July 8, 1969 L. JULIE 3,454,877

POTENTIOMETER MEANS FOR PROVIDING A STANDARDIZED PRECISION LOW VOLTAGE

Filed July 2, 1965 Sheet 1 of 4

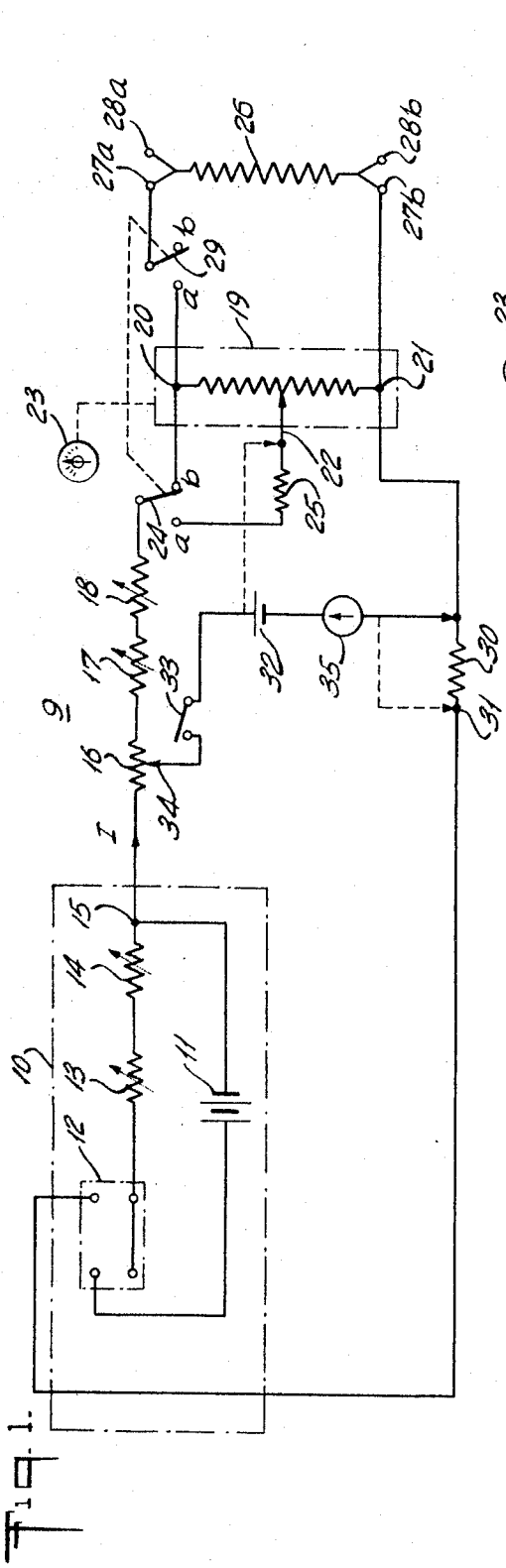


FIG. 1.

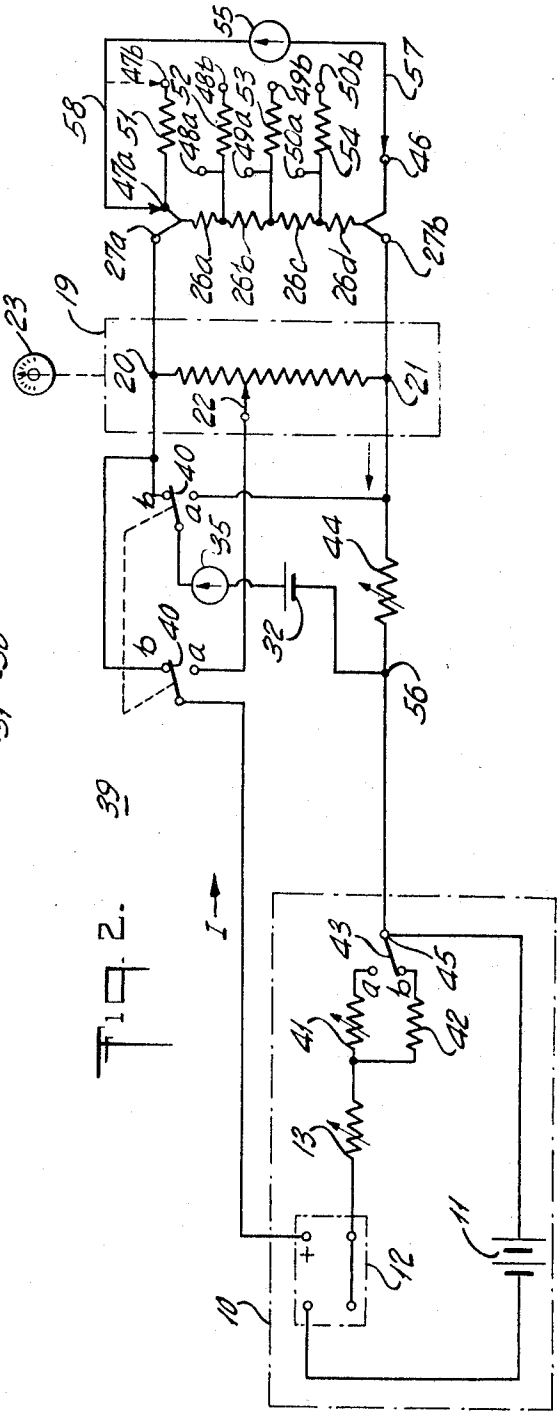


FIG. 2.

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Fig. 2a

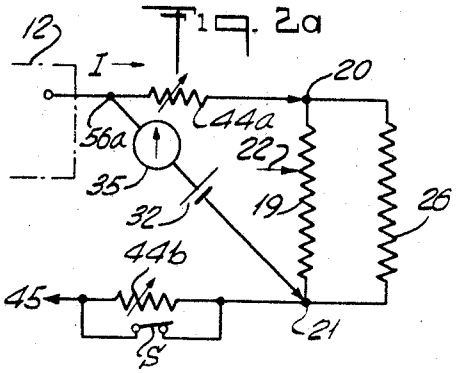


Fig. 2b

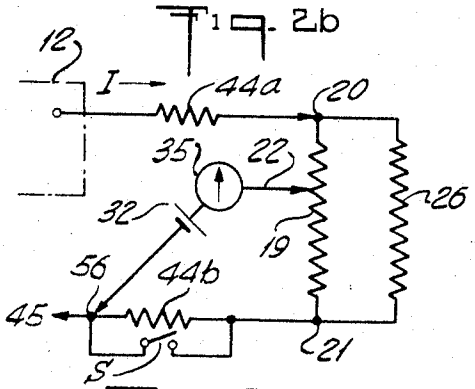


Fig. 2c

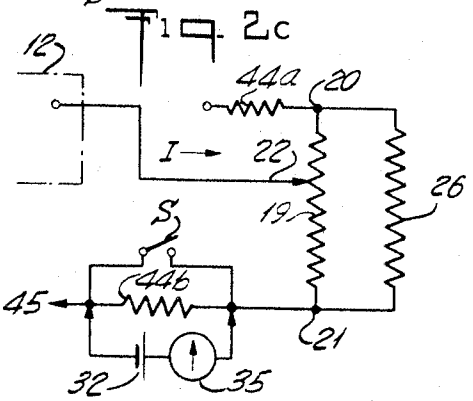


Fig. 3.

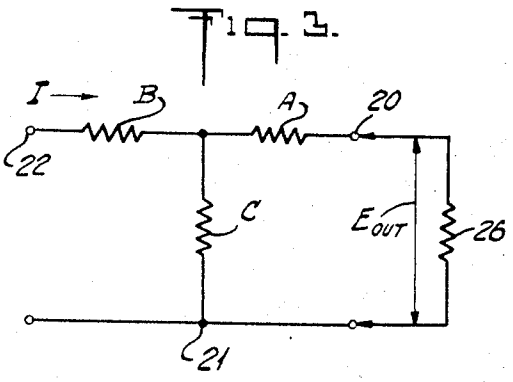
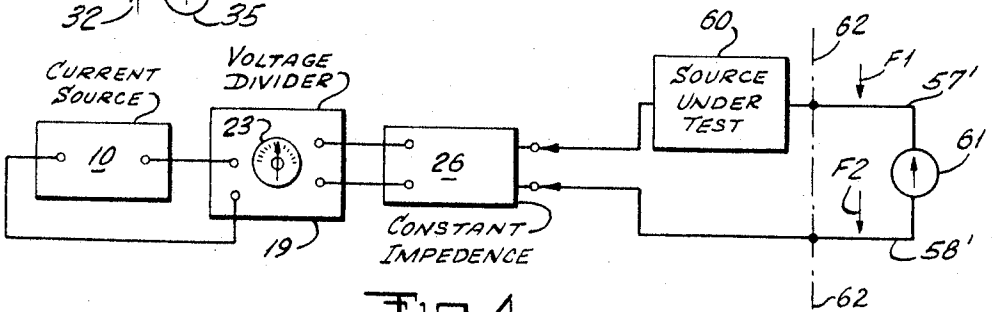


Fig. 4.



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Fig. 5.

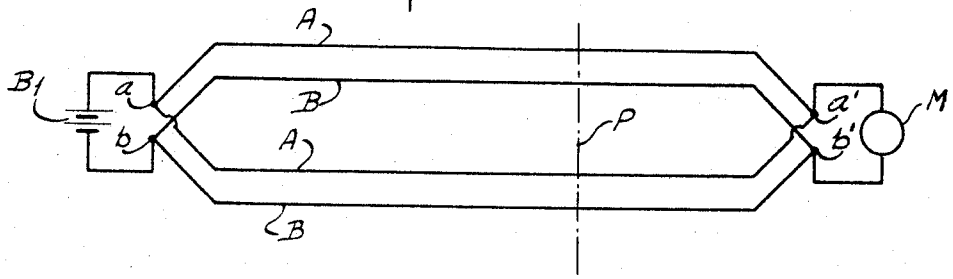


Fig. 6.

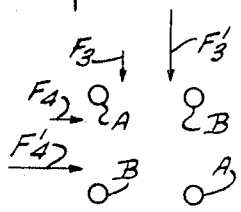
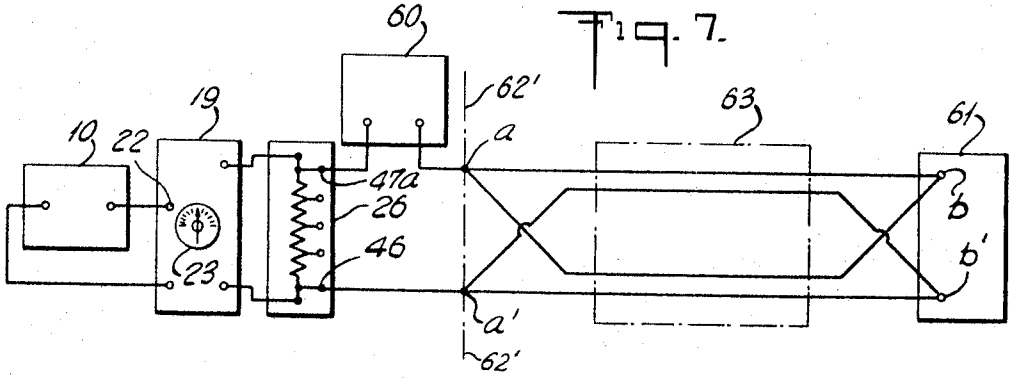


Fig. 7.



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Fig. 8.

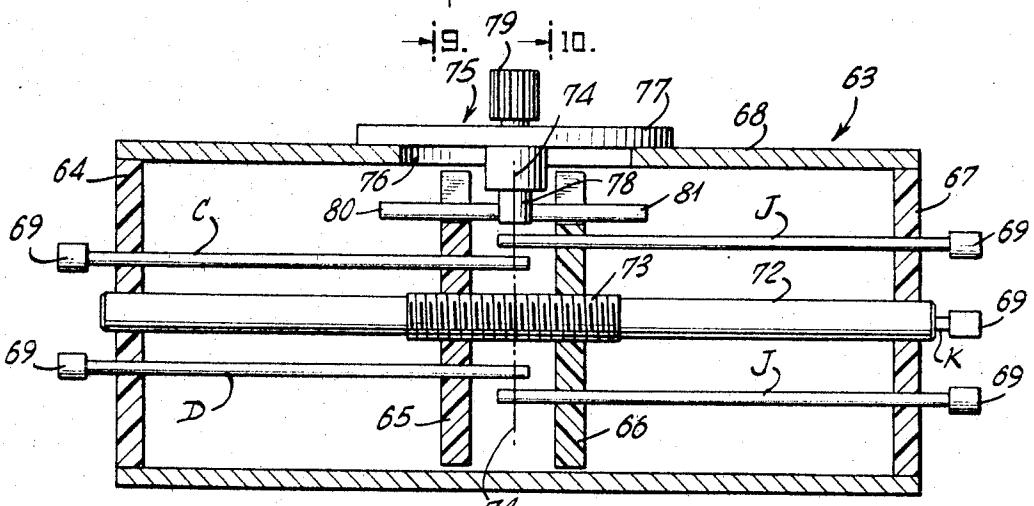


Fig. 8a. Fig. 8b.

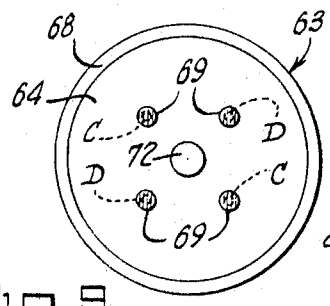
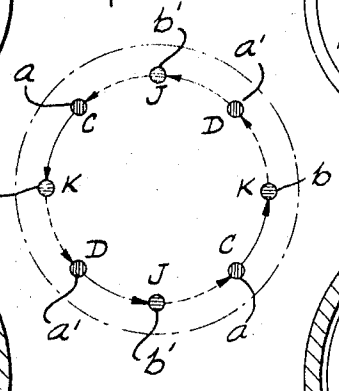


Fig. 11.



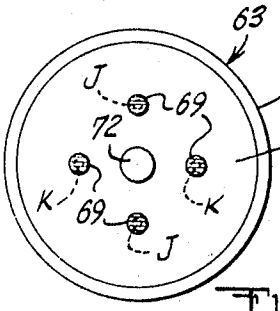


Fig. 9.

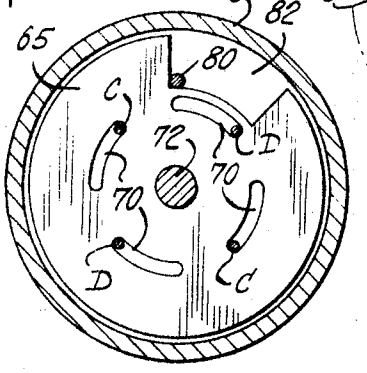
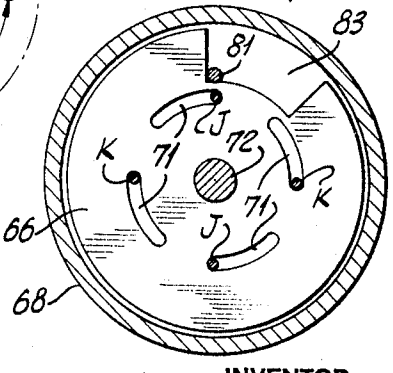


Fig. 10.



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3,454,877

POTENTIOMETER MEANS FOR PROVIDING A STANDARDIZED PRECISION LOW VOLTAGE

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Int. Cl. G01r 17/02; H02p 13/00; H02m 5/06
U.S. Cl. 324—98 9 Claims

ABSTRACT OF THE DISCLOSURE

A circuit for producing a high precision low voltage, i.e., microvolt source, is adjustable as to its output. The circuit includes a constant current source and a voltage divider. The voltage divider is characterized by a linear transfer ratio and a constant input impedance.

The instant invention relates to a calibrated potentiometer system for producing a high precision microvolt source and, in particular, the invention herein contemplates the use of a voltage divider characterized by a linear transfer ratio as the variable potentiometer parameter, which divider is combined with preselected calibrating elements in the network to produce a calibrated and low output impedance microvolt source.

Known technology includes various potentiometer circuits designed to provide accurate parameter measurements and standard cell comparison means. In addition, my copending application Ser. No. 308,492, filed Sept. 12, 1963, for "Precision Potentiometer Circuit and Method for Establishing Same," teaches a precision potentiometer system employing a voltage divider characterized by a linear transfer ratio and a preselected constant input impedance as the variable parameter of the potentiometer system. This system is designed to establish a preselected voltage of one part per million (1 p.p.m.) accuracy, such as 1.000000 volt across the voltage divider input terminals, whereby calibrated linear values of output voltage from zero to 1.000000 are obtainable at the potentiometer output. The disclosed system employs a certified standard cell, a power source, a galvanometer and standardizing resistors of specified value for calibrating the potentiometer system. The circuit also includes a fixed value resistor having a value one-tenth the input impedance of the divider in series with such divider to provide potentiometer self-calibration to overcome divider scaling errors. Although the system of the copending application provides electrical parameter values of extreme accuracies in the order of one part per million, the design thereof is not entirely satisfactory for achieving comparable accuracies in the very low microvolt ranges. For example, when measuring or calibrating voltages in the range of 0.001 microvolt the known potentiometer systems intrinsically are not suitable because of thermal EMF's originating in the complex circuitry thereof and such phenomena tend to obscure the small values of microvolts being calibrated and measured. The maximum source impedance is at about midpoint on the voltage divider. At this point, the source impedance is about 30,000 ohms. The Johnson noise level resulting from such impedance is of the order of 0.03 microvolt, thereby obscuring the smaller value voltages to be measured.

The instant invention provides a new and improved potentiometer circuit designed for precision microvolt range measurements and calibrations by using a linear transfer ratio voltage divider as the variable parameter of the potentiometer system. In this application, the voltage divider is essentially reversed, wherein a source exciting power is fed into the variable arm of the divider

while a load impedance of fixed low impedance value is connected across the input end terminals of the voltage divider. The source power is supplied by a constant current generator for driving the potentiometer system.

It is a principal object of this invention to provide method and apparatus for achieving a high accuracy, easily calibrated, low thermal EMF and low output impedance microvolt potentiometer system and measurements.

It is a further object of this invention to provide a method and potentiometer system capable of precision voltage potentials in the microvolt range, wherein the potentiometer output voltage is a calibrated and direct function of a linear transfer ratio, and further where the variable control device of the potentiometer system is a voltage divider characterized by a linear transfer ratio and a fixed value terminal impedance.

It is a further object of the invention to provide means for reducing the effects of thermal EMF's produced by an external temperature difference in the load circuit of a potentiometer system as contemplated herein, and also to provide means for reducing the effects of loading the output of such potentiometer system.

Further objects and advantages will become apparent from the following description of the invention taken in conjunction with the figures, in which:

FIG. 1 is a circuit diagram of a microvolt potentiometer system in accordance with the invention;

FIG. 2 is a circuit diagram of an alternate embodiment of the invention which, in addition, illustrates load compensation means in the output circuit of the system;

FIGS. 2*a*, 2*b* and 2*c* illustrate schematically the sequence of an alternate embodiment for calibrating and monitoring the standardized element of the potentiometer system;

FIG. 3 is an equivalent T circuit of the voltage divider and load impedance of the potentiometer system;

FIG. 4 is a block diagram illustrating the concept of the instant invention;

FIG. 5 illustrates schematically multiwire thermal center of gravity connections between two electrical devices in accordance with the invention;

FIG. 6 is a cross-sectional view of the connection wire array employed in FIG. 5;

FIG. 7 illustrates schematically the use of the thermal center of gravity technique in an output circuit of a potentiometer system in accordance with the invention;

FIG. 8 is a sectional axially elevational view of a thermal gradient reversing polarity switch in accordance with the invention;

FIGS. 8*a* and 8*b* are end views of the left and right ends of the switch embodiment of FIG. 8 to permit a comparison of the geometry of one group of switch wires with respect to the other;

FIG. 9 is a view taken along line 9—9 of FIG. 8;

FIG. 10 is a view taken along line 10—10 of FIG. 8; and

FIG. 11 is a schematic illustration for the purpose of depicting the operation of the switch embodiment of FIG. 8.

FIG. 1 illustrates a potentiometer system **9** in accordance with the invention. The potentiometer system **9** contemplated herein is driven by a feedback type of constant current generator **10**. One side of a reference voltage **11** is connected to the input side of a high gain amplifier **12**. The output common of amplifier **12** is in series with current regulating resistances **13**, **14**. The other side of reference voltage **11** connects to resistance **14** at junction **15** to complete the feedback loop in generator **10**. Current generator is preset and regulated to provide a fixed value of 10 microamps as the potentiometer source. Adjustable

standardizing resistors **16, 17, 18** are series connected to current generator **10** by the connection at junction **15**. The values of the individuals resistors **16, 17, 18** are selected to standardize potentiometer system **9** in accordance with the aforesaid copending patent application.

The potentiometer variable is a voltage divider **19** having at least three terminals defining its input and output and further characterized by a fixed input impedance of known value and a linear transfer ratio K. Terminals **20, 21** are the usual input terminals of such voltage divider. Terminal **22** represents the adjustable arm terminal. Reference is made to said copending application and to United States Patent No. 3,179,880, issued Apr. 20, 1965 for a detailed review of such voltage dividers. The transfer ratio and the output impedance of voltage divider **19** is varied linearly by adjustment of a six digit direct reading dial **23**.

A switch **24** is connected in series between standardizing resistor **18** and divider terminal **20**. When switch **24** is in its position *a*, the exciting current of 10 microamps supplied by generator **10** flows through a fixed value 100K resistor **25** to adjustable divider arm terminal **22**. Resistor **25** serves to load suitably the output of amplifier **12** when divider slide **22** is at the low end of the divider and at point **21**. When switch **24** is in its position *b*, the generator circuit **10** is connected to divider input terminal **20**.

A fixed value resstance **26** is connected as a load across divider terminals **20, 21** by a four terminal yoke connection. The yoke current terminals are **27***a* and **27***b*. The yoke voltage terminals are **28***a* and **28***b*. A switch **29** is designed to connect yoke terminal **27***a* to divider terminal **20**. Switch **29** is ganged to switch **24**. When switch **29** is in its *a* position, load impedance **26** is connected across the fixed value input impedance of divider **19**. When switch **29** is in its *b* position, load impedance **26** is disconnected from the circuit.

A resistor **30** connects to divider terminals **21**. A junction **31** at the other end of resistor **30** connects back to constant current supply **10** at the negative output side of amplifier **12**. With the divider input impedance (terminals **20** to **21**) of a fixed value of 100K ohms, resistor **30** is selected to be 10K ohms and is used in self-calibration of potentiometer circuit **9** for scaling error as described in the aforesaid copending patent application.

A certified absolute standard DC source **32** has its positive side connected to a normally open switch **33**. When switch **33** is closed, standard cell **32** is connected to a variable tap arm **34** of resistor **16**. The negative side of standard cell **32** is in series with a null-galvanometer **35** which is connected to divider terminal **21**.

Potentiometer **9** must be calibrated in order to use same. For such calibration, ganged switches **24** and **29** are connected to their respective *b* positions, and switch **33** is temporarily closed. By using preselected values for the standardizing resistors **16, 17, 18** and knowing the exact value of the certified standard cell **32**, a 1 p.p.m. precision voltage of 1.000000 volt is established across voltage divider terminals **20, 21**. For example, if cell **32** is certified at 1.01830 volts, the series resistance sum starting from slide contact **34** and going to the right (FIG. 1) through resistor **16** plus resistors **17** and **18** is set at 1830 ohms, whereby the series resistance sum of said 1830 ohms plus 100,000 ohms (divider resistance **19**) provides the potential drop across which certified cell **32** is bucked for a null. If the foregoing bucking voltages match, source **10** will be feeding a current of 10 microamps through the foregoing mentioned series resistances and this is indicated by meter **35** nulling. If meter **35** does not null, amplifier resistance **13** is adjusted to establish a null at meter **35**. Furthermore, by selecting the resistance value of standardizing resistors **16, 17, 18** to be relatively small in comparison to the input impedance of divider **19**, the inherent error of the potentiometer system is effectively attenuated; said copending application illustrates the details of this point.

The illustrated circuit permits self-calibration of voltage divider **19** to compensate for scaling errors. Since the voltage of standard cell **32** is larger than the voltage established across divider **19**, a simple galvanometer comparison is not suitable. A resistor **30** of one-tenth the value of the input impedance of voltage divider **19** is connected in series with voltage divider **19**. For divider scaling error calibration, ganged switches **24, 29** are set in positions *b*, whereby the same current flows through resistor **30** and divider **19**. Considering the voltage drop from terminal **20** through divider **19** and through resistor **30** to junction **31**, one-tenth the voltage is impressed across resistor **30** and nine-tenths drop will appear across terminals **20, 21**. Without disturbing the calibrating setting of supply **10** and the setting of standardizing resistors **16, 17, 18**, the standard cell **32** in series with galvanometer **35** is connected at one end to arm terminal **22** and at the other end to junction **31**. This is depicted by the arrowheads and dashed lines in FIG. 1. If standard cell **32** is certified at 1.01830 volts, the dial setting of voltage divider **19** should be 0.918300 to null galvanometer **35**. Any deviation from 918300 in the divider reading will indicate the scaling error of the system. Refer to the aforesaid copending application for further formulas and explanations of the standardizing and self-calibration techniques employed for potentiometer system **9**.

Constant current supply **10** includes the feedback network of amplifier **12**, reference voltage **11** and current regulating resistors **13, 14**. At a set and operating equilibrium, generator **12** adjusts itself to almost a zero input voltage. Thus, value of the supplied current I times the value of resistors **13** plus **14** must be equal to the reference voltage, or

$$I=\frac{E_{11}}{R_{13}+R_{14}}$$

The values of E_{11} and $R_{13}+R_{14}$ are selected so that I is regulated to be 10 microamps.

During potentiometer use, i.e. measuring and calibrating procedures, ganged switches **24** and **29** are set in positions *a* and switch **33** is open. Essentially, this reverses divider **19**, whereby the fixed 10 microamps supply current flows into divider arm **22** while a load resistor **26** is connected across divider input terminals **20, 21**. The potentiometer output E_{out} is taken across the load resistor potential terminals **28***a*, **28***b*.

In order to understand the operation of potentiometer **9**, divider **19** and load **26** are shown in FIG. 3 as an equivalent T circuit. The three divider terminals are the divider input side **20**, arm **22** and the low side **21**. The values of the equivalent resistances A, B, C are:

$$A=(1-K)Z_{in}$$
$$B=Z_{out}-K(1-K)Z_{in}$$
$$C=KZ_{in}$$

where:

K is the divider ratio, such that when arm **22** contacts terminal **21** then K=0; and when arm **22** contacts terminal **20** then K=1;

Z_{in} is the divider input impedance with output open; and

Z_{out} is the divider output impedance with input shorted.

To check the values of A, B and C, we use Thevenin's theorem. The total input impedance between terminals **20, 21** with terminal **22** open is:

$$\begin{aligned} Z_{in}&=A+C \\ &=(1-K)Z_{in}+KZ_{in} \\ &=Z_{in} \end{aligned} \qquad (1)$$

The output impedance with the input short circuited is between terminals **21, 22** with terminals **20** and **21**

shorted. Resistors A and C are now in parallel. This parallel combination is:

$$\frac{(1-K)Z_{in}(KZ_{in})}{(1-K)Z_{in}+KZ_{in}}=\frac{KZ_{in}^2-K^2Z_{in}^2}{Z_{in}-KZ_{in}+KZ_{in}}=\frac{KZ_{in}^2(1-K)}{Z_{in}}=K(1-K)Z_{in}$$

The last term is added to the value of B to provide

$$Z_{out}=A\,C+B$$
$$Z_{out}=K(1-K)Z_{in}+Z_{out}-K(1-K)Z_{in}$$
$$=Z_{out}$$

In the instant invention, a fixed value current I is fed into divider arm terminal **22**. A load impedance **26** (Z_{load}) is connected across divider input terminals **20, 21**. The output voltage E_{out} is taken across load impedance terminals **28***a*, **28***b*. The following development employing Thevenin's theorem provides the value of E_{out}. The value of Z_{in}, the divider input impedance, from terminal **20** to terminal **21** and the values of parameters Z_{load} and I are preselected fixed constants. First open circuit terminals **20, 21**. The voltage across the equivalent resistance C is I K Z_{in}. The circuit to the left of equivalent resistance A now can be considered as a generator whose voltage is K Z_{in} I. The load Z_{load} (Z_{26}) is now connected across terminals **20, 21**. Looking into divider terminals **20, 21**, the Z_{load} sees an equivalent generator voltage K Z_{in} I, having a source impedance of

$$A+C=KZ_{in}+(1-K)Z_{in}=Z_{in}$$

The voltage E_{out} is then:

$$E_{out}=KZ_{in}I\times\frac{Z_{load}}{Z_{load}+Z_{in}} \quad (2)$$

since Z_{in}, Z_{load} and I are preselected constants, E_{out} is directly proportional to the divider transfer ratio K.

$$E_{out} \propto K$$

As an example, let:

Z_{in}=100,000 ohms
Z_{load}=1,010.101 ohms, and
I=10 microamps

then, from Equation 2:

$$E_{out}=\frac{K\times10^5\times10^{-5}\times1{,}010.101}{100{,}000+1{,}010.101}=0.01K \text{ volts}$$

The foregoing value of E_{out} represents a full scale range of 0.01 volt. Since the accuracy of divider **19** is 1 p.p.m., the maximum potentiometer error will be 0.01 microvolt.

The output impedance of potentiometer **9** is the parallel combination of the Z_{load} and the Z_{in}:

$$Z_{out}=\frac{Z_{load}Z_{in}}{Z_{load}+Z_{in}} \quad (3)$$

whereby the example establishes Z_{out}=1000 ohms. This is a relatively very low impedance, which impedance remains constant. By reason of such parameters, the resulting Johnson noise will hardly affect microvolt measurements.

In microvolt potentiometers, the thermal EMF's produced by the system present a substantial problem. With the described circuit, the thermal EMF's produced are substantially reduced. Referring to FIG. 3, thermal EMF's are regarded as originating in divider **19** in association with each equivalent impedance A, B, C, whereby such EMF's are referred to as E_A, E_B, E_C, respectively. These thermal EMF's are considered as being voltage generators in series with the respective equivalent impedances A, B, C. Voltage E_B is in series with the infinite source feeding terminals **21, 22** and thus may be disregarded. The total thermal voltage E_{th} is thus a resultant of the individual EMF's, E_A and E_C. Such resultant voltage E_{th} may be ascertained from Thevenin's theorem; in this case the Thevenin voltage is (E_A+E_C) and its impedance is $A+C=Z_{in}$. This is essentially Equation 2 with the value of the equivalent generator now E_A+E_C. Using the parameter values previously given, the resultant voltage E_{th} across the potentiometer output produced by the internal thermal generators is expressed as follows:

$$E_{th}=(E_A+E_C)\frac{Z_{load}}{Z_{load}+Z_{in}}=(E_A+E_C)\times\frac{1}{100} \quad (4)$$

Equation 4 shows that a potentiometer system in accordance with the invention will attenuate the divider thermal EMF's to .01 of its value. For example, a divider thermal EMF of 0.1 microvolt is thus reduced to 0.001 microvolt at the output.

A second embodiment of the instant invention is shown as potentiometer **39** in FIG. 2. Constant current supply **10** includes high gain amplifier **12**, current regulating resistors **13, 41, 42**, switch **43** and a feedback loop involving reference voltage **11**. Switch **43** is normally in one or the other of its *a* or *b* positions in order to complete the circuit to divider **19**. Resistors **41, 42** are designed to be switched alternately in series with resistor **13** by switch means **43**. Reference voltage **11** has its negative side connected to the input of amplifier **12**. The positive side of reference voltage **11** is connected to junction **45**. The amplifier common is in series with resistor **13**. The output of amplifier **12** is connected to divider arm terminal **22** when the first blade of ganged switch **40** is in its *a* position.

Current supply **10** is regulated to supply a fixed value current I of 100 microamps to divider **19**. The standardizing circuit includes certified DC supply **32** and null meter **35** connected in series from a junction **56** to a second blade of ganged switch **40**. A standardizing resistor **44** is in series between divider terminal **21** and junction **56**, whereby current I flows through resistor **44**. Divider terminals **20, 21** are connected to respective current yoke connections **27***a*, **27***b* of load impedance **26**. Load impedance **26** is a tapped output resistor having four sections **26***a*, **26***b*, **26***c* and **26***d*. The values of these sections are:

R_{26a}=10,000 ohms R_{26c}=100 ohms
R_{26b}=1,000 ohms R_{26d}=11.11 ohms

thereby providing a total value of R_{26} of 11,111.11 ohms. The yoke voltage output terminals include the low side terminal **46** and individual ones of the tap terminals **47***a*, **48***a*, **49***a* and **50***a*. Individual load compensation resistors **51, 52, 53, 54** are connected between correlated *a* voltage output terminals and correspondingly numbered *b* voltage output terminals, such as **47***b*, **48***b*, etc.

The concept of the potentiometer system **39** depicted in FIG. 2 is similar to the previously described system **9**. Voltage divider **19** is reversed so that during operation the input driving current I feeds through divider arm **22**, whereas the divider output voltage is taken from divider end terminals **20, 21**. A load impedance **26** of fixed and selected value of 11,111.11 ohms is connected across divider end terminals **20, 21**. The result provides a potentiometer system characterized by reduced thermal EMF's and at low reading linear scale.

In the FIG. 2 embodiment, divider **19** is standardized by connecting switch **40** to its *b* positions. For this arrangement, source current I is connected to divider terminal **20** and the series combination of cell **32** and null meter **35** are shunted across junction **56** and terminal **20**. Assuming cell **32** to be certified at 1.01830 volts, and knowing that an input divider impedance of 100K ohms is shunted by R_{26}=11,111.11 ohms, resistor **44** is adjusted to provide 183 ohms since such resistance is in series with the parallel combination of 11,111.11 ohms and 100K ohms. The total of resistance from terminal **20** to junction **56** is 10,183 ohms, thereby establishing I=1.01830 volts/10,183 ohms=100 microamps. During the foregoing, it is assured that switch **43** is in its *b* position. A driving current I of 100 microamps esstablishes

a 1 volt drop, 1 p.p.m., from terminal **20** to terminal **21**. The calibration of the 1 volt across the divider input terminals **20–21** is confirmed by a meter null at **35**.

Essentially, after selecting the proper value for resistor **44** to obtain a preselected exciting current I for a given cell voltage E_{32}, meter **35** should null to indicate the desired current I. If meter **35** does not null, amplifier resistor **13** is adjusted to achieve such null. Thereafter, ganged switch **40** may be set in its *a* positions thereby connecting the output of amplifier **12** directly to divider arm **22** and also for connecting the standardizing circuit, the series combination of cell **32** and meter **35** in shunt across resistor **44**. For this arrangement, resistor **44** is adjusted to provide 10,183 ohms for a current flow of 100 microamps through said resistor. Cell **32** will buck such voltage when switched into its *a* position, thereby providing continuous monitoring of potentiometer system **39** during its operation. Since certified cells are within the range of 1.01700 and 1.02000 volts, resistor **44** is selected to provide two ranges of resistance values. The first range is between 170 ohms to 200 ohms to cover the initial standardizing procedure. The second range is between 10,170 ohms to 10,200 ohms to provide continuous monitoring of potentiometer **39** during use of same.

FIG. 2*a* through 2*c* illustrated an embodiment of FIG. 2, wherein resistor **44** is replaced by two variable resistor **44***a* and **44***b* in series, respectively, with divider terminals **20, 21**. Resistor **44***a* is a variable in the range from 170 ohms to 200 ohms and is essentially the equivalent of resistor **44** of the FIG. 2 embodiment. A normally open shorting switch S appears across resistor **44***b*.

FIG. 2*a* depicts calibrating and standardizing potentiometer **39** with 1 volt, 1 p.p.m., across divider terminals **20, 21** by bucking the drop from junction **56***a* to divider terminal **21** with the series combination of cell **32** and null meter **35**. Switch S is closed to short out resistor **44***b*. Resistor **44***a* is set at 183 ohms for a certified cell **32** as previously specified.

FIG. 2*b* illustrates calibrating divider **19** for scaling errors after 1 volt is established across its terminals **20, 21**. In this case, the series combination of cell **32** and meter **35** is connected across divider arm **22** and junction **56**. Resistor **44***b* is set to provide a voltage drop across same which is a known percentage of the drop across divider terminals **20–21** and thus serves as resistor **30** in the FIG. 1 embodiment.

Finally, FIG. 2*c* illustrates the arrangement for continuously monitoring divider **19** during its operation by sensing the voltage across resistor **44***b* which is now set to provide 10,183 ohms for the reasons described hereinbefore.

The full scale output voltage E_{out} from terminal **46** to terminal **47***a* can be determined from Equation 2:

$$E_{out}=(KZ_{in}I)\frac{Z_{load}}{Z_{in}+Z_{load}}$$

where:

Z_{in}=100,000 ohms,
Z_{load}=11,111.11 ohms,
I=100 microamps, and
K=1 for full scale; therefore,
E_{out}=1 volt.

Similarly, the full scale E_{out} can be calculated for the other resistor sections. For example, if the output is taken between **48***a* and **46**, the full scale output voltage is .1 volt; between **49***a* and **46**, E_{out} full scale is .01 volt; from **50***a* to **46**, full scale output voltage is .001 volt. Since voltage divider **19** is accurate to 1 p.p.m., the lowest range provides reading values to .001 microvolt.

When the illustrated microvolt potentiometers are used with an external load, such as a digital voltmeter **55**, the problem of source load impedance arises. In the instant invention, output impedance Z_{out} is a constant and equal to the parallel combination of the voltage divider input impedance Z_{in} and load impedance Z_{26}, as shown in Equation 3. The error due to loading effects can be eliminated by using appropriate load compensation resistors. FIG. 2 illustrates load compensation resistors **51, 52, 53, 54** at the output of potentiometer **39**. The values of these load compensation resistors are individually selected to equal the output terminal impedance at the taps the output is being taken. For E_{out} between terminals **47***a* and **46**, the total output impedance is:

$$Z_{out}=\frac{Z_{load}Z_{in}}{Z_{load}+Z_{in}}$$

where Z_{in}=100,000 ohms and Z_{load}=11,111.11 ohms. Hence, Z_{out}=10,000 ohms, thus resistor **51** is selected to have a value of 10,000 ohms.

Similarly, the values of the other load compensation resistors **52, 53** and **54** can be determined. Resistor **52**, for the foregoing example, is 1100 ohms; resistor **53** is 111 ohms; and resistor **54** is 11.11 ohms. By mathematical development, it can be shown that 1 p.p.m. operation is retained when the ratio

$$\frac{Z_{out}}{Z_{out}+Z_L}$$

is equal to or less than 0.001, where Z_{out} is the output impedance of the potentiometer system looking into the resistor **26** tap terminals across which the external load, such as voltmeter **55**, is connected; and Z_L the value of the impedance of the external load, such as voltmeter **55**. By the above definition, Z_{out} may be considered as the source impedance of potentiometer **39** to which a load Z_L is connected.

Consider the following illustration as outlining a procedure for achieving automatic load compensating upon applying an external, digital voltmeter **55**, to the tapped output of resistor **26**. Divider arm **22** is moved to terminal end **20** so that K=1. Initially, switch **43** is set at its *b* position. The potentiometer system is standardized and current supply **10** is regulated to deliver the fixed value 100 microamps as described hereinbefore. Load **55** is connected to the tapped output with one lead **57** thereof connected to terminal **46** and the other leads **58** connected to the desired one of the *a* voltage output terminals, such as **47***a* or **48***a*, etc. A voltmeter reading is taken and its value is noted. Load lead **58** is then connected to the correlated *b* output terminal (shown in dashed outline), for example, if the upper lead **58** was at **47***a*, then the upper lead **58** is then connected to **47***b*. This inserts resistor **51** in the potentiometer circuit. Switch **43** is now set in its *a* position and current booster resistor **41** is adjusted until the *b* voltmeter output reading equals the prior *a* output reading. This automatically compensates the output reading as to load errors. Allowing switch **43** to remain in its *a* positon and without disturbing the adjustment to resistor **41**, upper load lead **58** is returned to connect with the original *a* output terminal. All further measurements and external load sensing against the calibrated potentiometer for the scale represented by output terminals **46–47***a* are now taken from such terminals **46–47***a* because the potentiometer circuit is now automatically load compensated. As an example, assume the voltmeter reading at terminal *a* is 0.9998 volt; and at terminal *b*, the reading before adjustment is 0.9997 volt. For the *b* reading, the source impedance has been doubled because of the introduction of load compensator **51**. The resultant error upon doubling the source impedance is 0.0001 volt. This indicates an initial loading error of 0.0001 volt due to potentiometer loading. After adjustment and upon returning the voltmeter to terminal *a*, if its reading is off 1.00000 volt this indicates a scaling error for the voltmeter.

It will be understood that the embodiment of FIG. 1 also may include the foregoing tapped resistor **26**, load compensating resistors **51** through **54**, and current reg-

ulating resistor **41** at supply **10** for the purposes as described with respect to FIG. 2.

The instant invention can be seen in the illustrative block diagram form in FIG. 4. The potentiometer consists of a current source **10** designed to supply a constant current I to arm **22** of voltage divider **19**. The end terminals **20, 21** of voltage divider **19** are connected to a load impedance **26**. Load impedance **26** must be constant, but may be either a variable or tapped resistor. Although the description has been made using a three terminal voltage divider, the invention is not limited to its use. Any linear transfer ratio device with constant input impedance can be used.

The foregoing low thermal potentiometer systems have been designed and compensated to cancel out and attenuate spurious thermal EMF's. In order to secure a continuity of precision low voltage operation at the external load end of the circuit during use of the disclosed potentiometer systems, the problem of external wiring effects are also contemplated herein. Some wiring materials heat up at a faster rate or to higher temperatures than others, thereby generating thermal gradient EMF's. External connecting wires and switch assemblies are affected by differences in room temperatures and other ambient variations. Such phenomenon causes one wire to become hotter than another causing the generation of spurious thermal EMF's. This is of principal concern with regard to measurements or calibrations of unknown voltages when dealing with high precision voltages in the low value range. To some extent, the thermal EMF problem may be mitigated by the use of similar conducting material throughout the circuit, for example, one uses identical copper wiring throughout the entire system. However, for the very sensitive high precision system operation as contemplated herein, the use of heretofore known prior techniques is not satisfactory.

The instant invention contemplates multiwire connections, wherein these wires are arrayed in geometric patterns in accordance with the principle of achieving thermal electrical center of gravity connections. For example, in FIG. 2, meter **55** is connected by two leads **57, 58** to the potentiometer output. The potentiometer circuit and a substantial portion of leads **57, 58** may be encased in a thermally controlled environment. However, small portions of leads **57, 58** and meter **55** will be exposed to ambient environment and thus exposed to ambient thermal fields. As another example, in FIG. 4, a voltage source **60** under test is in series with a null meter **61**. The series combination is connected across the output of the potentiometer system for the purpose of ascertaining or calibrating the voltage of source **60**. Setting of divider dial **23** is adjusted until meter **61** nulls. The measured voltage value of source **60** is determined by the setting of dial **23**. Here again, the external load connection wires to the greatest extent possible are placed in a thermally controlled environment with the potentiometer system. For example, everything to the left of dash line **62—62** is in such controlled environment, whereas short sections of leads **57′, 58′** and null meter **61** are exposed to ambient fluctuations and thermal fields. Assume a thermal field flowing in the direction depicted in FIG. 4 by arrows F1 and F2 envelopes lead portions **57′, 58′** and that the thermal field F1 is hotter than at F2, this causes a thermal gradient to exist between single leads **57′** and **58′**. As a result, thermal EMF's are generated in these wires, which EMF's are spurious output signals sensed by meter **61**.

FIG. 5 illustrates the principle of the thermal center of gravity arrangement of multiple connection wires. Battery B is connected to a meter or external load M. The interconnected terminals *a–a′* are actually connected by a pair of lengthwise wires A, A. Similarly, interconnected terminals *b–b′* are connected by a pair of lengthwise wires B, B. The cross-sectional space arrangement or order of the wires is depicted by FIG. 6 showing the wires in an array for a plane (depicted by dashed line P) perpendicular to the lengthwise axis of wires A and B. The wires are grouped so that each A wire is suitably spaced symmetrically with respect to the pair of B wires; similarly, each B wire is suitably spaced symmetrically with respect to the pair of A wires. Arrows F3, F3′, F4 and F4′ are assumed to be the components of the thermal fields enveloping the wires in the cross-sectional plane. Assume the prime fields (F3′, F4′) are hotter than the unprimed fields (F3, F4). The set of A wires taken as a pair are acted upon by a summation of thermal fields of the same strength as that acting upon the B set of wires taken as a pair with the net result that there is no resultant thermal gradient between the interconnections from terminals *a, a′* to terminals *b, b′*. Essentially, the invention contemplates multiple wire connections and terminations arranged geometrically in a pattern so as to be symmetrically disposed in the thermal fields enveloping same, whereby there is a cancellation of temperature gradient thermal EMF's over external connections between two electrical devices.

FIG. 7 illustrates the connection of source or unknown **60** connected in series with meter **61** to the output of the potentiometer system with everything to the left of dashed line **62′** in a thermally controlled environment and the circuit to the right of dashed line **62′** in the ambient atmosphere. In this instance, a polarity reversing switch **63** (shown in dashed outline in FIG. 7) is inserted in the external load circuit to connect the four wire lines leading to **61** in accordance with the principles taught in FIG. 5.

FIGS. 8 through 11 illustrate an embodiment of the thermal center of gravity and polarity reversing switch **63**. Switch **63** is made up of a first group of four lengthwise conducting wires C–D, C–D and a second group of four lengthwise conducting wires J–K, J–K. The two wire groups are supported in tandem relationship by respective pairs of axially spaced disc-shaped members **64, 65** and **66, 67**. Members **64, 65** and **66, 67** are made of electrical insulator material to avoid shorting the switch wires. The switch wires are encased in a substantially enclosed isothermal shield container which for convenience consists of a cylindrical metallic sleeve **68**. The opposite ends of sleeve **68** are enclosed by respective members **64, 67**. The outer end portions of the wires of the respective groups are rigidly supported and held in fixed position by correlated end members **64, 67**. These wires extend through correlated members **64, 67** and are provided with external terminal posts **69** to which electrical connections are made.

The inner end portions of the two groups of wires pass through individual arcuate slots **70, 71** of respective closely spaced apart and confronting members **65, 66**. Members **65, 66** are individually mounted for threaded screw turning on an axial shaft **72**. Shaft **72** is rigidly supported by end members **64, 67**. Shaft **72** is threaded at **73** to permit screw turning of either member **65, 66** upon selective actuation of switch **63**.

When switch **63** is in a non-conducting status, each of the four wires in the C–D group is held by supporting members **64, 65** in straight lengthwise and parallel relationship with respect to each other. In cross-section, i.e., a plane perpendicular to the axis of shaft **72**, the individual four C–D wires are each geometrically arrayed to lie at an individual corner of a square, but at respective radial lines of 45°, 135°, 225° and 315°. This array is depicted in FIG. 9. Similarly, the four wires of the J–K group are also held in lengthwise straight and parallel relationship with respect to each other. However, in the cross-sectional plane, the individual J–K wires are held by members **66, 67** in a symmetrical array lying along respective radials of 0°, 90°, 180° and 270° as depicted in FIG. 10. Since it is assumed that switch **63** is isolated from thermal gradient fields by its isothermal container, the cross-sectional arrays of its two wire groups are both geometrically symmetrical. However, it is noted that the

J–K wires are angularly offset 45° with respect to individual ones of a pair of C–D wires as seen in FIG. 11. At the center of switch **63**, that is to say, in the region of the plane taken along line **74—74** of FIG. 8, the inner ends of the individual wires of one group axially overlap the inner ends of the wires of the other group to permit switching connection therebetween upon actuation of switch **63**. However, there is no contact between any one wire of one group with a wire of the other group for the non-connecting status of switch **63**. This is depicted in FIG. 11. It is seen that the foregoing switch arrays locate the eight wires along the same circumference about the axis of shaft **72**.

By reason of the foregoing described cross-sectional array of switch wires, the inner end of each wire of one group is in juxtaposed and mutually spaced apart relationship between inner ends of a pair of wires of the other group without contact being made therebetween. This defines the non-connecting status of switch **63**.

Switch actuating means **75** is mounted at a sleeve opening **76**. Actuating means **75** has a flange **77** for enclosing opening **76**. Means **75** includes a member **78** extending between members **65, 66** and mounted for rotation about its vertical axis upon turning an exterior knob **79**. A horizontal rod is integrally carried at the inner end of member **78**, which rod has oppositely extending ends **80, 81**. Rod ends **80, 81** at all times are in driving engagement with a wall of individual recesses **82, 83** of respective members **65, 66**, as shown in FIGS. 9 and 10. When knob **79** is turned in one direction about its vertical axis, rod end **80** drives against its adjacent recessed wall to turn disc **65** counterclockwise as viewed in FIG. 9. This action simultaneously twists the free end portions of the four C–D wires counterclockwise about the axis of shaft **72** until each C wire electrically contacts a stationary adjacent K wire. Simultaneously, each D wire electrically contacts a stationary J wire. A 45° turning movement of member **65**, as depicted by the four full line arrows in FIG. 11, achieves the foregoing switching connection. The foregoing movement does not disturb the stationary status of member **66** because the originating turning of knob **79** drives rod end **81** to the right, as seen in FIG. 10, through the open clearance of its slot **83**. Turning of knob **79** in the opposite direction drives rod end **81** to the left, as seen in FIG. 10, to rotate member **66** counterclockwise about shaft **72** until the free end of each J wire connects with an adjacent stationary C wire, while the free end of each K wire connects with a stationary D wire. This switching action is depicted by the four dash line arrows in FIG. 11. The foregoing knob turning does not disturb member **65** because rod end **80** is driven through the open clearance of its recesses **82**, as viewed in FIG. 9.

To assure good switch contact between juxtaposed adjacent group wires, the inner ends of the wires may be suitably bent or shaped. When switch **63** is in one or the other of its connecting phases, the free inner ends of one group of wires are essentially twisted about the axis of shaft **72** to effect the switch connections, whereby the corresponding member **65–66** turns along shaft thread **73**. As seen, switch wires are essentially cantilever supported from their respective rigid supports **64, 67**. The spring force developed by the twisted wires spring loads the wires to assist returning switch **63** to its non-connecting status upon release of knob **79**. It will be understood that the switch wires are selected to have sufficient elasticity and resilience so as to return to their respective axially straight and parallel relationship each time knob **79** return to a non-connecting status. Furthermore, the dimensions of slots **70, 71** are selected to provide suitable clearance for respective switch wires extending through same to permit the foregoing switching action to take place and to assure freedom of binding of the coacting moving parts. From FIGS. 9 and 10, it is seen that the switch wires are nested at the ends of the respective slots **70, 71** so as to undergo twisting upon turning of the respective members **65, 66**.

Although knob **79** is manually operated herein, a system may be devised for actuating knob **79** by a servo signal. The foregoing embodiment contemplates a 45° turn of each member **65, 66** in order to drive switch **63** into a connection status. If the respective recesses **82, 83** are made narrow, that is to say, without the disclosed open clearances for rod ends **80, 81**, so that both members **65, 66** turn simultaneously upon knob turning but in opposite directions about shaft **72** as viewed in FIGS. 9 and 10, each member **65, 66** need turn only 22.5° to effect a switch connection status. This offers advantages of requiring less rotational travel for each member **65, 66** and balances the spring load on the actuating means for a switch connection.

In FIG. 7, consider switch **63** connected into the four wire connections between potentiometer source external terminals *a–a'* and load terminals *b–b'*. Assume that the individual wires from terminal *a* are connected to respective C, C switch wires, those from terminal *a'* are connected to the D, D switch wires; and on the other side, the wires from terminal *b* are connected to the K, K switch wires and those from terminal *b'* are connected to the J, J switch wires. This is shown schematically in FIG. 11. For the switching connection as depicted by movement of member **65** counterclockwise as viewed in FIG. 9, the connection is essentially that shown in FIG. 11 by the four solid line arrows, whereby terminal *a* connects to terminal *b* and terminal *a'* connects to terminal *b'* through switch **63**. For the reverse switching action depicted by the four dash line arrows in FIG. 11, terminal *a* is now connected to terminal *b'*, and terminal *a'* is now connected to terminal *b*. Hence, switch **63** reverses the polarity of the DC connection of member **61** to sense an output measurement. If both of the foregoing meter **61** readings are equal, the thermal gradient EMF's are essentially all cancelled out. If the second reading differs from the first reading, one-half of the difference of the two readings is the amount of residual thermal gradient EMF's in the exterior output circuit. Upn release of knob **79**, switch **63** returns to its normally open switch status and thus output power is drawn from the potentiometer system only during an actual switching connection.

What is claimed is:

1. Potentiometer means useable for precision microvolt range measurements and providing standardized-precision low voltages effectively free of spurious random noise and thermal EMF's comprising, means providing a constant current source, linear transfer ratio means having at least three terminals for defining an input and output thereof and characterized by a predetermined and fixed value of input impedance at first and second of said terminals and a selectable output impedance at a third of said terminals in accordance with said linear transfer ratio, means for varying said transfer ratio, means for connecting a load of selected and fixed impedance to the input of said transfer means, means including said source for applying a current of selected fixed value to said transfer means for establishing a standardized predetermined potential difference across said transfer means input, and means for applying said constant current source to the output of said transfer means for establishing standardized predetermined values of voltage potential across said load directly proportional to the transfer ratio of said transfer means.

2. Potentiometer means as defined in claim **1**, said load having voltage output terminals for providing an output measurement, said potentiometer serving as a source having a source impedance looking into said voltage output terminals upon connecting an external load across same, means for connecting an external load to said voltage output terminals and for providing a measurement of the output voltage sensed by said external load, means for connecting a load compensation imped-

ance in series with one of said voltage output terminals and said external load for providing a measurement of output voltage sensed by said external load with the potentiometer source impedance increased by said load compensation impedance, the value of said load compensation impedance being equal to the source impedance of said potentiometer system looking into said pair of voltage output terminals, and means for regulating said constant current source to adjust the second measured output voltage to equal the first measured output voltage if a difference exists therebetween, wherein said potentiometer means is automatically compensated for loading effect errors introduced upon connecting said external load across said voltage output terminals.

3. Potentiometer means as defined in claim 1, said load having voltage output terminals for providing an output measurement, wherein said potentiometer serving as a source having a source impedance Z_o looking into said voltage output terminals for an external load connected across same, means for connecting an external load to said voltage output terminals and for providing a measurement of the output voltage sensed by said external load, means for connecting a load compensation impedance in series with one of said voltage output terminals and said external load for providing a measurement of output voltage sensed by said external load with the potentiometer source impedance increased by the value of said load compensation impedance, and means for regulating said constant current source to adjust the second measured output voltage to equal the first measured output voltage if a difference exists therebetween, wherein said potentiometer means is automatically compensated for loading effect errors introduced upon connecting said external load across said voltage output terminals.

4. Means as defined in claim 3, wherein the ratio of $Z_o/(Z_o+Z_L)$ is in the order of equal to or less than 0.001 for the purpose of retaining a very high degree of precision potentiometer operation.

5. A potentiometer system useable for precision microvolt range measurements and calibration comprising, a constant current supply, voltage transfer means having a constant impedance input and variable output impedance related to said input by a linear transfer ratio, first means including said supply for establishing a standardized voltage at the input of said transfer means, second means for connecting said input of said transfer means in a closed circuit, and third means for connecting said current supply to the variable output of said transfer means, wherein output voltages established at said input are a direct function of said linear transfer ratio.

6. A system as defined in claim 5, wherein said first means including, a circuit means for providing a reference voltage for establishing said standard voltage across said transfer means input, first impedance means of selected value in series with the input of said transfer means for establishing a given value of constant current for standardizing said transfer means, and second impedance means in series with said transfer means for monitoring said supply constant current fed to said transfer means.

7. In a potentiometer system as defined in claim 5 further comprising, a fixed impedance load in said closed circuit having voltage output terminals for sensing output voltages, an external load connected to said voltage output terminals, means including respective sets of plurality of wires for nullifying the effects of thermal field gradients in low voltage electrical connections between said output voltage terminals and said external load, said external load having a plurality of terminals for electrical connection with individual ones of said voltage output terminals by said respective sets of a plurality of wires, each set including a wire connection for the interconnected terminals between said external load and voltage output terminals, each wire of one set being in symmetrical spaced arrangement regarding a wire of the other set with respect to thermal fields passing over said wires to compensate for thermal gradient effects produced in the individual connections between said external load and potentiometer system.

8. A potentiometer system useable for precision microvolt range measurements and calibrations comprising, a constant current supply, voltage divider transfer means having at least three terminals for providing a constant impedance input and a variable output impedance related to said input by a linear transfer ratio, means having a selected value of impedance in series with said supply for establishing a standardized voltage across the input of said voltage divider means, a load of fixed value impedance, means for connecting said load to the input of said divider, and means for connecting said current supply to the divider variable output, wherein voltages established at said load are a direct function of said linear transfer ratio.

9. A potentiometer system useable for precision microvolt range measurements and calibrations comprising, a predetermined current supply presenting an essential infinite impedance, voltage transfer means of at least three terminals and having at least a pair of constant impedance terminals and at least a pair of variable impedance terminals such that there is a predetermined transfer ratio between the said pairs of terminals, means for connecting said constant impedance terminals of said transfer means in a closed circuit, and means connecting said current supply to the variable impedance terminals of said transfer means, wherein output voltages established at said constant impedance terminals are a direct function of said transfer ratio.

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