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J. STATSINGER
SIGNAL MULTIPLYING DEVICE

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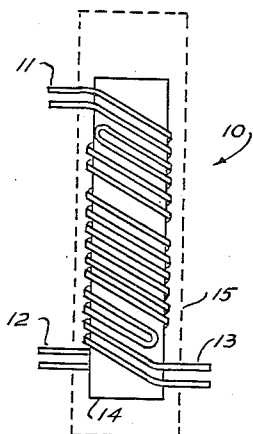


FIG. 1

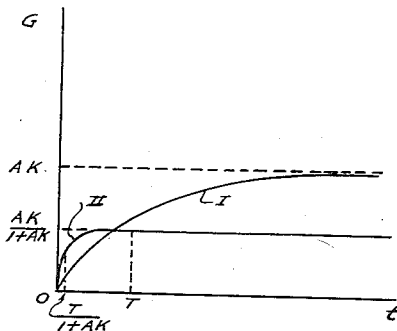


FIG. 3

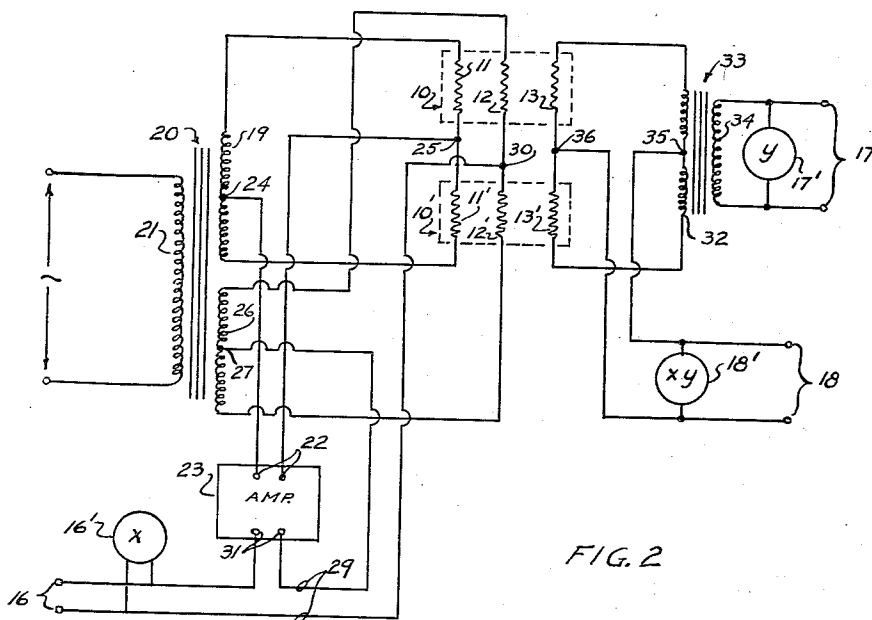


FIG. 2

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SIGNAL MULTIPLYING DEVICE

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This invention relates to a device which produces a voltage whose amplitude is proportional to the product of the amplitudes of two signal voltages without the use of mechanical transformations and moving members for use in computers and the like.

It is believed that in the present invention voltages are multiplied directly with precision for the first time. The usual means of multiplying voltages requires transformation of one signal voltage into a mechanical displacement which is then combined with the second signal to produce the desired product, as in a potentiometer for instance.

The multiplying device of this invention contains two similar thermal units each of which consists of three resistors in close thermal contact, but which are electrically uncoupled. One resistor of each unit is constructed of low temperature coefficient material and is connected in series with the corresponding resistor of the second thermal unit across a center tapped constant voltage supply. The remaining two resistors of each thermal unit are made of high temperature coefficient material. One of the high temperature coefficient resistors of one thermal unit is connected in series with the corresponding resistor of the other thermal unit across a center tapped voltage supply whose amplitude is proportional to one multiplier, y .

An input voltage whose amplitude is proportional to the other multiplier x , applied between the junction of the low temperature coefficient resistors and the center tap of their voltage supply, creates an unbalance in the temperatures of the thermal units as a result of the difference in the current through the low temperature coefficient resistors. The resistance values of the high temperature coefficient resistors are thereby unbalanced so that an output voltage is produced between the junction of the high temperature coefficient resistors and the center tap of their voltage supply which corresponds, in amplitude, to the product of their excitation voltage amplitude and the temperature difference, or corresponds to xy .

For practical application in computer circuits the time constant of the device thus far described is too long. To reduce the time constant the third resistor of one thermal unit is connected in series with the corresponding resistor of the other thermal unit across a constant center tapped voltage supply of the same frequency as the voltage supply for the low temperature coefficient resistor, and the voltage developed between the junction of the resistors and the center tap of the power supply is fed back degeneratively to the input. This results in a reduction of the time required for the temperature difference of the thermal units to reach the steady state and therefore reduces the time constant of the device.

Another equally important reason for use of the degenerative feedback is the improvement provided thereby in the linearity of response, so that the output voltage is truly proportional to the product xy .

For a more complete understanding of the invention

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reference may be had to the accompanying diagram, in which:

Fig. 1 is a schematic representation of the basic thermal unit;

Fig. 2 is a schematic wiring diagram of the multiplying device; and

Fig. 3 shows two typical curves illustrating the operation of the thermal unit with and without feedback.

In the preferred embodiment of this invention, as herein described, the signal voltages and constant voltage supply are alternating voltages, although direct current power supplies and signals can be used. Thus, the description should not be construed as limiting the invention to the use of alternating voltage supplies.

The basic thermal unit 10 shown in Fig. 1 of the drawings is composed of three resistors 11, 12, 13 wound non-inductively on a non-magnetic core 14, such as ceramic for instance, enclosed within case 15 which may be evacuated. Resistor 11 is constructed of low temperature coefficient material while resistors 12, 13 are made of high temperature coefficient material. Resistors 11, 12, 13 are electrically uncoupled but are in close thermal contact so that the temperature of resistors 12, 13 is always exactly equal to the temperature of resistor 11, as nearly as practicable.

Figure 2 shows two similar thermal units 10, 10' electrically connected so as to form a computing circuit in which signal voltages whose amplitudes are proportional to x and y are applied to terminals 16 and 17 respectively and a signal voltage whose amplitude is proportional to xy , the product of x and y , is available at terminals 18. The values x , y , and xy may be read respectively on the scales of voltmeters 16', 17' and 18'.

Similar resistors 11, 11' of thermal units 10, 10' are connected in series across secondary winding 19 of transformer 20, the primary winding 21 of which is supplied with a constant alternating voltage.

The output terminals 22 of voltage amplifier 23 which is of any standard design are connected between center tap 24 of secondary winding 19 and junction 25 of resistors 11, 11'.

Resistors 12, 12', similar to each other, are connected in series with secondary winding 26 of transformer 20, the center tap 27 of which is connected to one of the terminals 29 while the junction point 30 of resistors 12, 12' is connected to the other of terminals 29.

Terminals 16 are connected in series with terminals 29 and the input terminals 31 of amplifier 23 so that the amplitude of the voltage at terminals 31 is the algebraic difference of the amplitudes of the voltages at terminals 16 and 29.

In operation, the voltage output of secondary winding 26 is small so that no self-heating of resistors 12, 12' occurs due to the current through these resistors. With zero signal at terminals 22, thermal units 10, 10' are heated to the same temperature since the same current flows in resistors 11, 11' due to the output voltage of secondary winding 19. There is, therefore, no signal at terminals 29 since the voltage drop across resistor 12 is equal to the drop resistor 12'.

Assume for the moment that terminals 29 are disconnected from terminals 31, 16, and that terminals 16 are connected directly to input terminals 31 of amplifier 23.

An input signal at terminals 16 of the same frequency as the supply voltage to primary winding 21 and having an amplitude proportional to the multiplier x results in a proportional voltage being applied between terminals 22. This voltage causes current to flow through the resistors 11, 11' which adds to the current in the resistor due to the constant voltage of secondary winding 19 in one of the resistors and subtracts from that current in the other resistor. Thus the signal voltage at terminals 16 causes

more current to flow in one resistor, resistor 11 for example when in phase with the voltage across resistor 11, and less current to flow in resistor 11'. The temperature of resistor 11 therefore increases and the temperature of resistor 11' decreases, the difference in temperature increasing substantially exponentially to a value proportional to the multiplier x . If the voltage at terminals 22 should be out of phase with the voltage of secondary winding 19 by an angle ϕ , the resulting quadrature component of current produces no heating in the resistors so that the temperature difference of resistors 11 and 11' will be proportional to the in-phase component, $X \cos \phi$. Considerable phase difference can be tolerated, although it will be assumed here that ϕ is zero.

The temperature difference of resistors 11, 11' causes an identical temperature difference of resistors 12, 12' and therefore a proportional difference in the resistance values of resistors 12, 12'. A voltage appears between terminals 27, 30 since there is a greater voltage drop across resistor 12 than across resistor 12' (for the assumed phase of the input signal) and the amplitude of this voltage between terminals 27, 30 corresponds to x in the steady state condition.

The gain, G , or the ratio between the signal amplitude at terminals 27, 30 and the signal amplitude at terminals 16, is derived from an electrical analog of the thermal unit. If the heat energy supplied to the unit is considered as being partly stored in heating the unit and partly lost through dissipation by radiation, for example, the unit can be compared to a parallel connected capacitance and resistance circuit connected to a step current source, where the energy supplied is partly stored by charging the capacitor and is partly lost in the resistor. The charging of the condenser is evidenced by a rising voltage across the condenser (or resistance). If such electrical circuit is supplied by a constant current i , the voltage drop E_r across the resistor and capacitor follows the exponential curve

$$E_r = iR \left(1 - e^{-\frac{1}{CR}t} \right)$$

Similarly, the absorption of heat energy by the thermal unit is evidenced by a change in the temperature according to the analogous relationship

$$Temp = K'Hi \left(1 - e^{-\frac{1}{T}t} \right)$$

Where $Temp$ is the temperature of the unit

Hi is the heat energy input

T is the time constant

K' is a proportionality factor

It can be shown that the heat energy input to the device of Fig. 2 is proportional to the magnitude of the voltage E_{22} at terminals 22, and that the output voltage E_o between terminals 30 and 27 is proportional to the difference between the temperatures of units 10 and 10'. It follows then that

$$E_o = KE_{22} \left(1 - e^{-\frac{1}{T}t} \right)$$

Since E_{22} is proportional to A times E_i where A is the gain of amplifier 23 and E_i is the amplitude of the input signal to amplifier 23, it may be written that

$$\frac{E_o}{E_i} = G_1 = AK \left(1 - e^{-\frac{1}{T}t} \right)$$

This equation may also be expressed as

$$G_1 = \frac{AK}{1+DT}$$

in which the ratio

$$\frac{AK}{1+DT}$$

is a differential operator indicating an exponential rise in the output voltage for a step voltage input signal where A is the voltage gain of amplifier 23, K is the ratio between the amplitudes of the signals at terminals 27, 30 and terminals 24 in the steady state, T is a constant, commonly referred to as the time constant, and D is the differential operator d/dt . The curve representing the rise of the output voltage according to this relationship is shown as curve I of Figure 3. At the present time the lowest obtainable value of T in practical construction has been on the order of 3 seconds, making the response of the unit as described too slow for those computers or such other devices which can tolerate only a short time delay.

The voltage developed between terminals 27, 30 is therefore fed back degeneratively to the input of amplifier 23 as shown in Fig. 2, to reduce the time constant of the circuit. This may be shown most easily in the following manner: The voltage gain of the device between terminals 16 and 29 without feedback has been expressed as $G = AK/1+DT$. It is well known that with 100% degenerative feedback the gain becomes

$$G' = \frac{G}{1+G}$$

or $(AK/1+DT)/(1+(AK/1+DT))$. This may be reduced algebraically to

$$(AK/1+AK)/(1+(DT/1+AK))$$

which shows that while the new gain G' is close to unity in the steady state (since $AK/1+AK \approx 1$ if AK is much greater than one), the time constant has been materially reduced to $T/1+AK$. The exponential curve corresponding to these values is shown as curve II in Figure 3.

It is well known that negative feedback also decreases the distortion which may be present in the output signal without feedback, so that the difference in temperature between the units 10, 10' is proportional to the magnitude of the input signal.

Evidently the increase in the temperature difference of units 10, 10' may be represented by a curve similar to II which, therefore, also describes the increase in the temperature difference between resistors 13, 13'.

Similar resistors 13, 13' are connected in series across secondary winding 32 of transformer 33, the primary winding 34 of which is energized by a voltage whose amplitude is proportional to the multiplier y . The center tap 35 of secondary winding 33 and the junction point 36 of resistors 13, 13' are connected to output terminals 18 across which voltmeter 18' is connected.

Since resistors 13, 13' are in close thermal contact with resistors 12, 12' they are at different temperatures, and their resistances are of different values so that the voltage drop across resistor 13 for the previously assumed phase of x is greater than that across resistor 13'. Furthermore since the resistance of the resistors 13, 13' varies directly with their temperature, a voltage appears at terminals 18 which is proportional in amplitude to the temperature difference of resistors 13, 13' for a constant excitation voltage energizing transformer winding 34. It has been shown that the difference in temperature of the units 10, 10' and resistors 13, 13' is proportional to x so that the voltage produced at terminals 18 is consequently proportional to x . However, the voltage at terminals 18 is also proportional to the amplitude of the voltage across winding 34 which is proportional to the multiplier y . The voltage at terminals 18 is, therefore, proportional to the product of the two controlling influences, viz the temperature difference of resistors 13, 13' and the voltage at winding 34, or is proportional to the product of x and y . This can be shown mathematically as follows:

For a voltage y at winding 32, the current I through resistors 13, 13' is

$$I = \frac{y}{R+R'}$$

Where R and R' are the resistance of resistors 13 and 13' respectively. The voltage E_{18} between center tap 35 and junction 36 is equal to $\frac{1}{2}$ the voltage at winding 32 less the voltage drop in resistor 13. Thus:

$$E_{18} = \frac{y}{2} - IR = \frac{y}{2} - \left(\frac{y}{R+R'} \right) R$$

$$E_{18} = \frac{y}{2} \left[1 - \frac{2R}{R+R'} \right] = \frac{y}{2} \left[\frac{R'-R}{R'+R} \right]$$

However

$$\frac{R'-R}{R'+R}$$

is proportional to x , so that

$$E_{18} \propto \frac{xy}{2}$$

Inspection of curve II Fig. 3 shows that the xy signal at terminals 18 is not obtainable after a time interval equal to the time constant but that more time must elapse before the correct answer (i. e. the steady state) is obtained. For accuracy within one percent the necessary time interval is approximately 4.6 times the time constant, while for accuracy within $\frac{1}{10}$ of one percent the required time interval is about 7 times the time constant. (These are derived mathematically from the equation for the exponential curve.)

It is expected that the time constant of the device (with feedback, as in Fig. 2) can be made to approach .02 second so that considerable accuracy is obtained after an elapsed time of about .15 second.

The phase of the voltage at terminals 18 is dependent on the relative phases of the signals at terminals 16, 17. The phase of the voltage at terminals 18 may be considered "positive" when signals corresponding to multipliers x , y of like signs are applied to terminals 16, 17, and for signal inputs corresponding to multipliers x , y of opposite signs the phase of the output signal at terminals 18 is of "negative" phase. The frequency of the output signal is determined by the frequency of the signal voltage supplied to terminals 17.

It will be seen that the invention herein disclosed has much wider application than the multiplying circuit described. For example, it may be used as a frequency changer by supplying a constant voltage to terminals 17 of the desired output frequency; in this instance its use may be extended to demodulation by using alternating current on the input side and direct current in the output circuit.

I claim:

1. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units electrically connected to said inputs and said output, each of said units having three resistors in close thermal contact with each other, one resistor of each unit being constructed of low temperature coefficient of resistance material, the other two resistors of each unit being of high temperature coefficient of resistance material, said resistor of each unit of low temperature coefficient of resistance material being connected in series with the corresponding resistor of the other unit, one of said high temperature coefficient resistors being connected in series with the corresponding resistor of the other unit and the third resistor of one unit being connected in series with the corresponding resistor of the other unit.

2. In a device of the character described, an electrical circuit having a pair of inputs and an output and said circuit including a pair of similar thermal units, each of said units having three resistors in close thermal contact with each other, one resistor of each unit being constructed of low temperature coefficient of resistance material, a constant voltage power supply for said low temperature coefficient of resistance resistors, the other two resistors of each unit being of high temperature coefficient

of resistance material, a second constant voltage power supply and a third variable power supply for said two resistors, said resistor of each unit of low temperature coefficient of resistance material being connected in series

5 with the corresponding resistor of the other unit, one of said high temperature coefficient of resistance resistors being connected in series with the corresponding resistor of the other unit and the third resistor of one unit being connected in series with the corresponding resistor of the other unit across said second constant center tapped voltage supply of the same frequency as the first voltage supply for the low temperature coefficient of resistance resistors, the voltage developed between the junction of the third named resistors and the center tap of the second

10 power supply being fed back degeneratively to one of said inputs, the difference between said developed voltage and the voltage at said one input being used to modify the effect of said first named constant voltage power supply on said low temperature coefficient of resistance resistors.

3. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units electrically connected to said inputs and said output, said units each consisting of three resistors in close thermal contact with each other but electrically uncoupled, one resistor of each unit being constructed of low temperature coefficient of resistance material and being connected in series with the corresponding resistor of the other unit across a center tapped constant voltage supply, the other two resistors of each unit being of high temperature coefficient of resistance material and one of said high temperature coefficient of resistance resistors of one unit being connected in series with the corresponding resistor of the other unit across a center tapped voltage supply, and the other of said resistors being connected in series with the corresponding resistor of the other unit across a constant center tapped voltage supply of the same substantial frequency as the voltage supply for the low temperature coefficient resistors.

4. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units electrically connected to said inputs and said output, said units each consisting of three resistors in close thermal contact but electrically uncoupled, one resistor of each unit being constructed of low temperature coefficient of resistance material and being connected in series with the corresponding resistor of the other unit across a center tapped constant voltage supply, the other two resistors of each unit being of high temperature coefficient of resistance material and one of said high temperature coefficient of resistance resistors of one unit being connected in series with the corresponding resistor of the other unit across a center tapped voltage supply, and the other of said resistors being connected in series with the corresponding resistor of the other unit across a constant center tapped voltage supply of the same substantial frequency as the voltage supply for the low temperature coefficient resistors, the voltage developed between the junction of the third named resistors and the center tap of the third named power supply being fed back degeneratively to said input.

5. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units electrically connected to said inputs and said output, each of said units consisting of a plurality of resistors in close thermal contact with each other, one resistor of each unit being connected in series with a corresponding resistor of the other unit across one of said center tapped constant voltage supplies, another resistor of said first unit being connected in series with a corresponding resistor of the other unit across said center tapped variable voltage supply provided by the voltage at one of said inputs whose amplitude is proportional to one multiplier, the amplitude of the voltage

at the other of said inputs being proportional to the other multiplier, a third resistor connected in series with the corresponding resistor of the other unit across the other of said constant center tapped voltage supplies, the amplitude of the voltage at said output being proportional to the product of the amplitudes of the voltages at said input.

6. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units electrically connected to said inputs and said output, each of said units consisting of a plurality of resistors in close thermal contact with each other, a pair of center tapped constant voltage supplies of the same frequency, a center tapped variable voltage supply, one resistor of each unit being connected in series with a corresponding resistor of the other unit across one of said center tapped constant voltage supplies, another resistor of said first unit being connected in series with a corresponding resistor of the other unit across said center tapped variable voltage supply provided by the voltage at one of said inputs whose amplitude is proportional to one multiplier, the amplitude of the voltage at the other of said inputs being proportional to the other multiplier, a third resistor connected in series with the corresponding resistor of the other unit across the other of said constant center tapped voltage supplies of the same frequency as the voltage supply for the first named resistors, the voltage developed between the junction of the third named resistors and the center tap of the third named power supply being fed back degeneratively to said input, the amplitude of the voltage at said output being proportional to the product of the amplitudes of the voltages at said input.

7. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units, each of said units including a plurality of resistors in close thermal contact with each other but electrically uncoupled, a pair of center tapped voltage supplies of the same frequency, a center tapped variable voltage supply, one resistor of each unit being of low temperature coefficient of resistance and being connected in series with the corresponding resistor of the other unit across one of said center tapped constant voltage supplies, two additional resistors of each unit being of high temperature coefficient of resistance and one of said resistors of one unit being connected in series with the corresponding resistor of the other unit across said center tapped variable voltage supply whose amplitude is proportional to one multiplier, the amplitude of the voltage of one of said inputs being proportional to the other multiplier, said input voltage being applied between the junction of the low temperature coefficient of resistance resistors and the center tap of their voltage supply, the third resistor of one unit being connected in series with the corresponding resistor of the other unit across said constant center tapped voltage supply of the same frequency as the voltage supply for the low temperature coefficient of resistance resistors a high gain amplifier interposed in the connections between one of said inputs and said connections to said low temperature coefficient of resistance resistors and a center tap on the corresponding power supply.

8. In a device of the character described, an electrical circuit having a pair of inputs and an output and a pair of similar thermal units, each of said units including a plurality of resistors in close thermal contact with each other but electrically uncoupled, a pair of center tapped voltage supplies of the same frequency, a center tapped variable voltage supply, one resistor of each unit being of low temperature coefficient of resistance and being connected in series with the corresponding resistor of the other unit across one of said center tapped constant voltage supplies, two additional resistors of each unit being of high temperature coefficient of resistance and one of said resistors of one unit being connected in series

with the corresponding resistor of the other unit across said center tapped variable voltage supply whose amplitude is proportional to one multiplier, the amplitude of the voltage of one of said inputs being proportional to the other multiplier, said input voltage being applied between the junction of the low temperature coefficient of resistance resistors and the center tap of their voltage supply, the third resistor of one unit being connected in series with the corresponding resistor of the other unit across said constant center tapped voltage supply of the same frequency as the voltage supply for the low temperature coefficient of resistance resistors, and the voltage developed between the junction of the third named resistors and the center tap of the third named power supply being fed back degeneratively to said input a high gain amplifier interposed in the connections between one of said inputs and said connections to said low temperature coefficient of resistance resistors and a center tap on the corresponding power supply.

9. In a device of the character described, an electrical circuit having a pair of inputs and an output, a pair of similar thermal units, each of said units having three resistors in close thermal contact, one resistor of each unit being constructed of low temperature coefficient of resistance material; the other two resistors of each unit being of high temperature coefficient of resistance material, means for differentially energizing said low temperature coefficient of resistance resistors according to one input; means for energizing one of said high temperature coefficient of resistance resistors of each of said thermal units according to the other input, connections between said output and said other input and said energized high temperature coefficient of resistance resistors, means for energizing said remaining high temperature coefficient of resistance resistors with a constant voltage, feed-back connections between said remaining high temperature coefficient of resistance resistors and said one input.

10. In a device of the character described, an electrical circuit having a pair of inputs and an output, a pair of similar thermal units, each of said units having three resistors in close thermal contact with each other, one resistor of each unit being constructed of a low temperature coefficient of resistance material, the other resistors of each unit being constructed of a high temperature coefficient of resistance material, a pair of center tapped constant voltage supplies of the same frequency, one of said resistors of each unit of low temperature coefficient of resistance material being connected in series with the corresponding resistor of the other unit across one of said constant voltage supplies, the second of said resistors of each unit of high temperature coefficient of resistance material being connected in series with a corresponding resistor of the other unit across the other of said constant voltage supplies, a third center tapped voltage supply variable according to the other input, the third of said resistors of each unit of high temperature coefficient of resistance material being connected in series with the corresponding resistor of the other unit across said third voltage supply, connections between the input and said first and second voltage supplies and said first and second resistors, connections between the output and said third voltage supply and said third resistors.

11. A thermal multiplier including in combination a pair of resistors and circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, thermal means for varying the resistance of one of the pair of resistors with respect to the resistance of the other of the pair of resistors in accordance with a first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

12. A thermal multiplier including in combination a pair of resistors and circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, thermal means for increasing the resistance of one of the pair of resistors and for decreasing the resistance of the other of said pair of resistors in accordance with a first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

13. A thermal multiplier including in combination a pair of resistors and circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, thermal means for increasing the resistance of one of the pair of resistors and for decreasing the resistance of the other of said pair of resistors in accordance with a first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge, the temperature coefficients of resistance of the resistors and their resistances being equal and the impedance values of the circuit coupling means being equal.

14. A thermal multiplier including in combination a pair of resistors and circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, heating resistor means, means for positioning one of the resistors of the pair in heat-exchange relation with the heating resistor means, means for heating the heating resistor means in accordance with a first voltage to unbalance the bridge, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

15. A thermal multiplier including in combination a pair of resistors and circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, the resistances and the thermal coefficients of resistance of the resistors being equal, the arms of the bridge containing said circuit coupling means having equal impedances, a pair of heating resistors, means for positioning one of the resistors of the pair of resistors in heat-exchange relation with one of the heating resistors, means for positioning the other resistor of the pair of resistors in heat-exchange relation with the other of said heating resistors, means for heating said heating resistors, means agreeable to a first voltage for increasing the heating of the first heating resistor and for decreasing the heating of the second heating resistor whereby to unbalance the bridge in proportion to said first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

16. A thermal multiplier including in combination a first pair of resistors and circuit coupling means connected in a bridge having a pair of input and a pair of output terminals, a second pair of resistors and a second coupling means connected in a second bridge having a pair of input terminals and a pair of output terminals, heating resistor means, means for impressing a constant voltage across the input terminals of the second bridge, means for impressing the output voltage of the second bridge and a first voltage in series across the heating resistor means, means for positioning one of the resistors of the first pair and one of the resistors of the second pair in heat-exchange relation with said heating resistor means, whereby to unbalance the second bridge to bring its output voltage equal to the first voltage and opposite in sign and to unbalance the first bridge agreeable to the first voltage, means for impressing a second voltage across the input terminals of the first bridge and means for removing a

voltage representing the product of the first and second voltages from the output terminals of the first bridge.

17. A thermal multiplier including in combination a first pair of resistors equal in resistance and having the same temperature coefficient of resistance, circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, a second pair of resistors equal in resistance and having the same temperature coefficient of resistance and a second coupling means connected in a second bridge having a pair of input terminals and a pair of output terminals, means for impressing a constant voltage across the input terminals of the second bridge, a pair of heating resistors, means for impressing a second constant voltage across the pair of heating resistors whereby to raise their temperatures, means for impressing the output voltage of the second bridge and a first voltage across said heating resistors in push-pull relationship whereby to increase the temperature of one of said heating resistors and decrease the temperature of the other of said heating resistors, means for positioning one of the resistors of the first pair and one of the resistors of the second pair in heat-exchange relation with one of the heating resistors, means for positioning the other of the resistors of the first pair and the other of the resistors of the second pair in heat-exchange relation with the other of said heating resistors whereby to unbalance the second bridge to bring its output voltage to a value equal to the first voltage and opposite in sign and to unbalance the first bridge in proportion to the first voltage, means for impressing a second voltage across the input terminals of the first bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the first bridge.

18. A thermal multiplier including in combination a multiplying bridge, a control bridge and a heating network, said multiplying bridge comprising a first pair of resistors having equal resistances and equal temperature coefficients of resistance and circuit coupling means connected in a bridge having a pair of input terminals and a pair of output terminals, said control bridge comprising a second pair of resistors equal in resistance and having the same temperature coefficient of resistance and a second circuit coupling means connected in a second bridge having a pair of input terminals and a pair of output terminals, said heating network comprising a pair of heating resistors having equal resistances connected in a network with a center tapped secondary winding of a transformer having a primary winding, means for impressing a first constant voltage across the input terminals of the control bridge, means for impressing a second constant voltage across said heating resistors whereby to raise the temperature of said heating resistors, an amplifier having a pair of input terminals and a pair of output terminals, means for connecting the output of the amplifier to the transformer whereby to increase the voltage across one of said heating resistors and decrease the voltage across the other of said heating resistors, means for impressing the output voltage of the control bridge and a first voltage in series across the input terminals of the amplifier whereby to increase the voltage across one of said heating resistors and decrease the voltage across the other of said heating resistors in proportion to said first voltage, means for positioning one of the resistances of the first pair and one of the resistances of the second pair in heat-exchange relation with one of the heating resistors, means for placing the other of the resistors of the first pair and the other of the resistors of the second pair in heat-exchange relation with the other of said heating resistors, the sign of the first constant voltage being such that the thermal unbalancing of the control bridge will be such that its output voltage will be equal to the first voltage and opposite in sign, means for impressing a second voltage across the input terminals of the multiplying bridge, the construction being such that the multi-

plying bridge will be thermally unbalanced proportionally to said first voltage, and means for removing a voltage representing the product of the first and second voltages from the output terminals of the multiplying bridge.

19. A thermal multiplier including in combination a pair of resistors and a center tapped secondary winding of a transformer connected in a bridge having a pair of input terminals and a pair of output terminals, thermal means for varying the resistance of one of the pair of resistors with respect to the resistance of the other of the pair of resistors in accordance with a first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

20. A thermal multiplier including in combination a pair of resistors and a center tapped secondary winding of a transformer connected in a bridge having a pair of input terminals and a pair of output terminals, thermal means for increasing the resistance of one of the pair of resistors and for decreasing the resistance of the other of said pair of resistors in accordance with a first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

21. A thermal multiplier including in combination a pair of resistors and a center tapped secondary winding of a transformer connected in a bridge having a pair of input terminals and a pair of output terminals, thermal means for increasing the resistance of one of the pair of resistors and for decreasing the resistance of the other of said pair of resistors in accordance with a first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge, the temperature coefficients of resistance of the resistors and their resistances being equal and the impedance of both halves of the center tapped secondary winding of said transformer being equal.

22. A thermal multiplier including in combination a first pair of resistors and a center tapped transformer connected in a bridge having a pair of input terminals and a pair of output terminals, heating resistor means, means for heating the heating resistor means in accordance with a first voltage to unbalance the bridge, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

23. A thermal multiplier including in combination a pair of resistors and a center tapped secondary winding of a transformer connected in a bridge having a pair of input terminals and a pair of output terminals, the resistances and the thermal coefficients of resistance of the resistors being equal, the impedance of both halves of the center tapped transformed secondary winding being equal, a pair of heating resistors, means for positioning one of the resistors of the pair of resistors in heat-exchange relation with one of the heating resistors, means for positioning the other resistor of the pair of resistors in heat-exchange relation with the other of said heating resistors, means for heating said heating resistors, means agreeable to a first voltage for increasing the heating of the first heating resistor and for decreasing the heating of the second heating resistor whereby to unbalance the bridge in proportion to said first voltage, means for impressing a second voltage across the input terminals of the bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the bridge.

24. A thermal multiplier including in combination a first pair of resistors and a center tapped secondary wind-

ing of a transformer connected in a first bridge having a pair of input and a pair of output terminals, a second pair of resistors and a second center tapped secondary winding of a transformer in a second bridge having a pair of input terminals and a pair of output terminals, heating resistor means, means for impressing a constant voltage across the input terminals of the second bridge, means for impressing the output voltage of the second bridge and a first voltage in series across the heating resistor means, means for positioning one of the resistors of the first pair and one of the resistors of the second pair in heat-exchange relation with said heating resistor means, whereby to unbalance the second bridge to bring its output voltage equal to the first voltage and opposite in sign and to unbalance the first bridge agreeable to the first voltage, means for impressing a second voltage across the input terminals of the first bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the first bridge.

25. A thermal multiplier including in combination a first pair of resistors equal in resistance and having the same temperature coefficient of resistance, a center tapped secondary winding of a transformer connected in a bridge having a pair of input terminals and a pair of output terminals, a second pair of resistors equal in resistance and having the same temperature coefficient of resistance and a second center tapped secondary winding including a transformer connected in a second bridge having a pair of input terminals and a pair of output terminals, means for impressing a constant voltage across the input terminals of the second bridge, a pair of heating resistors, means for impressing a second constant voltage across the pair of heating resistors whereby to raise their temperatures, means for impressing the output voltage of the second bridge and a first voltage across said heating resistors in push-pull relationship whereby to increase the temperature of one of said heating resistors and decrease the temperature of the other of said heating resistors, means for positioning one of the resistors of the first pair and one of the resistors of the second pair in heat-exchange relation with one of the heating resistors, means for positioning the other of the resistors of the first pair and the other of the resistors of the second pair in heat-exchange relation with the other of said heating resistors whereby to unbalance the second bridge to bring its output voltage to a value equal to the first voltage and opposite in sign and to unbalance the first bridge in proportion to the first voltage, means for impressing a second voltage across the input terminals of the first bridge and means for removing a voltage representing the product of the first and second voltages from the output terminals of the first bridge.

26. A thermal multiplier including in combination a multiplying bridge, a control bridge and a heating network, said multiplying bridge comprising a first pair of resistors having equal resistances and equal temperature coefficients of resistance and a center tapped secondary winding of a transformer connected in a bridge having a pair of input terminals and a pair of output terminals, said control bridge comprising a second pair of resistors equal in resistance and having the same temperature coefficient of resistance and a second center tapped secondary winding of a transformer connected in a second bridge having a pair of input terminals and a pair of output terminals, said heating network comprising a pair of heating resistors having equal resistances connected in a network with a third center tapped secondary winding of a transformer having a primary winding, means for impressing a first constant voltage across the input terminals of the control bridge, means for impressing a second constant voltage across said heating resistors whereby to raise the temperature of said heating resistors, an amplifier having a pair of input terminals and a pair of output terminals, means for connecting the output of the amplifier to the last named transformer whereby to increase the

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voltage across one of said heating resistors and decrease the voltage across the other of said heating resistors, means for impressing the output voltage of the control bridge and a first voltage in series across the input terminals of the amplifier whereby to increase the voltage across one of said heating resistors and decrease the voltage across the other of said heating resistors in proportion to said first voltage, means for positioning one of the resistances of the first pair and one of the resistances of the second pair in heat-exchange with one of the heating resistors, means for placing the other of the resistors of the first pair and the other of the resistors of the second pair in heat-exchange relation with the other of said heating resistors, the sign of the first constant voltage being such that the thermal unbalancing of the control

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bridge will be such that its output voltage will be equal to the first voltage and opposite in sign, means for impressing a second voltage across the input terminals of the multiplying bridge, the construction being such that the multiplying bridge will be thermally unbalanced proportionally to said first voltage, and means for removing a voltage representing the product of the first and second voltages from the output terminals of the multiplying bridge.

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