

[54] **VOLTAGE-TIME-VOLTAGE
COMPUTATION CIRCUIT USING R-C
EXPONENTIAL DECAY CIRCUITS TO
PERFORM MULTIPLICATION,
DIVISION, ROOT-FINDING AND
LOGARITHMIC CONVERSION**

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320/1, 328/145

[51] Int. Cl. **G06g 7/16, G06g 7/24**

[58] Field of Search **235/193, 193.5, 194, 195;**
320/1; 321/15; 307/246, 293, 294, 229;
328/146-149, 145, 129; 340/347

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[57]

ABSTRACT

A new class of linear circuits can multiply and divide, find powers and roots, and perform both logarithmic and antilogarithmic conversions. The circuits convert incoming voltages into logarithmically related time intervals and simultaneously convert the time intervals back into antilogarithmically related voltages. Resistor-capacitor exponential decay circuits perform the voltage-time and time-voltage conversions under the control of comparators and switches.

8 Claims, 12 Drawing Figures

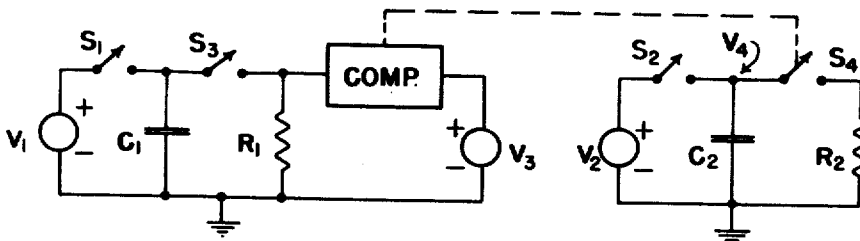


FIG. 1

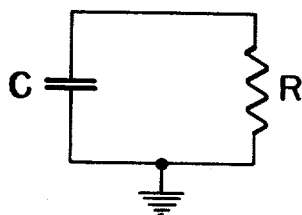


FIG. 2

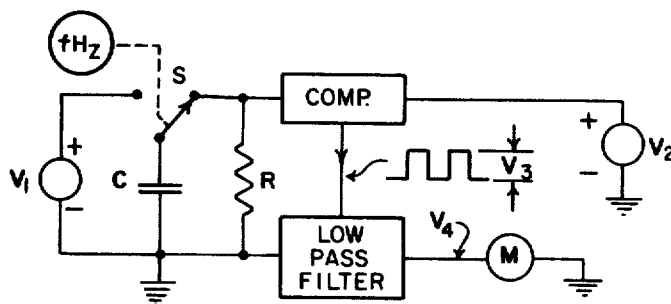
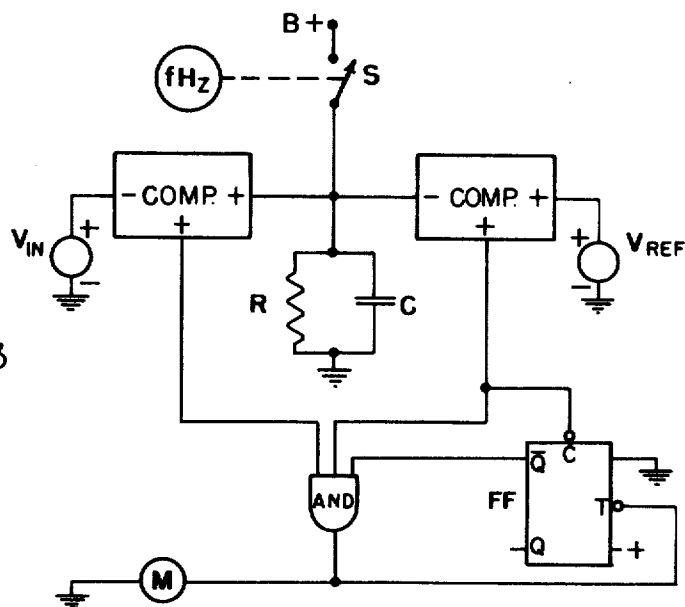
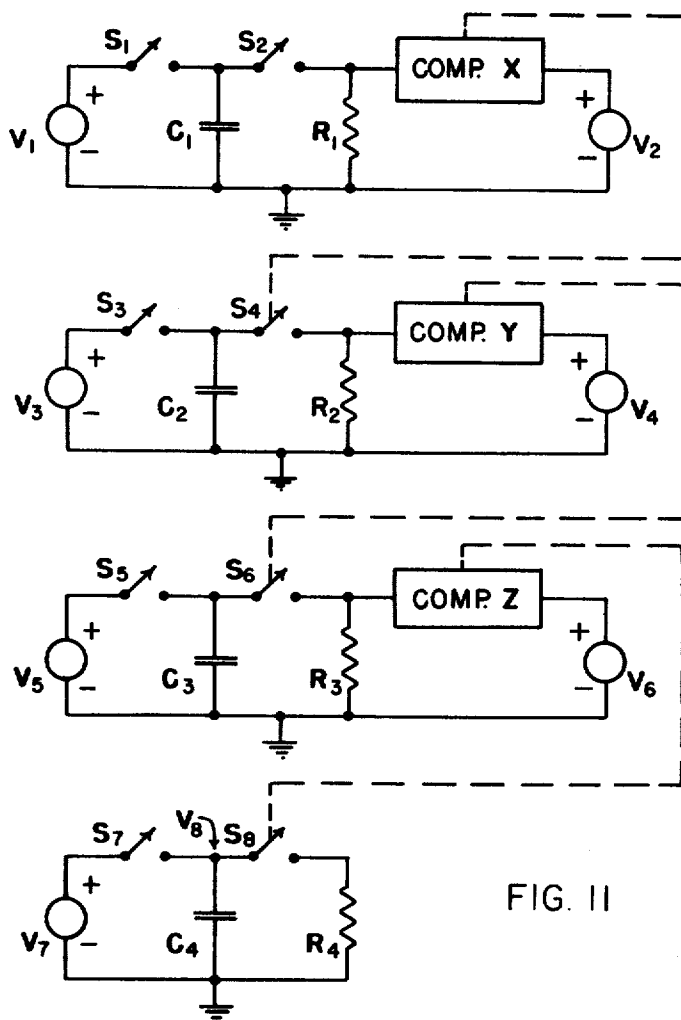
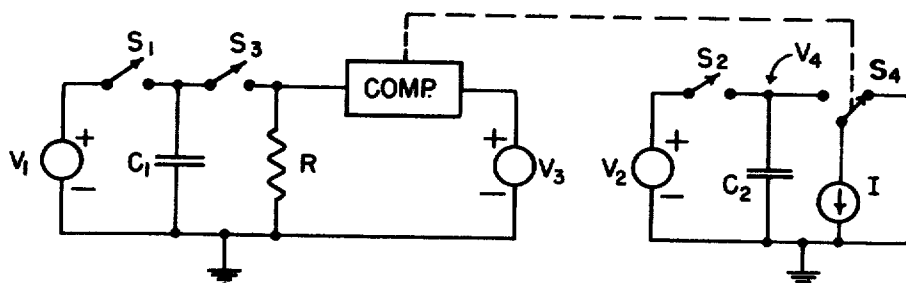


FIG. 3



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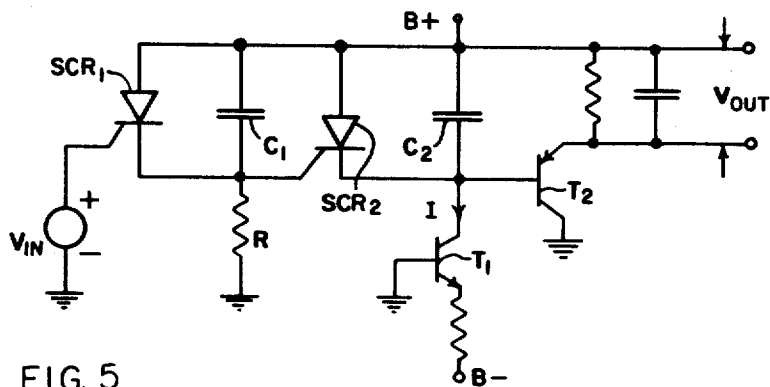


FIG. 5

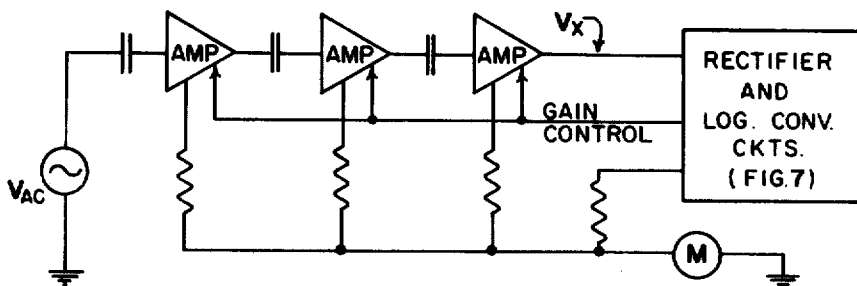


FIG. 6

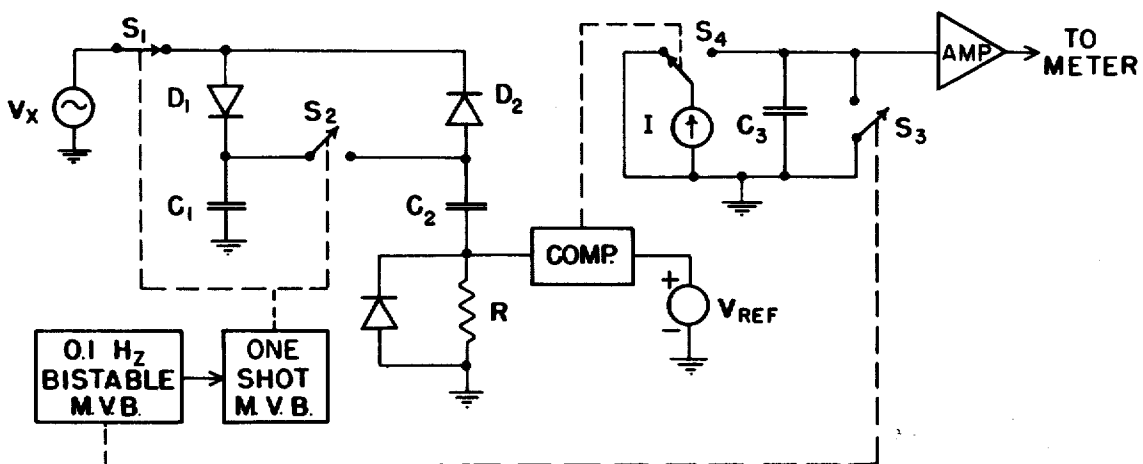


FIG. 7

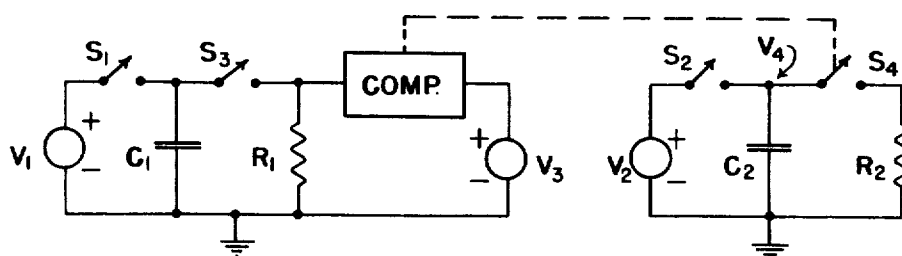


FIG. 9

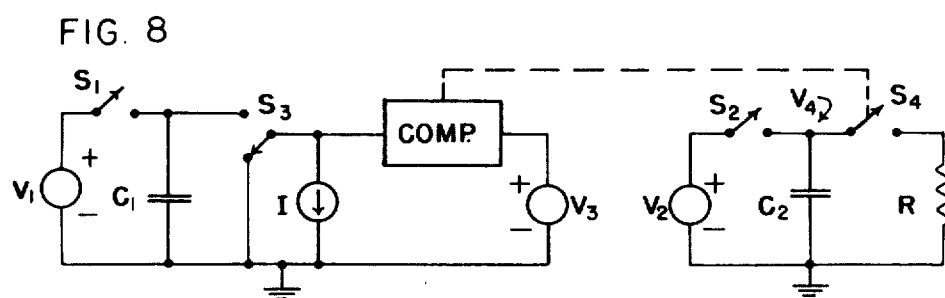


FIG. 8

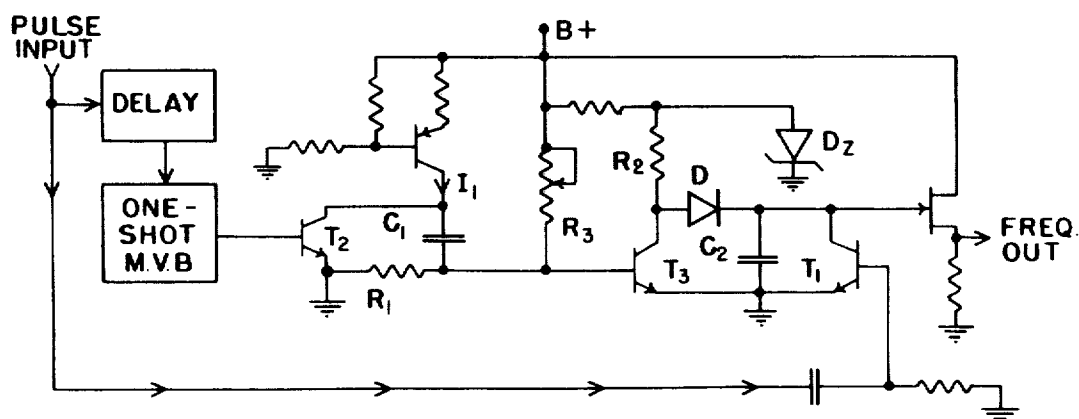
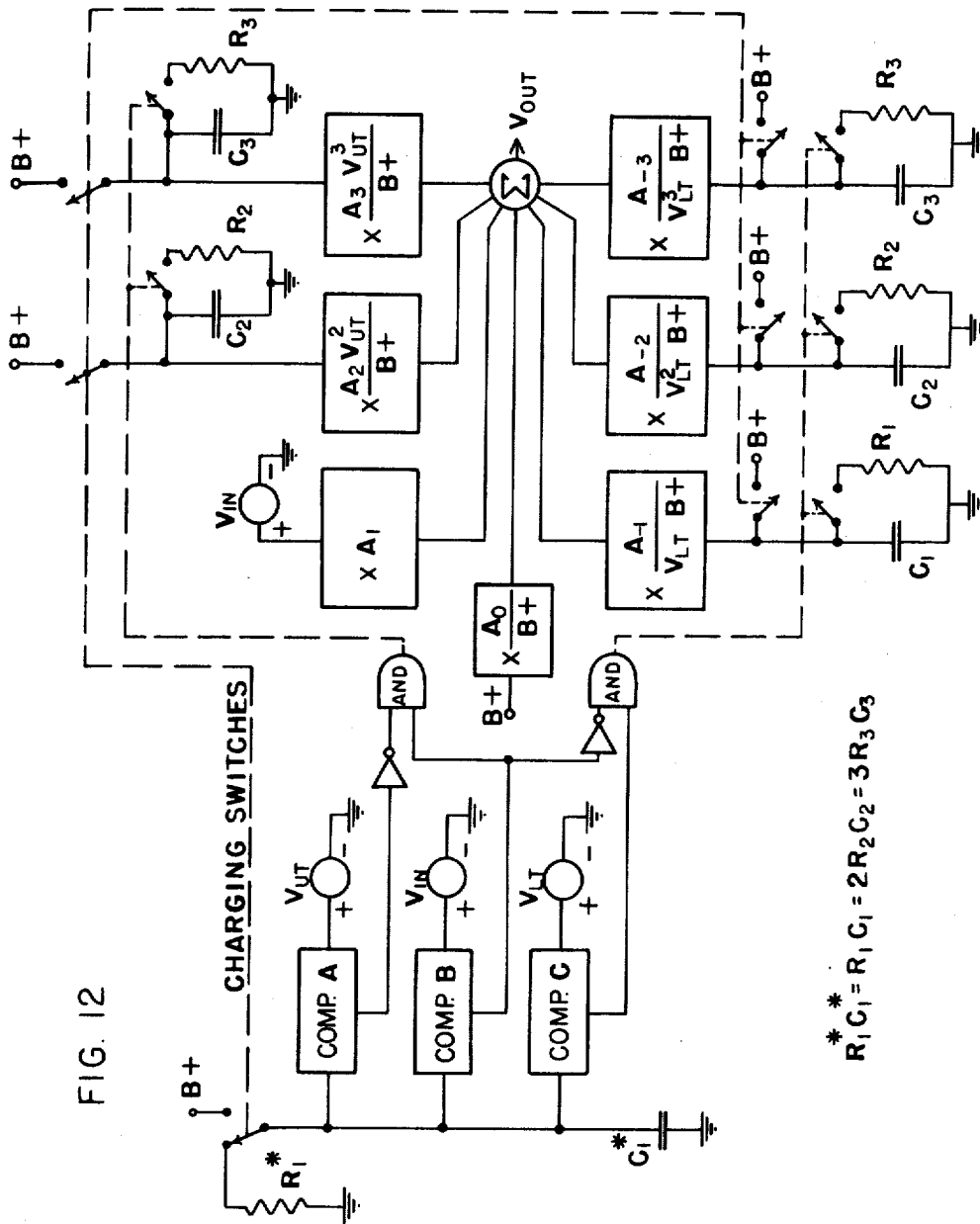


FIG. 10



$$R_1 C_1 = R_1 C_1 = 2 R_2 C_2 = 3 R_3 C_3$$

VOLTAGE-TIME-VOLTAGE COMPUTATION CIRCUIT USING R-C EXPONENTIAL DECAY CIRCUITS TO PERFORM MULTIPLICATION, DIVISION, ROOT-FINDING AND LOGARITHMIC CONVERSION

The present invention relates to non-linear electronic circuitry and, more particularly, to analogue circuitry which can perform non-linear computations or calculations with precision.

Linear computations such as addition, subtraction, integration, and differentiation can be performed with precision by electronic analogue computational circuits constructed from the so-called linear components — resistors, capacitors, and inductors. Computational circuits of this type derive their precision from the temperature stability and precise linearity of these components. It is not uncommon for linear computational circuits to give accuracies of hundredths of a percent over computational ranges of many powers of ten.

Non-linear computations such as multiplication, division, exponentiation, and logarithmic conversion cannot be performed directly by circuits containing only linear components. Therefore circuits capable of performing non-linear computations almost always include non-linear components — components in which voltage and current are not linearly related. The most commonly used non-linear component is the junction diode, but other non-linear components are also widely used. Typically both linear and non-linear components are interconnected in such a manner that the resulting circuit has the desired non-linear input-output characteristic.

The design of non-linear circuits is usually empirical and is often accomplished through a tedious procedure of trial and error. Precision is usually achieved only at the price of extreme complexity, and often hundreds of components must be used to give a specified degree of accuracy. While some non-linear components have characteristics which are logarithmic over a range of a few powers of ten, these components are almost always highly temperature sensitive and require either a controlled temperature environment or else careful temperature drift compensation. At their best, the precision of such logarithmic components cannot approach the precision of a linear resistor or capacitor.

Accordingly, a primary object of the present invention is the production of non-linear computational circuits whose non-linear characteristics are entirely determined by linear components and which, therefore, have the same potential for precision as conventional linear computational circuits.

Another object of the present invention is the production of simple computational circuits which can perform multiplication or division, find any power or root, and carry out both logarithmic and antilogarithmic conversions to any desired degree of precision.

A further object of the present invention is the production of computational circuits which can perform any non-linear transformation that can be represented by a power series expansion.

Yet another object of the present invention is the production of logarithmic conversion and antilogarithmic conversion computational circuits which can be combined with each other and with conventional linear computational circuits so as to perform any non-linear computation on any number of variables with any desired degree of accuracy.

Further objects and advantages of the present invention are apparent in the drawings and in the detailed description which follows. The features of novelty which characterize the present invention are pointed out with particularity in the claims annexed to and forming a part of this specification.

In brief, the present invention contemplates using exponential growth or decay circuits constructed from linear components to convert voltages or currents into logarithmically related time intervals and to convert time intervals into antilogarithmically related voltages or current. A typical circuit includes a single resistor and a single capacitor. The resistor discharges the capacitor from a first voltage level down to a second voltage level. The time interval required for this discharge to occur is measured, usually by another similar cir-

cuit. The time interval thus defined is then proportional to the logarithm of the ratio of the first voltage to the second voltage. Similarly, the ratio of the first voltage to the second voltage is proportional to the antilogarithm of the time interval.

A typical computational circuit might include two exponential decay circuits. The first exponential decay circuit is allowed to decay from an initial voltage level V_1 to a final voltage level V_2 . Simultaneously, the second exponential decay circuit is allowed to decay from an initial voltage level V_3 to a final voltage level V_4 . The voltage V_4 is then given by:

$$V_4 = V_3 (V_2/V_1)^K$$

where K is the ratio of the exponential decay circuit time constants. As the equation clearly shows, this simple computational circuit can perform multiplication, division, reciprocation, or exponentiation. Numerous alternative circuit configurations can be constructed which can perform numerous other non-linear computations, as is apparent in the detailed description which follows.

In the drawings:

FIG. 1 is a circuit diagram of the basic resistor-capacitor exponential decay circuit which is the basic building block for all voltage-time-voltage computational circuits;

FIG. 2 is a circuit diagram of a voltage-time logarithmic conversion circuit;

FIG. 3 is a circuit diagram of a practical embodiment of the basic circuit shown in FIG. 2;

FIG. 4 is a circuit diagram of a voltage-time-voltage logarithmic conversion circuit;

FIG. 5 is a circuit diagram of a silicon controlled rectifier embodiment of the basic circuit shown in FIG. 4;

FIG. 6 is a block diagram of a peak reading audio decibelmeter that includes a combined rectifier and voltage-time-voltage logarithmic conversion circuit;

FIG. 7 is a circuit diagram of the combined rectifier and voltage-time-voltage logarithmic conversion circuit used in the decibelmeter of FIG. 6;

FIG. 8 is a circuit diagram of a voltage-time-voltage antilogarithmic conversion circuit;

FIG. 9 is a circuit diagram of a basic voltage-time-voltage non-linear computational circuit that can perform multiplication, division, reciprocation, and exponentiation;

FIG. 10 is a circuit diagram of an instantaneous pulse frequency meter which includes a voltage-time-voltage reciprocal computation circuit;

FIG. 11 is a circuit diagram of a voltage-time-voltage computational circuit which performs multiple multiplications and divisions of voltages by addition in the logarithmic time domain; and

FIG. 12 is a circuit diagram of a voltage-time-voltage computational circuit which can perform a power series transformation.

The basic concept underlying the present invention is that of performing logarithmic conversion by measuring the time it takes a capacitor to discharge exponentially between two voltage levels. Consider the capacitor C shown in FIG. 1. The time Δt which it takes the capacitor C to discharge from a voltage level V_1 to a voltage level V_2 is:

$$\Delta t = RC \ln (V_1/V_2) \quad (\text{Eqn. 1})$$

Hence, the time interval Δt is proportional to the logarithm of the voltage ratio V_1/V_2 , and the voltage ratio V_1/V_2 is proportional to the antilogarithm of the time interval Δt .

FIG. 2 shows what can be called a voltage-time logarithmic conversion circuit. A switch S periodically charges a capacitor C to a voltage level V_1 . This charging procedure is carried out f times each second. The capacitor C is discharged f times each second through a resistor R . The time it takes the capacitor C to discharge between a first voltage level V_1 and a second voltage level V_2 is measured by a comparator. A low pass filter converts the rectangular wave output signal of the comparator into a D.C. voltage V_4 which is applied to a voltmeter M . The voltage V_4 is given by:

$$V_4 = V_3 RCf \ln \left[\frac{V_1}{V_2} \right] \text{ for } 1 > \frac{V_2}{V_1} > \exp \frac{-1}{RCf} \quad (2)$$

V_3 = comparator peak-to-peak output voltage

f = oscillator frequency

Hence, V_4 is proportional to the logarithm of V_1 divided by V_2 .

Accuracy and range can be traded against each other in this circuit by varying the magnitude of the product (RCf). If the voltage V_4 is displayed on a meter accurate to within 1 percent of full scale, for example, an input voltage range of 60 decibels (1 millivolt to 1 volt) can be measured with an accuracy of about 7 percent, while an input voltage range of 3 decibels (0.7 volt to 1.0 volt) can be measured with an accuracy of about 0.3 percent. A single circuit can be adapted to either of these modes of operation simply by changing the value of R , of C , or of f .

FIG. 3 illustrates a more sophisticated version of the basic circuit shown in FIG. 2. The switch S is a high speed relay that is actuated f times each second. The capacitor C is charged to a potential level higher than the incoming voltage V_{in} and is then discharged through a resistor R . Two comparators and an AND gate are used to generate a rectangular waveform whose D.C. component is proportional to the logarithm of V_{in} . A flip-flop FF disables the AND gate while the capacitor C is recharged. The accuracy and range of this circuit are limited only by the accuracy and range of the comparators and of the meter. This circuit could conceivably handle input signals which vary over a range of 160 decibels (10 microvolts to 1,000 volts). If a second input voltage is used in place of the reference voltage V_{ref} , this circuit generates an output that is directly proportional to the decibel difference between the two incoming voltages and therefore can measure the gain of an amplifier in decibels directly.

A voltage-time-voltage logarithmic conversion circuit is shown in FIG. 4. This circuit produces a stable output voltage which does not require filtering. Initially the switches S_1 , S_2 , S_3 , and S_4 are in the positions shown in FIG. 4. The switches S_1 and S_2 are closed momentarily and are then opened. C_1 is thus charged to a voltage level V_1 and C_2 is charged to a voltage level V_2 . The switches S_3 and S_4 are then thrown simultaneously. The resistor R now discharges the capacitor C_1 exponentially, and simultaneously the constant current source I discharges the capacitor C_2 linearly. When the voltage across the capacitor C_1 decays to a voltage level V_3 , a comparator throws the switch S_4 back to the position shown in FIG. 4. The final voltage across the capacitor C_2 is then:

$$V_4 = V_2 + \left[\left(\frac{I}{C_2} \right) RC_1 \ln \left(\frac{V_1}{V_3} \right) \right] \quad (3)$$

The voltage V_4 is thus proportional to the logarithm of the voltage ratio V_3/V_1 . The voltage V_4 is also proportional to the current I . Hence, this circuit can be used to perform the following non-linear calculation:

$$V_4 = K \ln \left[\left(\frac{V_3}{V_1} \right)^I \right] \text{ where } K = \text{constant} \quad (4)$$

FIG. 5 is a simple practical version of the circuit shown in FIG. 4. A silicon controlled rectifier SCR_1 discharges a capacitor C_1 whenever the voltage across a resistor R drops below V_{in} minus the threshold voltage of the rectifier SCR_1 . Whenever the rectifier SCR_1 is triggered, it triggers a second silicon controlled rectifier SCR_2 , and the rectifier SCR_2 discharges a capacitor C_2 . The capacitor C_2 is continuously charged by a constant current I which flows from the collector of a current source transistor T_1 . A peak detector transistor T_2 samples and holds the maximum voltage developed across the capacitor C_2 and presents this voltage as an output voltage V_{out} which is given by:

$$V_{out} = \frac{RC_1}{C_2} \ln \left[\left(\frac{V_{in}}{B+} \right)^I \right] \quad (5)$$

Hence, V_{out} is proportional to the logarithm of V_{in} . Both $B+$ and I can be used as additional input variables, if desired.

FIGS. 6 and 7 disclose an audio peak reading decibelmeter which includes a voltage-time-voltage log conversion circuit. The decibelmeter output meter has a scale that is calibrated linearly in decibels. The input range of this meter is from one millivolt to ten volts, or 80 decibels full scale. The decibelmeter rectifier and logarithmic conversion circuits can handle only a 30 decibel range of signals, so automatic amplifier gain changing circuits keep the signal supplied to the rectifier and logarithmic conversion circuits within the proper range. When the amplifiers are operating at low gain, they generate D.C. correction signals for the output meter. These correction signals add to the meter reading the same number of decibels as the amplifiers subtract from the meter reading when the amplifiers switch to low gain. The meter thus gives the same reading regardless of the amplifier gain settings.

FIG. 7 is a simplified schematic diagram of the rectifier and logarithmic conversion circuits used in the decibelmeter shown in FIG. 6. Normally a first switch S_1 is closed, and normally second and third switches S_2 and S_3 are open, as shown. A diode D_1 charges a capacitor C_1 to the peak positive value of an incoming signal V_x , and a diode D_2 charges a capacitor C_2 to the peak negative value of the incoming signal V_x . Once every tenth of a second, a bistable multi-vibrator momentarily closes the third switch S_3 to discharge the output capacitor C_3 and triggers a one-shot multivibrator. The one-shot multivibrator opens the first switch S_1 and thus disconnects the diodes D_1 and D_2 from the incoming signal V_x . The one-shot multivibrator then closes the second switch S_2 . When the second switch S_2 is closed, the capacitors C_1 and C_2 are interconnected in such a manner that the peak-to-peak value of the signal V_x is applied to a resistor R . From this point on, the circuit functions in exactly the same manner as the circuit shown in FIG. 4. A comparator allows a constant current I to charge the output capacitor C_3 until the voltage across the resistor R falls below a reference voltage level V_{ref} . The voltage across the capacitor C_3 is then the logarithm of the peak-to-peak value of V_x . This whole process takes about a millisecond. The one-shot multivibrator then opens the second switch S_2 and closes the first switch S_1 so that the circuit returns to its normal state.

This circuit is able to follow signal level increases and decreases in a tenth of a second or less, yet it has a frequency response that is absolutely flat down to 20 Hz. The circuit response time is so fast that an oscilloscope or oscillograph is required to give an accurate record of the output signal fluctuations. This decibelmeter can easily follow the envelopes of audio speech patterns.

A simple antilogarithmic conversion circuit is shown in FIG. 8. This circuit is almost identical to the logarithmic conversion circuit shown in FIG. 4. The one difference is that the resistor R and the current source I are interchanged so that the voltage-time conversion is linear and the time-voltage conversion is antilogarithmic. The final voltage V_4 across the capacitor C_2 is given by:

$$V_4 = V_2 \exp \left[\left(\frac{C_1}{RC_2} \right) \left(\frac{V_3 - V_1}{I} \right) \right] \quad (6)$$

V_2 and I can be used as input variables if desired.

If the basic logarithmic conversion circuit shown in FIG. 4 is modified by the substitution of a resistor for the constant current source, it becomes a powerful basic computation circuit that can multiply, divide, find powers, and extract roots. FIG. 9 shows the circuit modified in this manner. The circuit operates in exactly the same way as the circuits described above. Initially the switches S_3 and S_4 are both open. The switches S_1 and S_2 are both closed momentarily so that the capacitors C_1 and C_2 are respectively charged to voltage levels V_1 and V_2 . The switches S_3 and S_4 are then simultaneously closed. When the voltage across the capacitor C_1 drops to the voltage level V_3 , a comparator opens the switch S_4 . The final voltage V_4 across the capacitor C_2 is then:

$$V_4 = V_2 \left(\frac{V_3}{V_1} \right)^K \quad \text{where} \quad \frac{R_1 C_1}{R_2 C_2} = K \quad (7)$$

By selecting the proper voltages as independent input variables, this circuit can be made to perform multiplication, division, or reciprocation. By selecting an appropriate value for the constant K, this circuit can also be adapted to calculate powers or roots. The one limitation is that the input voltages must never change sign, a limitation which is inherent in all logarithmic calculators.

Table 1 illustrates various ways in which the simple circuit shown in FIG. 9 can be used to perform the computations listed above.

Table 1

Computation	Independent Variables	Value of K	Held Constant
A×B	A=V ₂ , B=V ₃	K=1	V ₁
A/B	A=V ₂ , B=V ₃	K=1	V ₃
A/B	A=V ₂ , B=V ₁	K=1	V ₂
1/A	A=V ₁	K=1	V ₂ V ₃
(A) ^x [x>0]	A=V ₁	K=x	V ₁ V ₂
(A) ^x [x<0]	A=V ₁	K=-x	V ₂ V ₃
A(B/C) ^x [x>0]	A=V ₂ , B=V ₃ C=V ₁	K=x	None

FIG. 10 is a schematic diagram of an instantaneous pulse frequency meter which utilizes a voltage-time-voltage computational circuit to calculate the reciprocal of a voltage. Since instantaneous pulse frequency is the reciprocal of the time which elapses between successive pulses, instantaneous pulse frequency can be calculated by measuring the time interval between successive pulses and by then calculating the reciprocal of this time interval. The simple circuit shown in FIG. 10 performs this calculation each time a new pulse is received and thus calculates and presents the instantaneous pulse frequency at the fastest possible rate. The time between successive pulses is measured by the amount of a constant current I₁ which flows into a capacitor C₁. Whenever a pulse occurs, first a transistor T₁ discharges an output capacitor C₂, and then a transistor T₂ clamps to ground the end of the capacitor C₁ that was receiving the current I₁. The capacitor C₁ immediately discharges exponentially through resistors R₁ and R₂ towards a rest potential level slightly positive of ground. Simultaneously, a comparator transistor T₃ becomes non-conductive and permits the output capacitor C₂ to charge exponentially through a diode D and a resistor R₂ towards a voltage level defined by a Zener diode D₂. When the voltage across R₁ goes slightly positive, the transistor T₃ becomes conductive and stops the flow of current into the capacitor C₂ by back biasing the diode D. The voltage across C₂ is then inversely proportional to the time between the adjacent pulses, or directly proportional to the instantaneous pulse frequency. A field effect transistor presents the voltage across C₂ to the circuit output for display on an oscilloscope. As in some of the logarithmic conversion circuits described above, when the input frequency range of this circuit is increased, the accuracy of the measurement is decreased, and vice versa. A tradeoff can thus be achieved between range and accuracy.

The basic concept underlying all of the above circuits is that of logarithmic transformation between what can be called the linear voltage domain and the logarithmic time domain. Since addition and subtraction in the logarithmic time domain are equivalent to multiplication and division in the linear voltage domain, voltage-time-voltage circuits can be designed which will perform almost any arithmetic computation. Addition and subtraction are performed in the linear voltage domain by addition and subtraction of voltages, and multiplication, division, reciprocation, and exponentiation are performed in the logarithmic time domain by addition and subtraction of time intervals. Exponential decay circuits, comparators, and switches are used to convert from one domain to the other

whenever necessary. Logarithmic and antilogarithmic conversions are carried out by using constant current capacitor discharge circuits to perform the transformation from one domain to the other, as explained above. Constant current capacitor discharge circuits can also be used to calculate powers and roots when the exponent is a variable, as was also noted above. Circuits can thus be designed which will perform any computation requiring addition, subtraction, multiplication, division, or exponentiation.

It remains to be explained just how addition in the logarithmic time domain is performed. For convenience, let the left half of FIG. 9 be defined as a voltage-time logarithmic conversion circuit and the right half of FIG. 9 be defined as a time-voltage antilogarithmic conversion circuit. Addition in the logarithmic time domain is performed by connecting the comparator of a first voltage-time logarithmic conversion circuit to the discharge switch of a second voltage-time logarithmic conversion circuit. The time required for both the circuits to discharge sequentially after closure of the discharge switch in the first circuit is then the sum of the individual circuit discharge times. Any number of voltage-time logarithmic conversion circuits may be interconnected in this manner, and a single time-voltage antilogarithmic conversion circuit may be used to measure the total time it takes all the voltage-time logarithmic conversion circuits to discharge. In this manner, any calculation of the form

$$V_1 = V_2 \left(\frac{V_3}{V_4} \right)^A \left(\frac{V_5}{V_6} \right)^B \quad (8)$$

is carried out by addition in the logarithmic time domain.

FIG. 11 illustrates such a combination of voltage-time circuits R₁C₁, R₂C₂, and R₃C₃ used with a single time-voltage circuit R₄C₄. The switches S₁, S₂, S₃ and S₇ are closed momentarily to charge the capacitors C₁, C₂, C₃, and C₄, respectively, to voltage levels V₁, V₂, V₃ and V₇. The switch S₂ is then closed, initiating the discharge of the capacitor C₁ through R₁. When the voltage across the capacitor C₁ equals V₂, a comparator X closes the switch S₄ and initiates the discharge of C₂ through R₂, and so on. Ultimately, the final voltage V₈ left across the capacitor C₄ is given by:

$$V_8 = V_7 \left(\frac{V_2}{V_1} \right) \left(\frac{V_4}{V_3} \right) \left(\frac{V_6}{V_5} \right)^{K_3} \quad (9)$$

$$K_1 = \frac{R_1 C_1}{R_4 C_4} \quad K_2 = \frac{R_2 C_2}{R_4 C_4} \quad K_3 = \frac{R_3 C_3}{R_4 C_4}$$

Since voltage-time-voltage computation circuits can calculate powers, an array of such circuits can perform a power series transformation of the type

$$V_{out} = \left(\frac{A-3}{V_{in}^3} \right) + \left(\frac{A-2}{V_{in}^2} \right) + \left(\frac{A-1}{V_{in}} \right) + A_0 + A_1 V_{in} + A_2 V_{in}^2 + A_3 V_{in}^3 \quad (10)$$

FIG. 12 shows such an array. A common voltage-time logarithmic conversion circuit R₁*C₁* is used for all the computation circuits, and each computation circuit has its own time-voltage antilogarithmic conversion circuit. The circuit outputs are multiplied by appropriate fixed constants and are summed to form V_{out}. V_{in} is required to remain between an upper threshold voltage V_{LT} and a lower threshold voltage V_{LT}.

Initially, all the circuit capacitors are charged by a momentary closure of the circuit charging switches. The capacitor C₁* is then discharged through the resistor R₁*. During the period of time when the voltage across the capacitor C₁* is between the upper threshold voltage V_{LT} and the input voltage V_{in}, a pair of comparators A and B enable a first array of two time-voltage antilogarithmic conversion circuits to calculate the values of (V_{in}²) (B+) (V_{LT}⁻²) and (V_{in}³) (B+) (V_{LT}⁻³). During the period of time when the voltage across the capaci-

tor C_1 is between V_{in} and the lower threshold voltage V_{LT} , the comparator B and a third comparator C enable a second array of three time-voltage antilogarithmic conversion circuits to calculate the values of $(V_{in}^{-1}) (B+)$ (V_{LT}), $(V_{in}^{-2}) (B+)$ (V_{LT}^2), and $(V_{in}^{-3}) (B+)$ (V_{LT}^3). These calculated values, plus the actual value of V_{in} and of $B+$, are then multiplied by the appropriate fixed constants as indicated in the figure and are summed to form V_{out} . The multiplications by fixed constants and the summing are performed by conventional analogue computer circuitry. For example, the voltage developed across each capacitor can be first passed through a conventional unity gain, high impedance amplifier; inverted, if the sign of the multiplication constant so requires, by a conventional unity gain inverting amplifier; and then fed into the input node of a conventional analogue computer summing amplifier through a resistor whose ohmic value is proportional to the size of the multiplication constant.

While only a few voltage-time, time-voltage, and voltage-time-voltage non-linear computational circuits have been presented, it is to be understood that numerous other computational circuits embodying the same basic inventive concepts can be constructed. In addition, while only a single form of exponential decay circuit has been used in the circuits presented, it is to be understood that any exponential growth or decay circuit can be used in the construction of such circuits. In regard to the particular circuits presented, it is to be understood that numerous modifications and changes will occur to those skilled in the art which still fall within the scope of the invention. It is therefore intended that the appended claims cover all computational circuits, combinations of computational circuits, exponential growth circuits, exponential decay circuits, modifications, and changes as come within the true spirit and scope of the present invention.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A computational circuit comprising:
an exponential circuit;
initializing means for placing said exponential circuit in an initial state; and
timing means for measuring the time interval which is required for said exponential circuit to change from said initial state to a specified final state, said timing means comprising a capacitor, a source of charging current for said capacitor, a gate controlling the flow of charging current to said capacitor, and comparator means for closing said gate when the state of said circuit is between said initial and said final states and for opening said gate when the state of said circuit is beyond said final state;
whereby said time interval, as indicated by the charge on said capacitor, is proportional to the logarithm of said initial and final states.
2. A computational circuit in accordance with claim 1 wherein the exponential circuit is a resistor connected to a capacitor.
3. A computational circuit comprising:
an exponential circuit;
initializing means for placing said exponential circuit in an initial state; and
timing means for measuring the time interval which is required for said exponential circuit to change from said initial state to a specified final state, said timing means comprising
a second exponential circuit, second initializing means for placing said second circuit in a second initial state simultaneously with the initializing of said first circuit, and comparator means including state recording means for recording the state of said second circuit when said first circuit reaches said final state;

whereby the recorded state of said second circuit is equal to the second initial state multiplied by the ratio of the initial and final states of the first circuit raised to a power equal to the ratio of the circuit time constants.

4. A computational circuit in accordance with claim 3 wherein the exponential circuits comprise resistances connected to capacitors.

5. A computational circuit comprising:

an exponential circuit including a resistance and a first capacitance;

initializing means for charging said first capacitance to an initial, non-zero state of charge;

switching means for connecting said resistance to said first capacitance; and

time measurement means connected to said switching means for actuating said switching means for a fixed period of time, said time measurement means comprising a second capacitance,

a current source for charging said second capacitance,

second initializing means for giving said second capacitance a first charge state when said exponential circuit is initialized, and

comparator means connecting to said switching means for actuating said switching means for the time it takes the current source to alter the charge on said second capacitance from the first charge state to a second charge state;

whereby the charge remaining on said first capacitance after operation of the time measurement means is proportional to the initial first capacitance charge multiplied by the antilogarithm of the time interval.

6. A computational circuit comprising:

an exponential circuit;

initializing means for placing said exponential circuit in an initial, non-zero state;

state recording means for recording the final state of said circuit; and

time measurement means energized when said exponential circuit is initialized for energizing said state recording means after a fixed period of time elapses following the initialization of said circuit, said time measurement means comprising

at least one additional exponential circuit, initializing means for placing each of said additional circuits in a plurality of first states and for energizing a first of said additional circuits simultaneously with the initialization of said original exponential circuit, and

comparator means for sequentially energizing said additional circuits one after another as each reaches a predetermined second state, and for energizing the state recording means when the last additional circuit has reached its predetermined second state.

7. A computational circuit in accordance with claim 6 wherein the exponential circuits comprise resistors connected to capacitors.

8. A nonlinear transformation computational circuit comprising:

at least one voltage time computational circuit means for converting an incoming signal into at least one logarithmically related time interval;

two or more time-voltage computational circuit means having two or more different time constants for converting the time intervals back into a second array of antilogarithmically related signals; and

second signal multiplying and summing means for weighting the second signals by multiplying the second signals by constants and for then summing the weighted second signals to form an output signal.

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