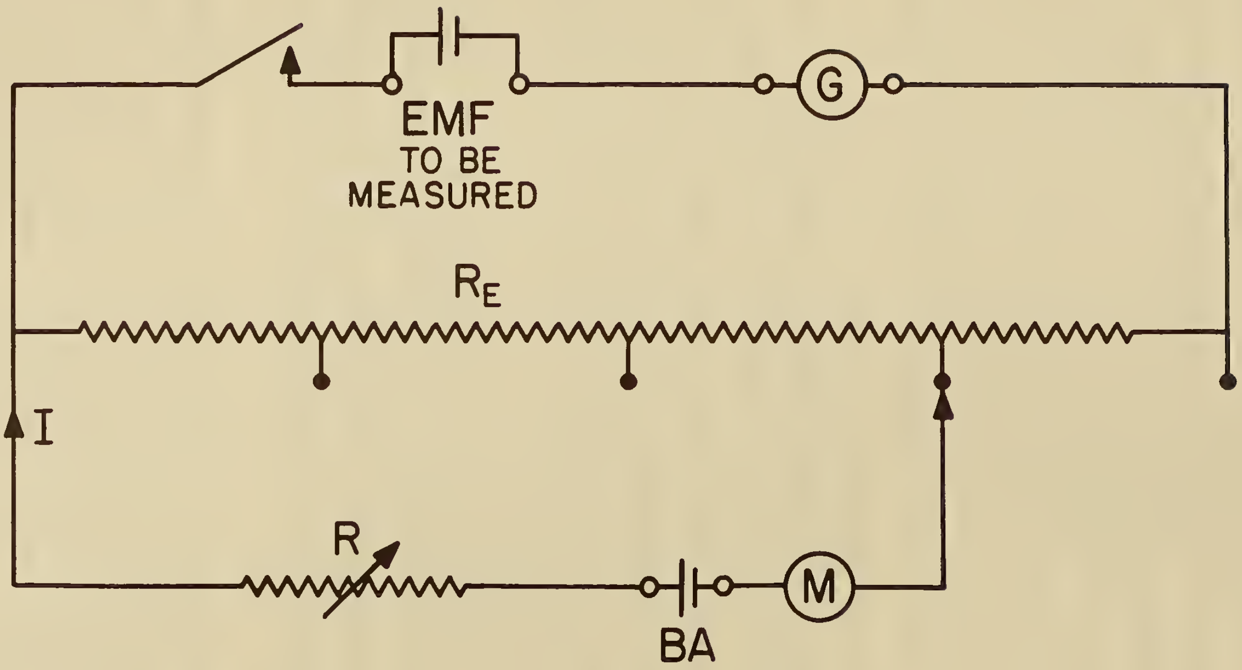


FIG. 8 SCHEMATIC DIAGRAM OF A SIMPLE LINDECK TYPE POTENTIOMETER

Dials D_1 and D_2 adjust the potential drop across S_1 and S_2, whereas dials D_3 and D_4 adjust the potential drop across S_3. Each potentiometer unit uses a separate battery.

5.2. Calibration of Lindeck and Combination Potentiometers

A simple Lindeck unit such as shown in figure 8, merely requires four-terminal resistance determinations on the resistor R_E for all ranges, and also a calibration of the meter. The resistance measurements do not require extreme precision and may be accomplished by a number of methods. One method is the comparison of the potential difference across R_E with the corresponding potential difference across a known standard resistor connected in series with R_E when the circuit is energized with a steady direct current. Likewise, any suitable bridge method of making moderately accurate four-terminal resistance measurements is acceptable.

The meter can be calibrated by any suitable method of calibrating sensitive, dc, low-current meters. In combination instruments, provision may be made for calibrating the meter directly against steps on the constant-current portion of the circuit.

In figure 9, EMF dials D_1 and D_2, as well as the standard cell circuit, are calibrated against standard resistors of appropriate magnitudes by means of a URS. Furthermore, the dials D_1 and D_2 must be checked to insure that the circuits are so compensated that the current in the potentiometer is independent of the positions of dials D_1 and D_2.

The range or factor measurements on the meter factors, as well as the factors for the constant-current portion of the circuit, can be accomplished by methods previously outlined. However, the procedure is somewhat more complicated and may require the soldering of some lead connections into various portions of the circuit for best

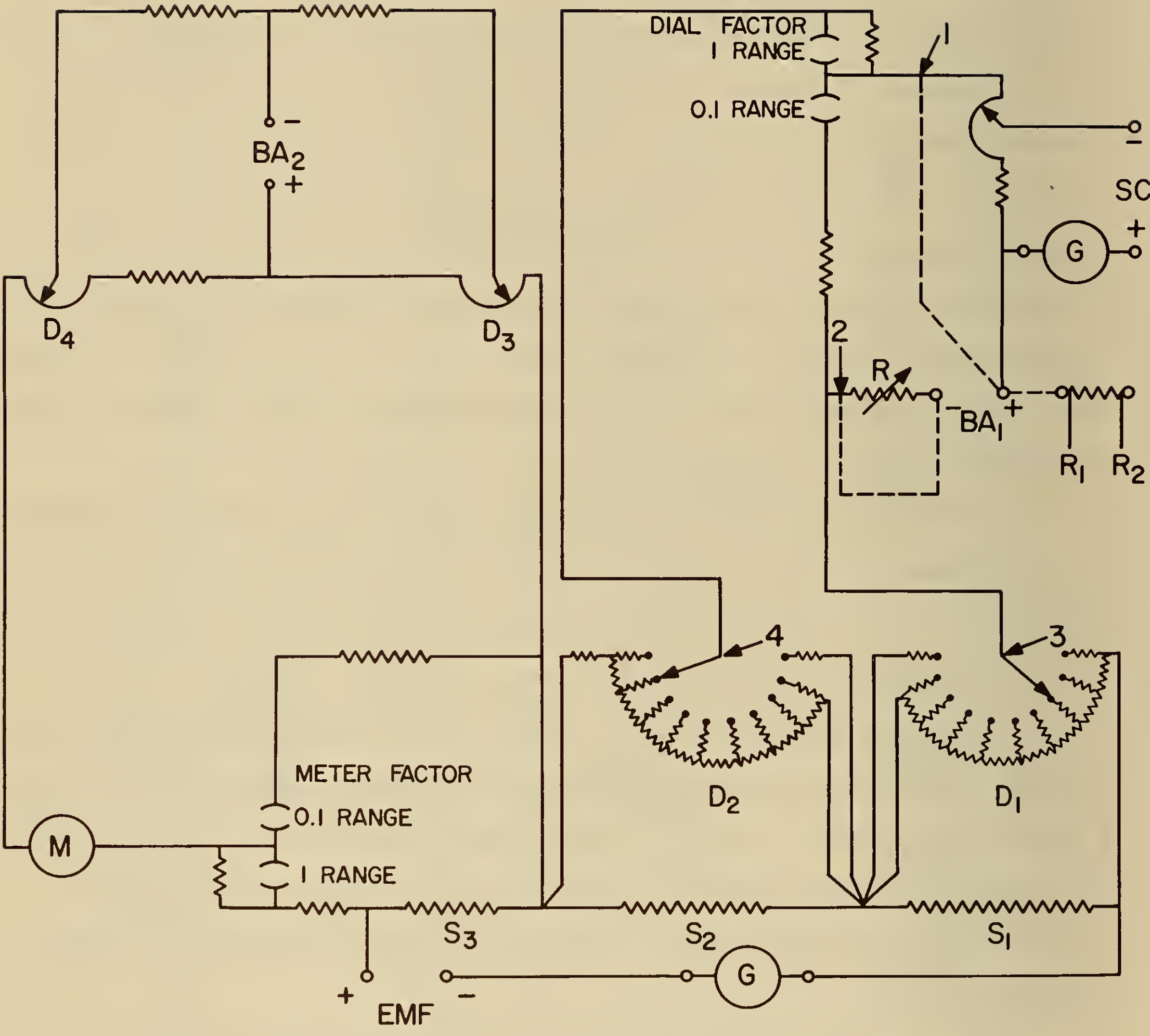


FIG. 9 SIMPLIFIED SCHEMATIC DIAGRAM OF COMBINATION OF CONSTANT CURRENT AND CONSTANT RESISTANCE POTENTIOMETER

results. In figure 9, leads may be soldered at the points indicated by arrows 1 and 2. These leads are then connected to the battery terminals as shown by the dashed lines in order to short out both the battery rheostat R and the standard cell circuit. Potential connections are obtained by clips on the shafts on the dials as indicated by arrows 3 and 4. The A and B terminals of the URS are connected to the special leads at points 1 and 2 or to the BA_1 terminals. Readings are taken on the URS corresponding to connections made at potential points 3 and 4 for both of the dial factor positions. In addition, a determination is made on the ratio of the overall resistances of the circuit between points 1 and 2, corresponding to the two positions of the dial factor switch. These measurements provide the data necessary to compute the factor.

The same factor can be measured without any checks on overall resistances or any extra leads soldered in if we simply connect the BA_1 terminals to the A and B terminals of the URS and then follow the procedure outlined in the section on potentiometers which standardize on all ranges. The points which should be used in place of the EMF terminals are the connections to the dial shafts. The precision of this method will be somewhat limited by the smaller difference obtainable in URS readings between the potential points 3 and 4 in the EMF circuit. This is because the ratio of the EMF circuit resistance to the total resistance of the standard cell circuit and the battery rheostat is small.

However, the spread of readings on the URS for the EMF potential points can be increased by shorting out the standard cell circuit and the battery adjusting rheostat R, and making the following modification. A high-quality resistor of a suitable magnitude about the same as that of the EMF circuit resistance between points 3 and 4 can be connected in place of the standard cell circuit. The connections to the resistor potential terminals R_1 and R_2 will then serve as substitutes for the SC+ and SC-# terminals when taking URS readings. In effect, a dummy standard cell circuit has been created to substitute for the original. URS reading differences for the EMF circuit and the dummy standard cell circuit are the same order of magnitude, and the accuracy of the measurement is thereby improved appreciably.

The meter factor in figure 9 can be measured by identical methods when the meter is disconnected from the circuit. The meter itself can be calibrated against the dials D_1 and D_2 by a so-called "self-checking" method.

The above examples serve to show some of the means of calibrating the factors of Lindeck-type potentiometers. However, these factors can be calibrated by measuring resistances of individual components. In general, each circuit should be carefully studied to determine the most appropriate calibration method.

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Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.


NBS