

May 20, 1969

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3,445,781

TEMPERATURE COMPENSATED TRANSFORMER CIRCUIT

Filed Feb. 23, 1968

Sheet 1 of 2

FIG. 1.

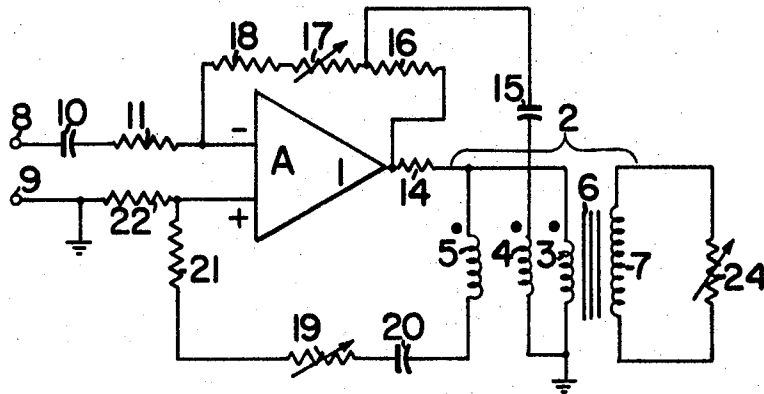


FIG. 2.

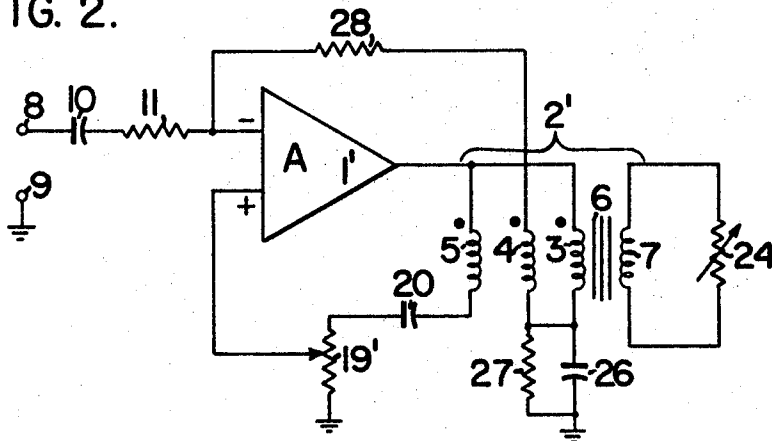


FIG. 3.

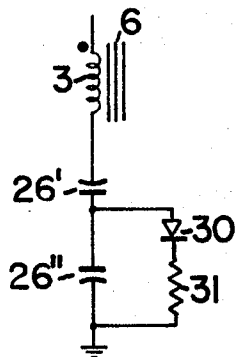
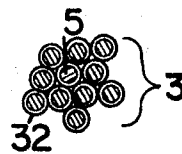


FIG. 4.



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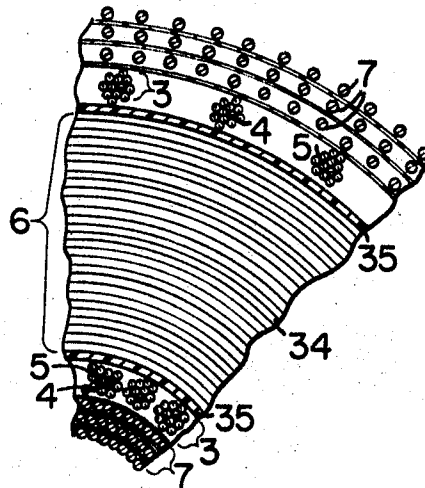
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FIG. 5.



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TEMPERATURE COMPENSATED TRANSFORMER CIRCUIT

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Int. Cl. H03f 1/34, 1/00

U.S. Cl. 330-104

8 Claims

ABSTRACT OF THE DISCLOSURE

A circuit compensating for the variation loss in the secondary of a transformer under load, such as occasioned by changes in temperature. A canceler winding is intimately wound with the primary of the transformer and acts to reduce negative feedback on an amplifier energizing the transformer. Negative feedback may be originated by a tertiary winding also having close coupling to the primary. The resistivity of the wire of the secondary winding with respect to that of the primary is made directly proportional to the ratio of the number of turns of the secondary to the number of turns of the primary. The compensation obtained is independent of the value of the load on the secondary.

Background of the invention

This invention pertains to transformer circuits having means to enhance the stability of the electrical characteristics of the transformer despite variations in ambient operational conditions.

A small segment of the prior art has sought to stabilize the characteristics of transformers so that precision electrical devices employing transformers would be reliable under varied operating conditions. A large segment of the prior art has not sought such precision.

A degree of stability can be obtained for an electrical device as a whole by including all of the output transformer in a negative feedback loop. But this has the opposed disadvantages of instability or of only partial improvement in fidelity, depending upon the degree of feedback employed. These disadvantages stem from changes in the phase of the feedback with frequency and with the reactive characteristic of the load. When the art may have taken feedback from the primary only, the imperfections of the transformer have had to have been accepted.

Summary of the invention

Negative feedback upon an amplifier is employed to excite the primary of an output transformer is provided to obtain desired fidelity of the system to and including the primary winding of the transformer. An additional, canceler, winding is wound with extremely close coupling to the primary winding and loose coupling to the secondary winding. The canceler winding is connected to the amplifier to reduce the amount of negative feedback proportional to the resistance (copper loss) of the primary winding. The copper loss of the secondary winding is made equal to that of the primary. Since the copper loss of the primary is already compensated for by the negative feedback per se, the reduction of the negative feedback by the action of the canceler winding compensates for the copper loss of the secondary. In this way full compensation for the transformer is obtained without incurring the disadvantages of negative feedback taken from the secondary thereof.

Variations in the copper loss of the secondary are automatically compensated for. These include variations of

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both ambient temperature and internal heating of the transformer caused by the flow of load current.

The equivalent internal impedance of the system as viewed from the secondary of the transformer is substantially zero over the operating frequency range of the transformer.

Brief description of the drawings

FIG. 1 is a schematic diagram of a direct current (D.C.) coupled embodiment of this invention.

FIG. 2 is a schematic diagram of an alternating current (A.C.) coupled embodiment of this invention.

FIG. 3 is a fragmentary diagram of an alternate embodiment of that of FIG. 2.

FIG. 4 is a sectional view, greatly enlarged, of a single turn of the composite primary winding of the transformer of this invention.

FIG. 5 is a sectional view, circumferentially fragmentary, of a transformer according to this invention.

Description of the preferred embodiment

In FIG. 1 numeral 1 indicates an amplifier employed to energize the transformer of the invention, which transformer is generally indicated as 2. The transformer has a primary winding 3, preferably a tertiary winding 4, a canceler winding 5, a magnetic core 6 in the typical case, and a secondary 7.

The input to the system is typically an alternating voltage having frequency components in the range of from the order of 20 hertz (cycles per second) to the order of 100,000 hertz. This input is impressed between high input terminal 8 and grounded input terminal 9. Normally a capacitor 10 and a resistor 11 are connected in series between terminal 8 and the inverting (—) input to amplifier 1. This inverting input also receives the negative feedback for the amplifier. A typical value for capacitor 10 is 0.8 microfarad (mfd.) and for resistor 11 is 20,000 ohms.

Amplifier 1 has a different input stage and a single-ended power output stage. It may consist of a known operational amplifier and an additional series-connected output stage. The whole of amplifier 1 may be the whole amplifier illustrated and described in my copending patent application, "Wide-Band Direct-Current Amplifier Having Series-Connected Output Vacuum Tubes," filed Jan. 22, 1968, Ser. No. 699,570.

The output of amplifier 1 is direct coupled through resistor 14 to primary 3 and thence to ground. The resistor is for current limiting purposes and may have a resistance of 0.1 ohm.

Alternating current negative feedback is preferably obtained by employing tertiary winding 4, as shown in FIG. 1. The bottom end of this winding is connected to ground and the top end connects to capacitor 15, of 0.22 mfd., and thence to a series resistor grouping which connects directly from the output of amplifier 1 to the inverting input terminal. Resistor 16, of 49,000 ohms, connects directly to the output of amplifier 1. Variable resistor 17, of 5,000 ohms maximum value, connects to resistor 16 and is variable for adjustment of the negative feedback to the amplifier. Resistor 18, of 121,000 ohms, connects to resistor 17 and also to the inverting (—) input to the amplifier.

The dots located at the top of each of windings 3, 4 and 5, indicate that these windings are all wound in the same direction upon the core and that the dots identify corresponding ends of the windings.

In the negative feedback circuit, at direct current all of the feedback energy is derived from the output of amplifier 1. At frequencies where the reactance of capacitor 15 is negligible as compared to the 49,000 ohms resistance of

resistor 16, such as at 100 Hertz and above, the feedback is substantially all from tertiary winding 4. This provides a desirable transition from a voltage gain of 1 at D.C. to a value equal to the ratio of input to feedback resistors; i.e., element 11 to the sum of elements 17 and 18, throughout the operating range of frequencies. Moreover, capacitor 15 is proportioned in relation to feedback resistors 17 and 18 to compensate for low frequency phase shift and decrease of amplification because of the finite capacitance of capacitor 10. The degree of compensation obtained is determined by the ratio of the resistance of resistor 16 to the reactance of capacitor 15 at the frequency involved.

Canceler winding 5 is connected to the high, dotted, ungrounded end of primary 3 at its corresponding dotted end and to a feedback circuit for positive feedback at its other end. The feedback circuit includes variable resistor 19, having a maximum resistance of 100 ohms, connected to the lower end of winding 5; capacitor 20, of 500 mfd., intervening in the above connection; and resistor 21, of 50 ohms, connected to resistor 19 and to the non-inverting (positive) input of amplifier 1. Resistor 22, of 10 ohms, is also connected to that input and to ground.

Capacitor 20 is included in this circuit so that positive feedback will not be obtained at direct current and at very low frequencies, lest there be instability in the system. However, capacitor 20 is selected to have relatively small reactance down to the lowest frequency at which full output from the transformer is desired, as 40 Hertz.

In this embodiment the impedance of the positive feedback path, elements 19, 20, 21 and 22, is low so that a quasi-differential amplifier may be used for the operational amplifier component of amplifier 1. Such an amplifier is the commercially obtainable Analog Devices, Inc. chopper stabilized operational amplifier, Model 210.

A true differential operational amplifier, such as the Analog Devices, Inc. Model 102 is not limited by the constraint of low impedance to ground for the non-inverting input terminal. Thus, resistor 22 may have a resistance many times larger than the 10 ohms previously specified and the resistances of resistors 19 and 21 may be correspondingly larger and the capacitance of capacitor 20 correspondingly smaller. The operational amplifier may have many forms as long as the amplification for an open loop is much greater than for the closed loop of this invention, and as long as it has negligible phase shift at low frequencies, as obtained by D.C. coupling internally.

The essential requirements for the operation of this invention are met by following the circuit of the schematic diagram and by employing a transformer construction to be later detailed. However, to form a system having desirable characteristics, attention must be given to the values of three time constants involved. The first is composed of capacitor 20 and the sum of resistors 19, 21 and 22. The second is composed of capacitor 10 and resistor 11. The third is composed of capacitor 15 and the combination of resistors 17 and 18 in series in shunt to resistor 16. The preferred relation between these time constants is approximate equality between the second and the third, with the first having approximately three times that value.

In FIG. 1 the load is shown as variable resistor 24, and this is shunted across secondary 7. A preferred load is a resistive one for usual transfer of power reasons. However, with the system of this invention the load may have substantially any value and any phase angle without affecting the amplification and/or the stability of the amplifier. This is an important attribute in precise work, such as the calibration of instruments.

Transformer 2 has nominal physical and electrical characteristics according to good practice, with the following novel aspects as well.

It is essential that canceler winding 5 have extremely close coupling to primary winding 3 and that it have loose coupling to secondary winding 7. Progressive construc-

tions revealed that bifilar winding of the canceler and primary windings and the usual insulation of a few thousandths of an inch between the canceler and the secondary windings provided satisfactory operation through the audio frequency range. If the canceler winding is not thus wound its error signal will not be proportional to the copper loss of the primary, but will increase as a function of frequency due to phase shift occurring between the primary and the canceler windings. Also, stray flux between primary and secondary windings will link the canceler winding and induce an additional voltage in it, giving an improper signal that tends toward oscillation of the whole system at high frequencies.

In bifilar winding, of course, the wire for the canceler winding is laid in contact with the wire for the primary winding and the two are wound together over the insulated core.

An improvement thereover is the winding configuration shown in sectional view in FIG. 4. Instead of employing one #16 wire for the primary winding, ten strands of #26 wire twisted together are employed. These are indicated as a plurality of wires in the figure all with cross-hatching in one direction and referenced as a group by numeral 3. An additional #26 wire 5 is shown in substantially the center of this group. This is the wire for canceler winding 5. In such an enclosed position it has been found that stability of the system is enhanced, as to a maximum frequency of operation of 100,000 Hertz.

A slightly different alternate arrangement to that shown in FIG. 4 has essentially the same physical arrangement of the conductors, but these are fabricated in the form of a coaxial cable. The woven strands of the outer conductor of the cable form the primary winding 3, while the inner conductor forms canceler winding 5.

In FIG. 4 each strand of wire is insulated one from the other by the enamel covering represented by space 32 between the concentric circles of each conductor. In the coaxial cable alternate, winding 5 is insulated from the several normally non-insulated strands of winding 3 by the known coaxial insulation between the two of such a cable. This insulation between the two different windings is mandatory; between individual conductors of winding 3 insulation is not mandatory. Of course, with the coaxial cable, an outer insulating covering thereon or insulation separately wound between the turns of primary 3 is required so that a coil of wire and not a shorted-turn current sheet will be obtained.

In the same manner, tertiary winding 4 is to have close coupling to primary 3, as by bifilar winding, and loose coupling to secondary 7. The closeness of coupling to the primary should be an order of magnitude (10 times) closer than the coupling to the secondary. System stability problems at high frequencies are again avoided by following this coupling criterion.

The tertiary winding provides negative feedback of superior constancy of phase regardless of the magnitude and the reactive characteristics of the load than should such feedback be taken from the secondary. It also eliminates the effect of the copper loss in the primary 3 of the transformer. This occurs because the signal amplitude in the tertiary winding reduces the negative feedback as the primary copper losses increase, such as to keep the magnetic flux constant in the transformer. Then, only secondary losses are uncompensated, but in this invention the canceler winding performs this function.

According to this invention the secondary losses of the transformer are made equal to the primary losses by the construction involved. In a simple one-to-one ratio transformer this can be accomplished by employing essentially the same size of wire for both primary and secondary, each having the same number of turns, of course. Assuming that the secondary is wound over the primary, one size larger wire may be used for winding the secondary to compensate for the slightly greater length of each turn.

For other than a one-to-one transformer, say a two-to-one step-up transformer, wire with twice the resistance per foot (twice the resistivity) is employed for the secondary as for the primary. Since there are twice as many turns on the secondary as on the primary, the resistance of the secondary is four times that of the primary. However, the current in the secondary is only half that in the primary. Since the value of the loss is I^2R , the value of I^2 is one-fourth of that for the primary. It was just above shown that the resistance of the secondary is four times that of the primary. The arithmetic product of one-fourth and four is one; thus the wattage losses of primary and secondary are still equal.

The rule for proper construction according to this invention is thus; "the resistivity ratio of the wire for the primary and secondary windings is to be directly proportional to the turns ratio between these windings." This rule is true for either step-up or step-down transformation ratios. The several transformer windings each have a temperature coefficient of resistance. With copper wire, which is normally employed, this is a positive coefficient; i.e., higher temperature results in greater resistance.

The manner in which the canceler winding compensates for secondary I^2R copper loss is as follows. The canceler winding is wound in intimate thermal and magnetic flux relation with the primary winding. The losses in the primary and the secondary windings are equal, as has been pointed out above. The loss in the primary winding is compensated for by the feedback operation of tertiary winding 4; thus, a second compensation for primary loss by the canceler winding compensates for the loss in the secondary winding. In this way the whole system is compensated without feedback having taken from the secondary winding.

Canceler winding 5 functions as follows. Since it is connected at the top end of the winding to the top end of primary winding 3, as shown in FIG. 1, when there is no current flowing in the primary there is no IR voltage drop in the primary winding and so the potential of the bottom of canceler winding 5 is the same as the bottom of primary winding 3; i.e., both are at ground potential. For this condition of the transformer there is also no current flow in secondary 7. However, when the secondary is loaded and secondary current flows, primary current also flows and the potential change at the bottom of canceler winding 5 is directly proportional to the IR voltage drop in the primary. The feedback voltage thereby produced is fed back through elements 19, 20 and 21 to give positive feedback. The current in canceler coil 5 is negligible, thus the desired results is not partly vitiated because of an IR voltage drop therein.

Because the output voltage of the canceler winding is directly related to the resistance of the primary winding, all factors affecting the performance of the transformer will be automatically compensated for. This includes not only the ambient temperature, but the temperature of the windings themselves, as increased by iron and copper losses. The difference in these factors from primary to secondary is very small because the windings are in such close proximity. Thus, a compensation that is based upon the temperature of the primary will be accurate for the secondary.

The parameters of a typical transformer 2 capable of handling 50 watts of signal power with a 40 cycle low frequency power response corner is as follows. A toroidal core 34 is formed of 12 mil grain-oriented steel, having an inside diameter of $1\frac{1}{4}$ inches, an outside diameter of $3\frac{1}{16}$ inches, and a $2\frac{1}{4}$ inch strip width. Over the usual serving of insulation 35 around the core, primary 3 is wound, extending circumferentially around the whole of the core. The canceler and tertiary windings are wound with the primary as has previously been described. Thirty-six turns of wire are employed for the primary. The

resistance thereof is slightly less than 0.1 ohm, see FIG. 5.

A multiple impedance secondary 7 was supplied, of which the whole winding shown in FIG. 1 may be taken as the total, with taps thereon supplying the lower impedance connections. The sections of the secondary had turns ratios of $2\frac{1}{2}$, 5, and 10 to 1 with respect to the turns on the primary. The wire sizes were #20 for the first section, #24 for the second section, and #27 for the third section. The secondary was wound as the primary, extending circumferentially around the whole core.

The transformer impedance is such as to maintain a voltage of 15 volts across the primary down to a frequency of 40 hertz. The resonant frequency was 450,000 hertz and the half power point was in excess of 100,000 hertz.

It will be understood that the transformer may be made larger or smaller, from milliwatt to kilowatt ratings, and that as long as the coupling and resistivity ratio criteria are observed the benefits of the invention will be obtained. Also, the "E, I" lamination type core may be used, rather than the toroidal ring core, in which case all windings are preferably wound on the center leg of the "E" part of the core. In any event, the secondary may be wound in part upon a core, then the primary, and then the remainder of the secondary, as long as the coupling and resistivity criteria are observed.

For the reason of precise stability of gain (constancy of amplification) the previously described D.C. embodiment of the invention is preferred. However, the so-called "D.C." of the output signal of the amplifier must be carefully controlled by the balance elements therein. A spurious direct current caused by unbalance in the amplifier must not be allowed to flow through primary 3, otherwise core 6 is saturated and the performance of the transformer is very seriously degraded. An unbalance of 20 millivolts from zero volts is all that can be allowed with the toroidal transformer described. This is not difficult to maintain. The gain of the amplifier at zero frequency is only one because input capacitor 10 is employed and all of the output is fed back to the input at zero frequency.

This tolerance can be increased by placing a smaller air gap in the core of the transformer. For the toroidal core this is of the order of 0.0001 inch and is obtained by sawing the core completely in two and then butting the two semicircular halves together. A single cut of 0.001 inch, maintained by a mica insert, was found to be an order of magnitude too large. In making this modification the inductance of the primary is reduced, thus causing increased distortion and some reduction of power output at low frequencies. The modification is, however, useful at applications where these aspects are not important.

FIG. 2 illustrates an A.C. coupled embodiment of the invention. The distinguishing feature is capacitor 26, interposed between the lower end of primary 3 and ground. The other circuit elements having the same function and essentially the same value are indicated by the same reference numeral as used in FIG. 1. Capacitor 26 has a capacitance of the order of 3,000 mfd. in view of the relatively low impedance elements comprising the remainder of the primary circuit and the low frequencies desired to be amplified in the preferred embodiment.

Resistor 27 is preferably shunted across capacitor 26 and a resistance of 10 ohms is typical for the value of the resistor. It prevents instability of the system when secondary 7 is not loaded. In the configuration of FIG. 2 a series resonant circuit is formed by the inductance of primary 3 and the capacitance of capacitor 26. This causes a resonant rise of response at the resonant frequency and below that frequency a 12 db/octave slope with a maximum phase shift of the order of 180° . This circuit, being included in the feedback loop of the amplifier, could oscillate or be unstable when transformer 2 is unloaded.

When the transformer is loaded the primary inductance is shunted by the reflected value of the load impedance and the Q is then so low that oscillation or instability cannot occur. Resistor 27 reduces the otherwise relatively high circuit Q of the series resonant circuit in the unloaded condition of the transformer.

The positive feedback circuit of FIG. 2 includes capacitor 20, now having a value of 1 mfd., and potentiometer 19', having a total resistance of 50,000 ohms. The capacitor connects between the lower end of winding 5 and the top end of potentiometer 19'. The lower end thereof is connected to ground, while the adjustable arm connects to the positive input terminal of amplifier 1'. As before, a proper degree of positive feedback is obtained by adjusting the variable resistor 19 or 19', respectively. It should be noted in passing that these adjustments and the adjustment of variable resistor 17 in FIG. 1 are essentially adjusted only once. No readjustments because of changes in temperature, or in magnitude or nominal changes in phase angle of the load, are required. This is true as long as the variation of impedance of the source of signal connected to input terminals 8 and 9 remains small with respect to the resistance of resistor 11.

In FIG. 2, single resistor 28 replaces resistors 17 and 18. Capacitor 15 of FIG. 1 is not employed because A.C. and D.C. feedback is summed in a series configuration for the tertiary circuit at the upper terminal of capacitor 26. This takes the place of the previous parallel summing point located at the common connection between resistors 16 and 17.

Resistor 19' combines the three resistors previously employed; i.e., resistor 19 for resistance variation, the resistance above the slider arm of 19' taking the place of prior resistor 21, and the resistance below the slider arm taking the place of prior resistor 22. Amplifier 1' differs from amplifier 1 in having a fully differential input, thus the impedance of positive feedback path 19', 20 is much higher than that of FIG. 1.

Because the resistance in the circuit of primary 5 is now 10.1 ohms rather than 0.2 ohm the undesired offset voltage may now increase up to 1 volt, rather than only to 20 millivolts as in FIG. 1, before functioning of the amplifier-transformer combination is impaired. If resistor 27 was eliminated, the offset voltage could become even very much greater, since a path for direct current would not be provided in view of the series connection of capacitor 26 in this circuit. However, an offset voltage tolerance of 1 volt is all that is needed in practice. The presence of resistor 27 eliminates the tendency toward low frequency oscillation ("motor-boating") with the 10 ohm value; thus, the circuit shown is a desirable arrangement.

Capacitor 26 is preferably of high quality, having a low and constant internal impedance, since variations thereof are not compensated for by functioning of other elements of the circuit. At the present state of the art a high quality electrolytic capacitor is satisfactory. This capacitor must carry the primary current, which is 5 amperes for a 50 watt amplifier.

Only a small D.C. voltage drop exists across capacitor 26. Thus, it tends to lose required polarization, if an electrolytic capacitor, and to suffer an increase in internal impedance with the possible introduction of "noise" variations. This condition can be entirely removed by the modification shown in FIG. 3. Here, capacitor 26 is divided into two capacitors, 26' and 26'', which are connected "back to back"; i.e., with preferably the two negative terminals connected together and the two positive terminals forming the output leads. This assembly occupies the place formerly held by single capacitor 26; namely, between the lower terminal of primary winding 3 and ground.

The anode of diode 30 is connected to the central capacitor connection and the cathode thereof to resistor 31. The second terminal of resistor 31 is connected to ground. Diode 30 may be the usual small rectifier type, such as

1U456, and resistor 31 may have a resistance of 1,000 ohms.

In operation, the circuit of FIG. 3 functions such that diode 30 clamps the A.C. signal voltage at the center point of capacitors 26' and 26'' and raises the potential at this point to the peak value of the signal. This may be of the order of 20 volts and so the capacitors are always adequately polarized.

It will be recognized that the functioning of canceler winding 5, along with the positive feedback elements 19, 20 and 21, or 19' and 20, acts to make the effective output impedance of secondary 7 equal to zero. The positive feedback signal, originated by the IR voltage drop in primary 3 and fed back by canceler winding 5, reduces the negative feedback from tertiary winding 4 such that the voltage across secondary 7 is constant regardless of the current through it. This is the characteristic of zero internal impedance.

A number of alternate embodiments according to the teaching of this specification are possible.

Rather than employing tertiary winding 4, the feedback connection to resistor 17 may be taken from the top (dot end) of primary 3. In this case elements 15 and 16 are omitted.

The primary-canceler winding relation that has been shown is much to be preferred. However, the canceler winding may be wound in intimate relation to secondary 7, with just the reverse conditions to those set forth being imposed. In the secondary embodiment, the secondary would have to have one terminal of the winding always connected to ground. Also, the correction voltage obtained would suffer from phase shift through the transformer, depending upon the type and degree of loading of the secondary.

I claim:

1. A temperature compensated transformer circuit comprising:

- (a) a primary winding (3) having a temperature coefficient of resistance,
- (b) a canceler winding (5) wound with close coupling to and in the same direction as said primary winding,
- (c) a tertiary winding (4) wound with close coupling to and in the same direction as said primary winding,
- (d) a secondary winding (7) having the same temperature coefficient of resistance as said primary winding, having fixed coupling to said primary winding, and having loose coupling to said tertiary and canceler windings,
- (e) an amplifier (1 or 1') having negative (15-18 or 28) and positive (19-21 or 19'-20) feedback paths and an output, said output connected to the primary of said transformer,
- (f) a connection from the end of said tertiary winding corresponding to the end of said primary winding that is connected to the output of said amplifier, said connection being to said negative feedback path of said amplifier to originate negative feedback at signal frequencies, and
- (g) a connection from said canceler winding to the corresponding end of said primary winding and a connection from the opposite end of said canceler winding to said positive feedback path of said amplifier to include said canceler winding in said positive feedback path, thereby to decrease negative feedback upon an increase in loss of said secondary winding.

2. The transformer circuit of claim 1 in which:

- (a) the resistivity of the winding of said secondary is related to the resistivity of the winding of said primary directly proportionally to the ratio of the number of turns of said secondary to said primary.

3. The transformer of claim 1 in which:

- (a) said primary winding (3) is wound with a plurality of conductors, and

- (b) said canceler winding (5) is wound with a conductor positioned within the group of said plurality of conductors.
4. The transformer circuit of claim 1 in which:
- (a) said amplifier (1) is direct coupled from the input (—) accepting said negative feedback throughout to said connection to the primary (3) of said transformer.
5. The transformer circuit of claim 1, which additionally includes:
- (a) a capacitor (26) connected between said primary (3), said tertiary (4), and ground to complete the circuit including said primary and the output of said amplifier (1') through said capacitor (26).
6. The transformer circuit of claim 5, which additionally includes:
- (a) a resistor (27) connected across said capacitor (26).
7. The transformer circuit of claim 1, which additionally includes:
- (a) a pair of polarized capacitors (26', 26'') connected in series, with like polarities connected together between said primary (3) and ground,
- (b) a rectifying device (30),
- (c) a resistor (31), and
- (d) connections between said rectifying device and said resistor to connect the same in series and across

one (26'') of said pair of capacitors, whereby alternating signals are rectified to provide a D.C. polarizing potential for said capacitors.

8. The transformer circuit of claim 1, which additionally includes:

- (a) a core (6) having toroidal form, and
- (b) a tertiary winding (4) connected to said amplifier (1) to provide negative feedback, and in which said transformer
- said primary winding (3),
- said canceler winding (5)
- and said tertiary winding (4) are wound closely together, turn for turn, around said core (6), and
- said secondary winding (7) is wound around said core (6) overlaying but spaced from the three previously recited windings.

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NATHAN KAUFMAN, *Primary Examiner*.

U.S. Cl. X.R.

330—195