Centimeter

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 mm

Inches

1.0 1.1 1.25 1.4 1.6

1 2 3 4 5

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SENSOR/SOURCE ELECTROMETER CIRCUIT

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BACKGROUND OF THE INVENTION

The present invention relates to circuitry for an electrometer and more particularly to an electrometer circuit for sourcing and measuring a wide range of current levels without delays due to scale changes. The Government has rights in this invention pursuant to Contract No. DE-AC12-76SN00052 awarded by the U.S. Department of Energy.

Solid state electrometers which employ transistors to attain high input impedance have proved uniquely suitable for the measurements of extremely low currents; for example, currents in the picoamp range which emanate from ionization chambers which are exposed to ionizing radiation. While a high degree of accuracy and stability may be attained with such electrometers, by the use of negative feedback obtained from high value resistors inserted into the feedback loop, problems arose in the need for a current range switching capability that covers several decades of an input signal.

U.S. Patent No. 4,050,019 to Nirschl discloses a circuit that provides range switching for solid state electrometers which includes structure for altering the sensitivity of the indicating means to provide a plurality of measurement ranges for an electrometer. However, Nirschl's circuit requires operation of a manual toggle switch to change the scale when the sensed current can no longer be read by the current scale of the electrometer. Furthermore, the electrometer circuit disclosed by Nirschl includes *calibration resistors which also have to be manually adjusted when the scale is changed.

Similarly, a meter control circuit disclosed by Stone in U.S. Patent No. 4,131,846 includes a plurality of amplifiers for controlling the variation of pointer movement over respective segments of a measuring scale. However, this circuit also comprises manual calibration resistors which must be adjusted each time the associated
segment of the scale changes. Thus, Stone's meter control circuit is not continuously operated without "dead time" from scale changes.

An analog automatic range selection circuit is described in U.S. Patent No. 4,105,967 to Macemon wherein switchable impedance elements are coupled between an input and output of an amplifier for adjustment of the gain thereof to implement scale changes. However, Macemon's circuit is not continuously automatic through a wide range of levels, since a mechanical switch must be manually operated to connect the circuit to a different reference voltage corresponding to a different range of the automatic range selection circuit.

In U.S. Patent No. 4,567,429 to Livsey, a digital servo indicator of the continuous null-balance potentiometric type is described which includes a microcomputer to provide a digital readout of the measured results and to perform further calculations, if desired. Livsey's indicator can be controlled by the microcomputer and employs a cascading series of circuits, each having a precision resistance element and a switch to produce a variable known voltage from a constant reference source. This circuit requires the connection of precision scaling resistors to either the reference voltage lead or the common lead to properly function.

U.S. Patent No. 4,114,094 to Cook also discloses a digital volt meter comprising a current prescaling unit which can be scaled automatically by using random access memory (RAM). However, Cook's circuit provides discreet movements when increasing the scale and is therefore non-continuous.

**SUMMARY OF THE INVENTION**

The present invention provides a new and improved electrometer system capable of operating as a current source or a current monitor which overcomes the above disadvantages of prior art electrometers.

The sensor/source electrometer system of the present invention includes a microprocessor system which
individually controls digitally programmed voltage to current converters and is capable of programming the ramping rate and level of sensed/sourced current to provide continuous input/output of current. In one embodiment of the invention, the microprocessor controls three groups of switching circuits each containing a plurality of resistance elements which may be selectively coupled to the outputs of digital to analog converters to provide a specific value of output current. The output currents from each group of switches are coupled to a current buss which provides the output current when the electrometer is operating in a source mode, and which senses the input when the electrometer is operating in a sensor mode. By establishing predetermined values of resistance for each of the resistance elements of the three groups of switching circuits, the microprocessor can be programmed to selectively add incremental values of current over a range of nine decades for current values of $10^{-12}$ to $10^3$ amps without significant discontinuity requiring a scale change.

In another embodiment of the invention, the microprocessor is coupled to control four groups of switching circuits each of which contain a plurality of resistance elements which may be selectively coupled to the outputs of a corresponding number of four digital to analog converters. The microprocessor is again programmed to cycle repeatedly through each of the four groups of switching circuits to incrementally add currents from each of the groups of switching circuits to a current buss to provide a desired output current from the electrometer. As the increments of current are selected, the cycling through the switching groups is controlled so that there is insignificant discontinuity over a range of eleven octaves.

In both embodiments, the electrometer system provides a substantially continuous output current which can be used to facilitate source and sensor modes of operation. In the source mode a true current source can
be established which automatically accommodates voltage burdens or offsets in excess of one volt. In the sensor mode, the microprocessor can automatically force the input voltage to zero by programming a nulling current and thereby allow a determination of the sensed voltage. In either mode of operation, the electrometer system can provide under microprocessor control, an output indication of the level of sourced current, the level of sensed current, or the rate of current change, through digital or analog devices at remote terminals.

It is therefore a feature of the invention to provide an electrometer system which may operate in either a source or sensor mode.

It is another feature of the invention to provide an electrometer system which operates over a wider current range without significant discontinuities of scale change.

It is still a further feature of the invention to provide an electrometer system which is microprocessor controlled.

Yet another feature of the invention is to provide a microprocessor controlled electrometer system which allows programming of the output current waveform.

Still another feature of the invention is to provide an electrometer system which allows remote digital or analog programming and remote digital or analog read-out.

A still further feature of the invention is to provide an electrometer system which may be self calibrating.

Yet a still further feature of the invention is to provide an electrometer system which improves isolation, reduces scaling requirements, and provides automatic switching.

It is still another feature of the invention to provide digital control of current increments to allow more simplified control for increased resolution.
These and other objects and advantages will become apparent from the following detailed description when considered in connection with the accompanying drawings.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The invention and its mode of operation will be described by way of non-limitive examples with reference to the accompanying drawings of which:

FIG. 1A is a schematic block diagram of an illustrative electrometer system according to the invention.

FIG. 1B is a schematic diagram of a feedback circuit for increasing accuracy in current output.

FIG. 2 is a schematic diagram showing the voltage to current conversion in an electrometer system according to a further embodiment of the invention.

FIG. 3 schematically illustrates a compensating circuit which may be optionally incorporated in the electrometer system of FIG. 2.

FIG. 4 schematically illustrates one embodiment of an input/scaling system circuit of the electrometer system of FIG. 2.

FIG. 5 is a schematic block diagram of one embodiment of an output circuit for providing an analog display from the electrometer system of Fig. 2.

**DESCRIPTION OF EXEMPLARY EMBODIMENTS OF THE INVENTION**

FIG. 1 illustrates a nine decade (e.g., $10^{-12}$ to $10^3$) electrometer system in which individual decades of current are derived by three microprocessor controlled voltage to current converters using digital to analog converters. In this embodiment, electrometer system includes a microprocessor 5, a multiplexer 7, four digital to analog converters (DA) 1, 2, 3, 4, a plurality of scaling resistors RA1-RA9 which provide voltage to current conversion from the D-A converters, and a common summing buss 6. Switches SSS1-SSS8 are coupled to the scaling resistors RA1-RA9 as shown, to form three groups of switching circuits GR1-GR3 which are coupled respectively
to the outputs of digital to analog converters DA1-DA3 to form three voltage to current converters, each contributing a decade of current, for the electrometer system 10. The switches SSSI-SSS8 as well as the other herein referenced switches depicted in Fig. 1 are controlled by programming of the microprocessor 5 through I/O port switch control 13. As will be appreciated, the programming necessary to accomplish the switch operation can be implemented in a conventional fashion in the microprocessor 5 in accordance with the description provided below. Furthermore, the I/O control 13 may be of any conventional construction which responds to digital indications of desired switch position from microprocessor 5 to cause switches, which may be of conventional solid state construction, to assume the position indicated by the microprocessor 5. Each of the switches SSSI-SSS10 as well as SSSA-SSSC and RS1 may be controlled through appropriate drivers (DR1-DR4, for example) to respond to the microprocessor controlled position locations through I/O control 13.

Electrometer system 10 can be operated as a source electrometer system to output current to an external device or as a sensor electrometer system to measure continuous current sensed from an external source, such as ion chamber in a nuclear reactor. By way of example, in the sensor mode, the electrometer can monitor reactor power levels by sensing currents which are proportional to the radiation in an ion chamber. By sensing the neutron flux density radiating from an ion chamber which produces a current proportional to radiation in the ion chamber, the electrometer according to the invention can output a signal representing the current or radiation readings to a remote digital and/or analog measurement display unit.

The operation of this embodiment of the electrometer system as a current source will be discussed first. However, it will be apparent that the structure described can be used for both source and sensor modes of operation. In the source mode, the electrometer system of
the instant invention can provide substantially continuous output of current from $10^{-12}$ to $10^3$ amps without significant scale change. Likewise, in the sensor mode, the electrometer system can sense and provide a substantially continuous output indication of an external current source over the same current range of $10^{-12}$ to $10^3$ amps. The following example will generally illustrate how this continuous operation is achieved.

In order to provide a current output from $10^{-12}$ to $10^3$ amps, the electrometer system 10 is initially set as follows: under the control of microprocessor 5, solid state switch SSSC is placed in the source mode position A, solid state switches SSS3 and SSS6 are closed to couple resistors RA4 and RA7, respectively, to the current buss 6, and solid state switch SSSA is placed in position A to connect resistor RA1 with the output of digital to analog convertors DA1 and DA4 through summing circuit SM1, as shown in Figure 1. Calibration of electrometer system 10 can then be achieved using the output of amplifier A3 and the output of DA4. Amplifier A3 monitors the voltage sensed at input/output terminal 11 and provides a signal which corrects for errors that may be caused by voltage offset or burden in the device coupled at terminal 11 by adding the offset values to the current sourcing voltage at summing points O, P, Q of algebraic summing circuits SM3, SM2 and SM1, respectively.

Initially, microprocessor 5 is programmed to output 100 millivolts (mv) from DA1 and zero volts from DA2 and DA3 through multiplexer 7. Since SSSA is in position A, the 100 mv from DA1 passes through resistor RA1 having a resistance of $10^{11}$ ohms thereby producing a current of $10^{-12}$ amps (100 mv through $10^{11}$ ohms) to be outputted to an external device coupled to terminal 11.

As shown in Figure 1, a second voltage from DA4 is added to the output voltage of DA1 through summing circuit SM1. In this instance, microprocessor 5 is programmed to output a voltage from DA4 which will produce a current proportional to the sum of extraneous leakage
currents. This voltage is initially established during calibration prior to current generation so that the output from DA4 adds a bipolar voltage which, through RA1, in turn produces a current proportional to the sum of the extraneous leakage currents thereby providing current nulling. Other stabilization and calibration techniques may be used to calibrate the electrometer system 10 as discussed below.

Following calibration, the electrometer system 10 may then be operated in the source mode by increasing the voltage from DA1 at a programmed rate controlled by microprocessor 5. In the present instance, microprocessor 5 is programmed over a range of 100 mv to 10 volts which is coupled from DA1 through resistor RA1 to provide source currents on current buss 6 ranging from $10^{-12}$ to $10^{-10}$ amps. The rate at which the sourced voltage from DA1 is increased is controlled by programming entered in microprocessor 5. Subsequently, under program control, digital to analog converter DA1 is held at 10V and digital to analog converter DA2 is operated by microprocessor 5 to ramp the current at buss 6 through resistor RA4 at the same programmed rate by passing the output voltage of DA2 (0 to 9 volts) through resistor RA4 of $10^{10}$ ohms. When the resulting sourced current on buss 6 reaches $10^{-9}$ amps, the output of DA2 is at 9 volts. At this time, DA2 is held at this value, while microprocessor 5, under program control through multiplexer 7, causes a voltage ramp (0 mv to 9 volts) through DA3 to ramp the current through the next decade to $10^{-4}$ amps by passing the output voltage of DA3 through resistor RA7 of $10^9$ ohms.

It will be appreciated that any offset voltage on resistor RA7, the lowest resistance on line, is a major cause of drift. Switch SSS6 may be left open to minimize drift at the risk of a possible perceptable switching feedthrough pulse on the output current buss.

As described above, the three programmed digital to analog voltage sources (DA1, DA2, DA3) in conjunction with scaled resistors RA1, RA4 and RA7, produce outputs
from switching circuits GR1-GR3 which provide electrometer currents from $10^{-12}$ to $10^{-8}$ amps. At this time, to increase the sourced current, the program of microprocessor 10 causes the electrometer system 10 to switch the lowest current source GR1 which is then 1% of the actual current value. In this example, since digital to analog converter DAI is providing the lowest voltage source, it is reset to zero volts while DA2 increments to 10 volts to make up in RA4 the loss of current in RA2. At the same time, solid state switch SSS1 is programmed to close and thereby connect digital to analog converter DAI through resistor RA2 to produce current on buss 6 for the next highest decade. As shown in Figure 1, the next scaled resistor RA2 has a value of $10^8$ ohms. Under program control microprocessor 5 causes digital to analog converter DAI to again output voltage at the previous programmed rate described above to ramp the current from GR1 through the next decade. It should be noted that because the current sourced through resistor RA1 is approximately 1% of scale after ramping through GR3, it is practically negligible. However, the next higher decade from DAI is programmed to 10 volts to compensate for the deleted current. Also, digital to analog converter DA4 is set to zero volts, since the sensed offset current as the sum of leakage values is insignificant and the DA4 voltage would be improperly scaled for RA2.

After the rescaled digital to analog converter DAI again reaches its 9V voltage, microprocessor 5 causes digital to analog converter DA2 to reset to zero, opens solid state switch SSS3 while incrementing DA3 to 10V for current make-up and in turn closes solid state switch SSS4 to connect DA2 through resistor RA5 which is scaled to source the next highest current decade from the output of GR2 as the voltage is ramped from DA2 in the same manner as before. The programming of microprocessor 5 causes electrometer system 10 to operate in this fashion, resetting the digital to analog converter sourcing the
lowest current value to zero while connecting the next successive D-A converter to a resistor scaled to produce current for the next highest decade. Thus, DA3 is reset to zero, switch SSS6 opened, switch SSS7 closed to couple the output of DA3 through resistor RA8 to buss 6, and DA3 is ramped as previously described to produce the next decade of current. Thereafter DA1, DA2 and DA3 are successively reset to zero and the switches SSS3, SSS5 and SSS8 closed successively in cooperation with the opening of their related switches SSS1, SSS4 and SSS7, to produce the next three decades of current at the outputs of the respective switching groups GR1-GR3 as the voltages are ramped in the same manner as previously described. As a result, by cyclically switching the ramp voltages of the converters DA1-DA3 through selected resistors of the switching groups GR1-GR3, the current output from the electrometer system 10 can be varied over the described range of $10^{12}$ to $10^3$ amps without substantial scale change or discontinuity.

It should be noted that in the final stage, in this example, the sourced current is designed to reach the 10 milliamp scale value. Because the final scale resistor RA9 is activated by closing SSS8 to pass the programmed output voltage of DA3 the resistance of RA9 and SSS8 must be equal to 1000 ohms if the maximum current of 10 milliamps is to be obtained. As one of ordinary skill in the art can appreciate, in practice the value of resistor RA9 is actually less than the designated 1K ohm so that the total resistance of solid state switch SSS8 (which equals about 100 ohms) and resistor RA9 equals the desired 1K ohm.

It will be appreciated that reversing the sequence will provide a decreasing current.

As an option, the voltage drop over resistor RA9 can be monitored and fed back by a circuit, such as that shown in Figure 1B to ensure the desired current output through RA9 is attained for greater accuracy. Thus, in accordance with Fig. 1B, two amplifiers 21 and 22 can be
connected such that the voltage drop across resistor RA9 is coupled as input to amplifier 21, having its output coupled as one input to differential amplifier 22. A second input of the differential amplifier 22 is derived as the sum of the outputs from DA3 and A3 through summing circuit SM4. The "Y" output signal of amplifier 22 is coupled as an input to the summing circuit SM3.

As will be appreciated, the above construction allows the operation of the electrometer system 10 to be controlled by remote digital or analog programming as schematically shown in Figure 1. When solid state switch SSSB is in position A, the electrometer system 10 is in a current source mode which may be externally programmed. Thus an analog signal may be applied to terminal 12 and provided as a programmed voltage at, for example 1 volt per decade (1 to 10 volts), from remote analog equipment to produce the desired source current at the output terminal 11. This would be accomplished by converting the analog voltage applied to terminal 12 to a control signal usable by the microprocessor 5. In one example, the conversion could be accomplished by circuit 8 which could be a voltage to frequency (V/F) converter or an analog to digital (A/D) converter of conventional construction.

Furthermore, the system could be operated by a remote digital serial link in lieu of the analog programming through terminal 12. In such an event, a conventional source of digital programming could be coupled via well known digital communication links to the microprocessor 5 to cause the control of the digital to analog converters DA1-DA3 in the manner described in cooperation with the groups of switches GR1-GR3 to produce the desired current output from terminal 11.

Also as mentioned above, several stabilization and calibration techniques can be used with the electrometer system of the instant invention. By way of example, to provide accurate offset and scaling values, a ground circuit solid state switch SSS10 can be employed
a conventional manner to provide a fixed ground reference. Additionally, an open circuit input/output can be created using reed switch R51.

Furthermore, the V/F or A/D circuit 8 can be used to establish a zero voltage for the system’s inputs.

Additionally, as was described above, digital to analog converter DA4 can be programmed to compensate for any measured leakage currents and produce a nulling current to establish the electrometer’s current zero for a predetermined input from circuit 8. In a similar manner, the system can be calibrated by monitoring circuit 8 output while the outputs from each resistor are viewed one at a time as the voltage standard is applied and the outputs of DA1-DA3 are driven between zero and full scale.

If sufficiently accurate resistors RA1-RA9 are not available the described electrometer system allows resistor calibration technique using a standard calibration resistor $R_{std}$ activated by a standard voltage $V_{std}$ to standardize the sourcing resistors RA1-RA9. As an example, the standard resistor $R_{std}$ can have a value of $10^6$ ohms where the standard voltage $V_{std}$ outputs 10 volts. Then solid state switches SSS7 and SSS9 can be closed to calibrate the 1 mega ohm resistor RA8 through nulling by microprocessor 5. From this calibration point the remaining sourcing resistors can be calibrated by bootstrapping. The output voltages of the converters compensate DA1-DA3 can then be programmed by microprocessor 5 to compensate for resistor tolerances. Hence the electrometer of the invention is self calibrating and no manual adjustments need to be made as in the prior art. Moreover, this circuit eliminates the prior art requirement of precision scaling resistors.

It will also be apparent from the above description that the electrometer system 10 may be used to measure an input voltage at terminal 11 rather than produce the output current as described. In such an instance the electrometer system 10 will be operated in
the sensor mode, which is substantially the same as the
source mode. However, in this mode, the switches SSSB and
SSSC are coupled to their respective B terminals. There-
after, the input current from terminal 11 is coupled upon
actuation of reed switch RSI to provide an input signal,
as well as the bucking current on buss 6, as input through
the electrometer voltage follower amplifier A1 (and
through surge protector 14). The output of A1 is coupled
as input to circuit 8, as well as through range and RF
filter amplifier A2 which has its output coupled to
terminal B of switch SSSB. This combined signal is
coupled through circuit 8 to provide a signal to micropro-
cessor 5 representing the difference in the input current
from terminal 11 and the bucking current from buss 6.

In this mode of operation, the microprocessor 5
is programmed to respond to the signal from circuit 8 to
cause the output voltages DAI-DA3 to cycle in the manner
described above to produce an output current on the buss 6
which will null the input current on terminal 11 and
produce a zero voltage on buss 6. The output which is
proportional to the input current signal on terminal 11
may be provided by a signal from the microprocessor as a
digital or an analog signal (e.g. volt/decade) to drive
local or remote meters indicating the current on terminal
11. As will be apparent, in this mode the microprocessor
5 could also be programmed to provide rate information as
well. Such an output signal could also be provided to
control circuits for the system being monitored by the
electrometer of the invention.

Furthermore, at low currents below the $10^{-12}$ amp
level described in connection with the electrometer system
10, the structure shown could be utilized to provide
higher accuracy at the expense of response time. Briefly,
rather than providing constant feedback to null the output
at terminal 11, the capacitor C1 could be charged.
Charging rate is proportional to current and could be
calculated or compared with internally sourced currents to
provide calibration. This ability points out the versatility of the above system in contrast to those of the prior art.

In another embodiment of the present invention, an electrometer system is shown in Fig. 2 which produces a current signal ranging from $10^{-12}$ to $10^{-2}$ amps without discontinuity associated with a major scale change. Figure 2 illustrates the voltage to current conversion circuitry of an electrometer system according to an alternative embodiment of the invention. By employing logarithmic bit weighing, this embodiment permits a ten decade range of current to be covered with less than $2^{16}$ steps and with less than 620 parts per million as the increment level change.

This embodiment contains four digitally programmed voltage to current converters VCA, VCB, VCC, VCD connected to a common current summing buss 60. Each converter is coupled to the buss 60 through switch groups GB1-GB4, respectively. In this embodiment each successive converter outputs a full scale current one octave above that of the preceding converter. For example, the first stage converter may be programmed over the range of zero to $8 \times 10^{-12}$ amps. To output current above this level the second stage is activated so that it contributes zero to $64 \times 10^{-12}$ amps. The third and fourth stages then have full scale outputs of 512 and $4096 \times 10^{-12}$ amps, respectively. Currents above the level produced by the aforementioned four stage operation are produced by cycling back through the same four stages, but changing the conversion resistors R1'-R11' to selectively insert such resistors into the output of the associated converter to produce the next octave of current on the buss 60 in a manner similar to that described in connection with Fig. 1. The circuit as shown in Fig. 2, thus provides for eleven scales of $2^3$ or eleven octaves to cover more than 9 decades of current levels.
While the starting level can be arbitrarily chosen, in this description the base level or starting level is set at $10^{12}$ amps. The highest current level achievable by this example is thus 11 octaves higher or $2^{33} \times 10^{12}$ amps (i.e., 8.6 ma), and when this current is summed with the lower octaves produced by the other three converters on line, the result is a maximum current output of approximately 9.66 ma.

In practice, each successive octave is ramped only to $7/8$ of its possible full scale current. The remaining $1/8$ is used to replace the current of the next lowest octave when the lower octave is rescaled (i.e., reset to zero) to a higher level current output in the manner previously described.

In this embodiment, three digital to analog converters are used in each of the four voltage converters VCA, VCB, VCC, VCD and are designated as DA1', DA2' or DA3' (having voltage inputs Y, X and R, respectively) plus the letter of the voltage to current converter with which it is associated. Each set of D/A converters is connected to the microprocessor and is used to output the voltage applied to the voltage to current conversion resistors (R1' through R11'). Each digital to analog converter DA3' outputs a voltage reference which is proportioned according to the selected voltage to current conversion resistor as will be apparent to one of ordinary skill in the art. This proportioning is determined during calibration to allow correction for resistor tolerances. The digital to analog converter DA1' provides a voltage which is at full scale when referenced by the digital to analog converter DA3', and can output a calibrated full scale current through the associated voltage to current conversion resistors (R1'–R11').

Each digital to analog converter in VCA, VCB, VCC and VCD is a 12 bit unit and can output any current between 0 and the full scale value in 4096 increments. Depending upon the desired increment of current levels,
the number of digital to analog converters in the voltage to current converters VCA, VCB, VCC and VCD may be changed. For example, if 4096 increment size bits are acceptable, the third digital to analog converters DA2' in each voltage to current converter would not be required. However, a digital to analog converter containing a higher bit count may be substituted for the 12 bit digital to analog converter to gain higher resolution, or, two 12 bit units DA1' and DA2' may be cascaded together in a multiplying mode to effectively increase the resolution as is shown in the circuit of Fig. 2.

As implemented in Fig. 2, each digital to analog converter DA2' reduces the increment change from 2000 (1953) parts per million to 620 parts per million as the maximum level change per bit. The voltage input X of each converter DA2' is used to divide the reference signal output by each DA3' into 4096 bits. The output voltage of each digital to analog converter DA2' then becomes the respective reference voltage for each digital to analog converter DA1'. If the input voltage Y to converters DA1' are initially set at 5/16 of full scale, the input voltage X of the converters DA2' can program the outputs of converters DA1' from zero to 5/16 of scale in 4096 steps. Converters DA1' are then programmed to increase the voltage from 5/16 of scale to the full scale output. The 5/16 breakpoint was chosen to produce the smallest percentage of scale increment by any one bit change over a one octave range.

The following will describe the operation of this circuitry in the current generation or source mode. Initially, a base level current output of $1 \times 10^{-12}$ amps can be provided by digital to analog converter DA-4' and base resistor $R_b$ which is equivalent to the nulling current, as described in Fig. 1. Quad digital to analog converters DA3' are programmed for the first four octaves to scale an output reference voltage to drive resistors $R_1'$, $R_2'$, $R_3'$ and $R_4'$, respectively. Nominal full scale voltage for the
output of converters DA1' is 8 volts ± .5 volts or 6.25% to accommodate the tolerances of the voltage to current conversion resistors (R1’-R11’). As mentioned above, the voltage output of converters DA2' will be multiplied by the full scale of the respective DA2's converter times the full scale of the respective DA1' converter, thus generating $2^3 \times$ the base level current on each scale position of the electrometer.

Buffer amplifiers 100,200,300,400 are programmed by means of solid state switches SWA2, SWB2, SWC2, SWD2 to reference the sink side of each appropriate voltage to current conversion resistor R1' through R11' (i.e., RR3 in position coupling A common to B common. This implements the following current pump circuitry which can drive a current output voltage burden in excess of one volt. Initially, switches SWA7, SWA2, SWB2, SWC2 and SWD2 are closed, all other SW switches are open, and reed relays RR1, RR2 and RR3 are off as shown.

The instrumentation amplifiers (106-113) in each current sourcing circuit are referenced to the current buss end of respective voltage to current conversion resistors (R1’-R11’) so that the voltage drops of the isolation diodes (D1-J16) shown in the circuit and the voltage burden of the device driven by the electrometer current source do not affect the current output. Electrometer amplifier 105 monitors the current buss (10) side of the isolation diodes. The output of A105 maintains commons A + B at output buss voltage. The resulting voltage across any inactive pair of isolation diodes is therefore near zero volts. The high diode impedance at near zero volts and the near zero forcing voltage brings diode leakage current to near zero.

As noted above, at high currents the resistance of the solid state switches becomes an appreciable percentage of the voltage to current conversion resistance. The typical solution is to use a sourcing resistor having an ohmic value that takes into account the static value of
the switch resistance. However, solid state switches exhibit temperature coefficients of resistance which can also be appreciable. This circuit solves this problem by adding a voltage follower amplifier (114) in the third stage. The input impedance of amplifier 114 can be very high, thus making the switch impedance insignificant. Amplifier 114 is referenced to guard common "A" of the current summing buss voltage, as are the solid state switches, when it is inactive to minimize isolation diode leakage currents.

The circuitry described above employs a new technique of electrometer buss isolation from scaling components to ensure that the voltage forcing leakage currents across the isolation diodes are on the order of 10's of microvolts. When only unipolar operation is desired, it may be advisable to eliminate the unused diode. The polarity function could be programmed by using reed switches and would improve the overall temperature stability of the circuit. Thus, the electrometer according to the invention by using low leakage diodes and guarding can allow automatic bipolar operation without manual switching.

To prevent any possible input surge, a 10 volt clamp 33 is provided in the high current level stage to limit the current summing buss 60 to ± 10 volts. Since isolation diodes D11, D12 are held to the current buss voltage reference by amplifier 114 when inactive or when active are driven by 114 through resistor R11' of 931 ohms, the clamp causes no additional leakage on the buss.

The following example generally describes the ramping operation of Fig. 2 to generate different current levels. The lowest current scale has a full scale current output of $8 \times 10^{-12}$ amps. The normal starting level for a current ramp would be $1 \times 10^{-12}$ amps. This "BASE" level of current can be provided by digital to analog converter DA4'. DA4' outputs a voltage to resistor $R_a$ which converts the voltage output by DA4' to a current which when algebraically summed with the leakage currents of the
elec

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tromer output buss 60, provides a net output current of $10^{-12}$ amps. This level is referred to as the "Base Current" in this specification. Each successive stage has a base level current one octave higher than the preceding stage and is equal to the full scale current of the preceding stage. Accordingly, the base level of each stage is one eighth of the full scale current. During the ramping operation, each stage provides seven eighths of the current. The remaining either is provided by lower current stages, or in the case of the starting level, the above assembly of DA4' and resistor R8.

Each of the four current source assemblies or converter stages VCA, VCB, VCC and VCD can be operated at several output current levels. When the current output reaches a full scale level, the electrometer output current becomes a base level for the next higher stage which continues the ramp, through one more octave. When the output current on buss 60 has been scaled through four octaves, the lowest current stage is reset to zero to provide current for the fifth octave. Synchronous with the reset of the lowest current stage, the next higher stage D-A increments the final 1/8 of scale and replaces the current deleted by reset of the lower stage. No net output current change takes place. In this way the ramp continues through eleven octaves without interruption as in the ramping described above in connection with Fig. 1.

The first stage amplifier 100 drives resistor R1' through switch SWA7 to provide an output current of $1 \times 10^{-12}$ amps per volt. The output of amplifier 100 is referenced to the electrometer output buss 60 through switch SWA2 to common voltage "B". Common voltages "A" and "B" are identical for current source operations. Therefore, the voltage forcing current through R1' is not affected by the burden voltage on the electrometer buss 60.

The individual digital to analog converters ramp the current output of converter VCA from zero to $7 \times 10^{-12}$
amps (7/8 full scale) as follows. A digital signal is sent from a microprocessor setting the Y input of DA1' of VCA at a digital input of 1280. With the nominal input reference voltage of 10V from DA2A, DA1-A provides an output voltage of 2.5 volts and a current of $2.5 \times 10^{-12}$ amps when driven through R1'. The X input of DA2' of VCA provides the reference voltage for the Y input of DA1' of VCA. The current ramp from zero to $2.5 \times 10^{-12}$ amp is provided by the output of DA2' of VCA which is effectively multiplied by the Y voltage input of DA1' of VCA.

Each increment input of current is $2.5 \times 10^{-12}$ amps divided by 4096 or approximately .61 femto amps ($6.1 \times 10^{-16}$). This ramp is continued to $7 \times 10^{-12}$ output current by programming Y (DA1-A) input. Each output current increment in this case is $8 \times 10^{-12}$ divided by 4096 or approximately 2 femto amps. The maximum level change is 610 PPM during the X voltage portion of the ramp ($6.1 \times 10^{-16}$ divided by $1 \times 10^{-12}$). During the Y voltage portion of the ramp it is 620 PPM ($2 \times 10^{-15}$ divided by $3.5 \times 10^{-12}$).

The electrometer according to Figure 2 can output a current of $8 \times 10^{-12}$ amps when the X voltage input of DA2' of VCA is filled (4096) and the Y voltage input of DA1' of VCA at 3584 and outputting a voltage of seven volts. Seven volts across R1' is a current of $7 \times 10^{-12}$ amps.

The R voltage inputs for each converter DA3' provide the reference voltage for the DA2' converters and in turn provide the scaling function for each full scale output current. During calibration the voltage output of the DA3' converters necessary to output the correct full scale output current is established. Errors of + or - 6.25% in the value of R1' through R11' are corrected by modifying the reference voltage from the nominal 8 volts.

To continue the ramp through the next octave, converter VCB is programmed exactly the same as converter VCA after the closing of switch SWB7. Current conversion resistor R2' is one eighth of the value of R1' and produces $5.6 \times 10^{-11}$ amps when driven by seven volts. The
base current of 8 \times 10^{-12} \text{ amps} added with this current produces an electrometer output of 6.4 \times 10^{-11} \text{ amps}. The output on buss 60 is now two octaves above the starting level. Thereafter, by operating converter VCC in the same manner, VCC ramps the total output current to 5.12 \times 10^{-10} \text{ amps} to obtain octave three from the third stage.

Converter VCD employs the first application of the isolation diodes D13 and D14. Resistor R4' is one five hundred and twelfth of the value of resistor R1', and as a result any leakage at a given offset voltage across R4' will produce an error in current 512 times that of resistor R1'. Isolation diodes D13 and D14 permit isolation of resistor R4' through a much higher impedance, than that of R4' alone. In effect the diode is placed in series with resistor R4' with their junction at the common "A" which equals the output buss voltage. The voltage across the diodes is therefore held at zero volts, which effectively open-circuits the R4 buss connection. For the highest isolation the common "A" voltage can be offset slightly to reverse bias the diode and this technique makes the effective resistance of the diode even higher. However, this is only possible with unipolar operation, i.e., when one diode is eliminated.

In standby prior to ramping in stage four, converter VCD is configured as follows. R4', a 1.95 \times 10^9 \text{ ohm} resistor is referenced to common "A" through a 1 \text{ meg ohm} resistor. Amplifier 109 is an electrometer amplifier which follows the voltage at the junction of R4' and isolation diodes D13 and D14. The reference common to amplifier 400 was listed initially on common "B" through switch SWD2. Since the output of amplifier 400 is not being used (SWD3, SWD4 open), it is of consequence only as a starting point for this discussion. Prior to third stage converter VCC reaching full scale current the reference of amplifier 400 is moved to the output of amplifier 109 (SWD2 opens, SWD5 closes) and amplifier 400 is referenced to the voltage at the junction of R4' and
the isolation diodes D13 and D14. The output of amplifier 400 with a zero voltage input from DA1' of VDC will be equal to that junction voltage and will produce no current through R4'. Switch SWD3 then closes when converter VCD begins the ramp through the fourth octave. A forward voltage develops across the isolation diodes to conduct the R4 current.

The fifth octave is then sourced by cycling to converter VCA. To accomplish this, converter VCA is taken off line and rescaled to output the fifth octave of current. Its original contribution of $7 \times 10^{-12}$ amps of current to current summing buss 60 is replaced by converter VCB, which is programmed to change from $5.6 \times 10^{-11}$ amps (digital input 3584) to a full scale value of $6.4 \times 10^{-11}$ amps except for the contribution of DA4' of $1 \times 10^{-12}$ amps, which is equivalent to 64 bits of converter VCB. Converter DA1' of VCB is thus set at 4032 to compensate for the bits/amps received from converter DA4'. Amplifier 100 is then re-referenced to the junction of R5' and the isolation diodes D1 and D2 by opening switch SWA2 and closing switch SWA5, thereby isolating the output of amplifier 100. Converter DA1' of VCA is then set at a digital input of 1280. DA2' of VCA is set at a digital input of zero. DA3' of VCA is set to output a reference voltage scaled for resistor R5'. When the fifth octave begins through stage 1, switch SWA7 is open, switch SWA3 closes and DA2' of VCA is incremented to 4096 where DA1' of VCA provides current for the remainder of the octave.

Converter VCB then operates in a way similar to converter VCA described above and is set up for the sixth octave. The only difference is that when converter VCC picks up the current lost by pulling converter VCB off line, DA1' of VCC is filled to 4088 as only 8 bits of converter VCB are equal to the $10^{-12}$ amps from DA4' (i.e., $2^9 \times 10^{-12} \times 8/4096$).

It is to be noted that if DA4 were set at zero when VCA goes off line, the contribution of DA4' would not need to be taken into account in the programming of
converter VCB, and all stages would "fill" as the next lower stage drops out.

The ramp continues through successive octaves of the successive stages in a similar way to a final current of \(2^{23} \times 10^{-12}\) or 9.66 ma. The final stage is different only in that amplifier 104 is added to drive output currents beyond the capability of the amplifier 300 while also eliminating the error caused by the effect of the resistance of the solid state switch SWC4 on R4'.

To ramp from high to low level currents the above described programmed process may be reversed. Current excursions can be programmed to start at any current level. Any wave form including step changes may be generated from a PROM chip or an external digital source which can furnish rate or actual levels for the electrometer system. An analog signal also can be used to program rate, but probably would degrade the accuracy of level programming. The microprocessor of the instant embodiment could also output rate and current level to a remote station if desirable in a manner similar to that described in connection with Fig. 1.

With reference to Figure 4, a 16 pole multiplexer 17 receives output signals from the amplifiers in the voltage to current conversion circuitry of Figure 2, as shown. Common voltages "A" and "C" are also input to multiplexer 17. The signal of the optional remote analog programming device mentioned above can also be connected to multiplexer 17. The signals received by multiplexer 17 may be selectively sent to analog to digital converter 50 of conventional 16 bit construction, which is connected to the microprocessor to output the sourced current, or, to output the sensed current, or to provide the other functions described herein under the control of microprocessor programming. The A/D converter 50 can also be used to check offsets and full scale outputs of each voltage to current converter VCA, VCB, VCC
and VCD by monitoring the respective output signals of amplifiers 100, 200, 300 and 400.

The same circuits used to generate current can measure input currents from an external current source such as the ion chamber in a nuclear reactor. In this way the electrometer circuit according to the invention can be used to monitor reactor power levels.

As shown in Figure 4, electrometer amplifier 105 can be operated to couple the voltage on the electrometer buss 60 through the multiplexer 17 to the analog to digital converter A/D 50. If currents generated by the four converters VCA, VCB, VCC and VCD are not equal and opposite to the input current, the buss 60 voltage will deviate from ground or zero voltage. This error signal may be used by the microprocessor to program the appropriate nulling currents which will force the electrometer voltage on the buss 60 back to zero volts. At this time, a signal proportional to the required nulling current can be outputted to an analog or digital circuit to provide level or rate information. Figure 5 shows a typical analog output circuit which could be coupled to convert a digital signal from digital to analog converter DA5 to a signal proportional to the nulling current for driving an analog meter. Digital to analog converter DA5 may be a 16 bit chip for sending current level information, and an 8 bit device for rate information.

Additional calibration techniques of the electrometer system of Figure 2 are discussed below. By way of example, voltage offset of amplifier 105 may be checked by connecting electrometer buss 60 to common via reed relays RR1 and RR2. The output of A/D 50 can then be monitored to check the offset of amplifier 105 coupled as input to multiplexer 17. Also while the circuits are in a stand by mode, the outputs of amplifiers 106-113 also can be checked for acceptable operation by comparing their output to common "A" through the same checking of the output of A/D 50 as a result of the input to multiplexer 17.
To initially zero the electrometer system, any sensed offset currents are nulled while zero outputs are provided from converters VCA, VCB, VCC, and VCD using digital to analog converter DA4' and floating the output buss via reed switch R$\$1 and solid state switch SW1. To accomplish this, the output of amplifier 105 multiplexed by M (17) and monitored through A/D converter 50, while converter DA4' is programmed to null the output of amplifier 105 to zero. The microprocessor of this system then holds the output of converter DA4' at the programmed value to maintain null. The circuit of Fig. 3 is an example of an optional circuit for providing the nulling current from DA4' which will allow for compensation by amplifier 214 for a change in the burden voltage on buss 60. Furthermore, the reference adjustment on DA4' allows compensation for internal sign and scaling adjustments of offset control by the converter DA4' through R$_n$.

The electrometer system of Figure 2 can also be calibrated by methods similar to those discussed above with reference to Figure 1. Scaling calibration is necessary to eliminate the consequences of tolerances on the voltage to current conversion resistors (R1'-R11'). The scaling information obtained by one of the above methods or other conventional means could be stored in an EEPROM chip in order to program the respective digital to analog converters DA3' of each converter VCA, VCB, VCC and VCD to output accurate reference voltages for the selected scaling resistor. This technique ensures a high degree of linearity when ramping from minimum to maximum currents and monotonicity between internal scales.

While the embodiment of Fig. 2 has been described without reference to the microprocessor and programming in as great a detail as was set forth in connection with Fig. 1., it is clear that the same operation and accompanying elements (e.g., switch drivers DRA-DRD and I/O port switch control) are desirable in implementing Fig. 2. Such implementation will be apparent
to one skilled in the art from the references made to Fig. 1.

From the foregoing description it will be apparent that the automatic, continuous and self-calibrating electrometer circuit of the instant invention has a number of advantages some of which have been described above and others which are inherent in the invention. Also, it should be understood that numerous modifications and variations may be made to the detailed circuits described above without departing from the scope of the invention.
ABSTRACT

A multiple decade electrometer circuit is claimed which can measure low input currents or act as a current source and is comprised of a microprocessor controlled digital to analog converters to derive individual decades. A plurality of decades are created by multiple D-A voltage sources which generate electrometer currents through scaled resistors. After a first series of decades of current are successively produced, the converters are cycled to generate current through new resistors scaled to produce another series decades of current. In this manner, the electrometer circuit generates or senses a plurality of decades of current without significant scale change.
FIG. 2B