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Kiko

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[54] **COMPENSATED TRANSFORMER CIRCUIT**

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[73] Assignee: **Lorain Products Corporation**, Lorain, Ohio

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[21] Appl. No.: **391,145**

[52] **U.S. Cl.** ..... **323/6**; 323/44 R; 323/60; 324/127; 324/158 R

[51] **Int. Cl.** **G01r 19/00**

[58] **Field of Search** ..... 323/44 R, 48, 60, 112, 323/6; 324/158 R, 127; 340/410; 307/89

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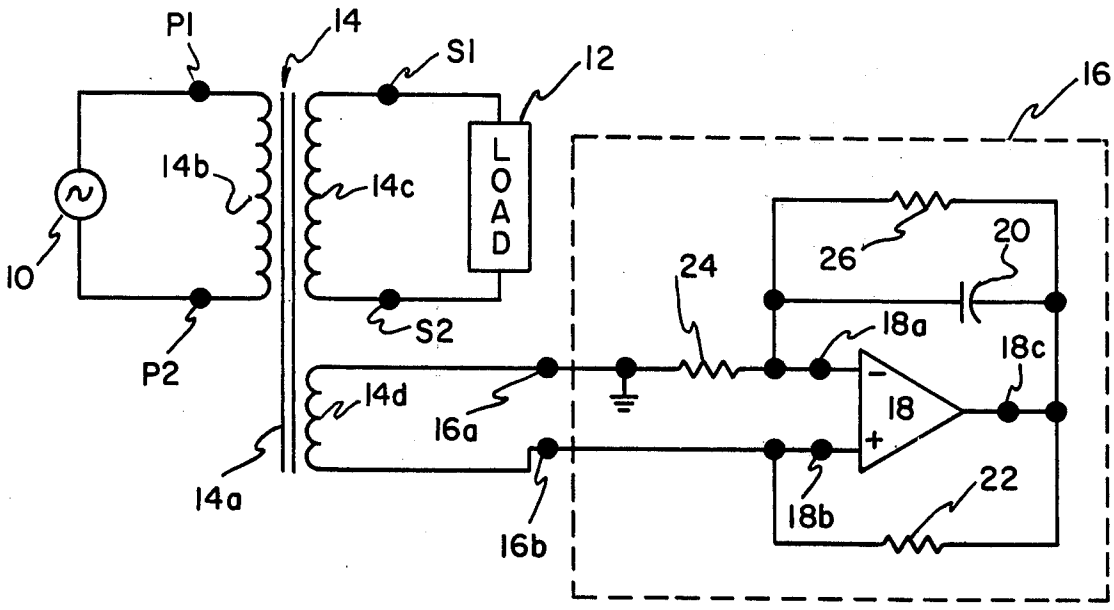
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Primary Examiner—Gerald Goldberg
Attorney, Agent, or Firm—Edward C. Jason

[57] **ABSTRACT**

A circuit for reducing or eliminating the effect of the magnetizing inductance of a transformer on voice-frequency signals coupled through that transformer. Circuitry is provided to generate voltages and currents which simulate the presence of a negative inductance and to couple those voltages and currents to a transformer in cancelling relationship to the magnetizing inductance thereof. Circuitry is also provided to reduce or eliminate the effect of the equivalent shunt resistance of the transformer and thereby render the transformer virtually free of core losses. Finally, circuitry is provided to linearize the non-linear magnetization characteristics of non-linear cores and thereby substantially reduce the distortion of signals coupled through the transformer.

15 Claims, 7 Drawing Figures



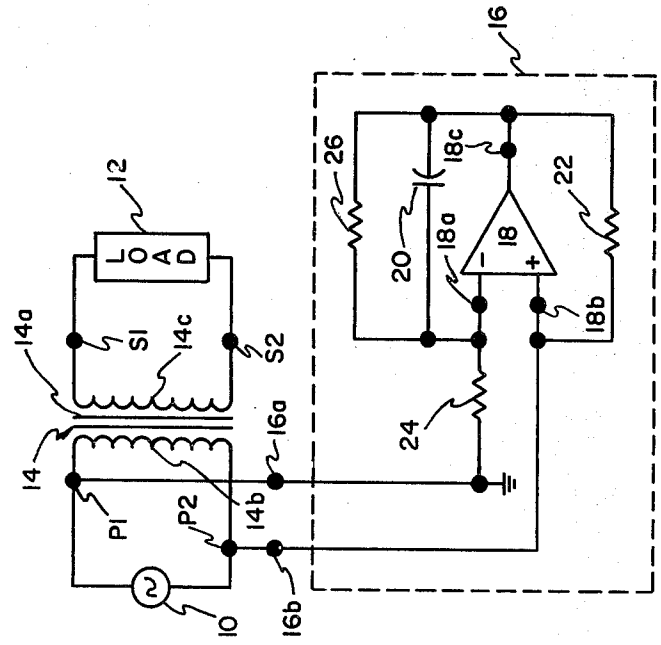


FIG. 2

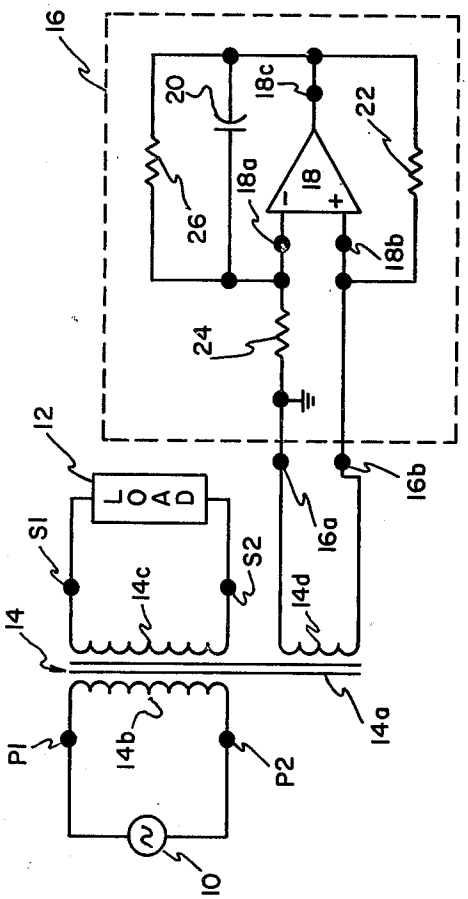


FIG. 1

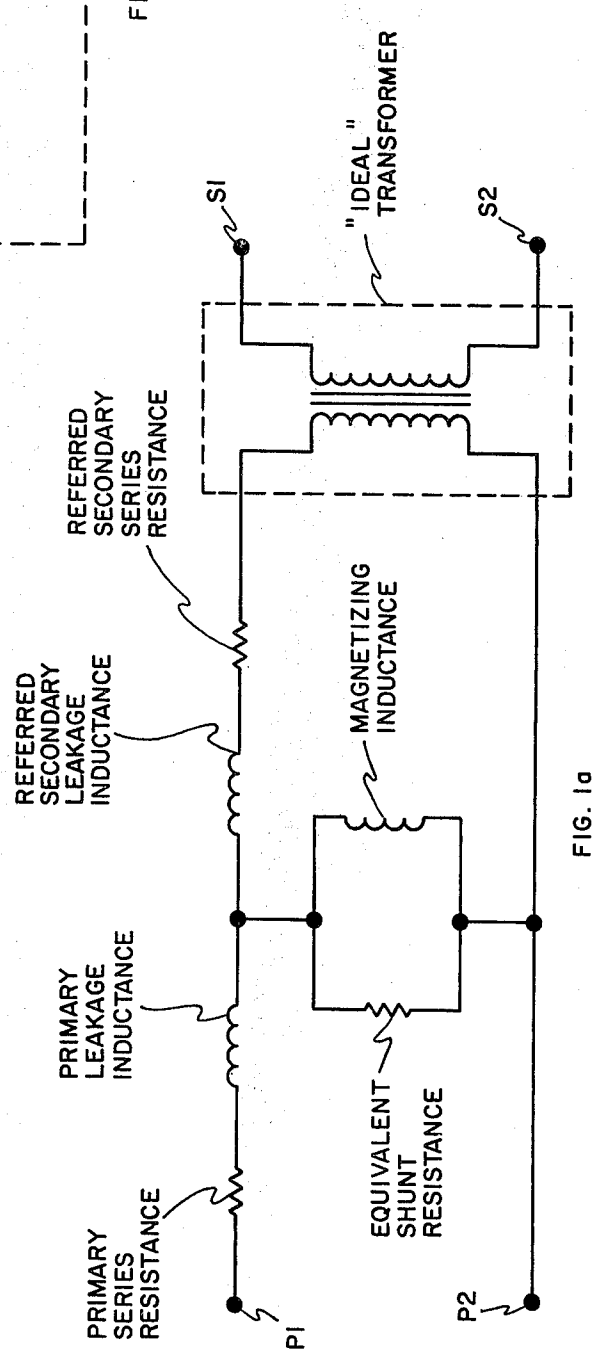


FIG. 1a

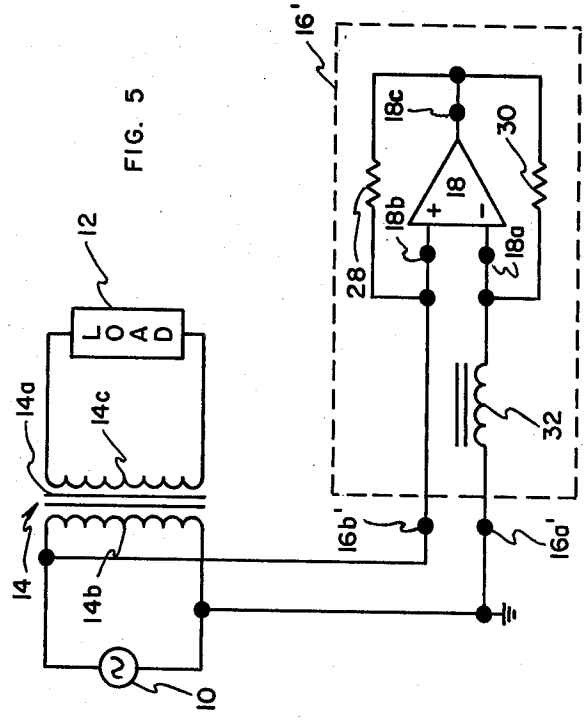


FIG. 5

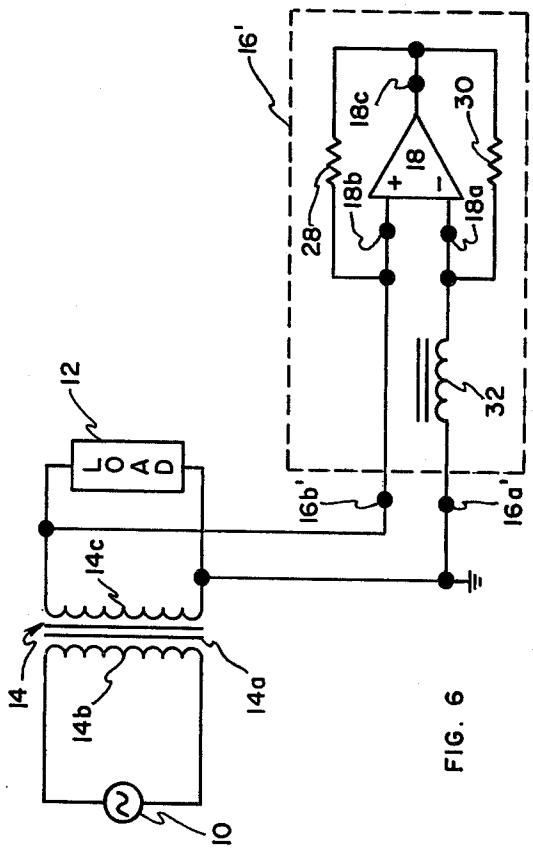


FIG. 6

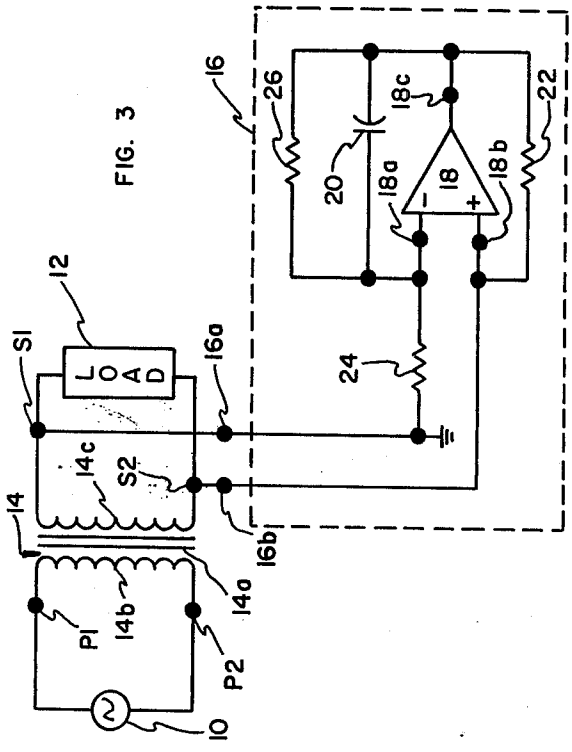


FIG. 3

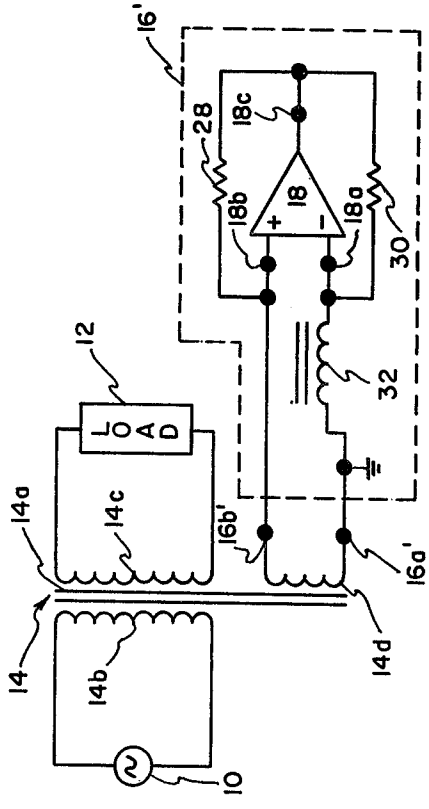


FIG. 4

COMPENSATED TRANSFORMER CIRCUIT

BACKGROUND OF THE INVENTION

The present invention relates to auxiliary circuits for transformers and is directed more particularly to circuits for reducing the effect of magnetizing current flow on power transmission through transformers.

Because of their usefulness in providing isolation, impedance transformation, and voltage and current transformations, transformers have become widely used in voice-frequency circuits. In a voice-frequency repeater circuit such as, for example, that described in the U.S. Pat. No. **3,706,862** of Charles W. Chambers, Jr., entitled "Amplifier Circuit for Transmission Lines", transformers play a useful role in coupling the repeater circuitry is series with and across a transmission line. Because of the desirability of reducing the size of and stray flux produced by these transformers, it is desirable to utilize therein a core material such as iron or ferrite which has magnetic properties.

One serious problem with utilizing magnetic core transformers in voice-frequency circuits is that the magnetizing currents drawn thereby are a function of frequency. In particular, the magnetizing current drawn by a transformer is often negligible in the upper or middle regions of the voice-frequency band, due to the relatively large magnetizing impedance presented by the magnetizing inductance in such regions. At the lower end of the voice-frequency band, however, the magnetizing impedance of such transformers is much smaller, causing a substantial reduction in the amplitude of the low frequency components of the voltages and currents coupled through such transformers. This relatively large magnetizing current flow at low frequencies is manifested as a reduction in the quality of signal transmission.

Another problem with the utilization of magnetic core transformers in voice-frequency circuits is that, with the exception of magnetic core materials having special magnetization characteristics, the magnetizing inductance of such cores is a non-linear function of current. This non-linearity causes distortion of the signals coupled through such transformers and results in a reduction in signal quality. More frequently, voice-frequency transformers cause signal distortion both as a result of frequency dependent magnetizing current flow and as a result of non-linearity as a function of current.

In accordance with the present invention, there is provided compensating circuitry for transformers which linearizes the response of such transformers as a function of frequency, as a function of current or as a function of both frequency and current. More specifically, the circuit of the invention is adapted to allow a transformer which has a frequency dependent magnetizing current characteristic to transform voltages and currents having frequencies relatively near the low end of the voice-frequency band as accurately as it transforms voltages and currents having frequencies near the middle or upper end of the voice-frequency band. In addition, the circuit of the invention compensates for nonlinearities in the response of magnetic cores which exhibit non-linear current characteristics. Together these compensation characteristics allow the utilization of transformers made up of ordinary magnetic core materials to provide a response which closely approaches that heretofore attributed to the

"ideal" transformer so often discussed in electronics textbooks.

SUMMARY OF THE INVENTION

It is an object of the invention to provide circuitry for reducing the signal distortion incident to the utilization of transformers in voice-frequency circuits.

Another object of the invention is to provide correction circuitry for reducing or eliminating the effect of frequency dependent magnetizing current flow in voice-frequency transformers.

Yet another object of the invention is to provide correction circuitry for reducing or eliminating signal distortion resulting from the utilization of a non-linear magnetic cores in voicefrequency transformers.

Still another object of the invention is to provide correction circuitry for reducing or eliminating signal distortion resulting from frequency dependent magnetizing current flow and from the utilization of non-linear core materials in voice-frequency transformers.

It is another object of the invention to provide correction circuitry of the above character which includes circuitry for substantially cancelling the effect of the equivalent shunt resistance of a voice-frequency transformer.

Another object of the invention is to provide circuitry of the above character which is usable in connection with existing voice-frequency transformers.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of one exemplary circuit embodying the invention,

FIG. **1***a* is a schematic diagram showing the equivalent circuit of a transformer,

FIG. **2** is a schematic diagram of a second embodiment of the circuit of the invention,

FIG. **3** is a schematic diagram of a third embodiment of the circuit of the invention,

FIG. **4** is a schematic diagram of a fourth embodiment of the circuit of the invention,

FIG. **5** is a schematic diagram of a fifth embodiment of the circuit of the invention, and

FIG. **6** is a schematic diagram of a sixth embodiment of the circuit of the invention.

DESCRIPTION OF THE INVENTION

Referring to FIG. **1** there is shown a source of voice-frequency voltage **10** for energizing a voice-frequency load **12** through a transformer **14.** Source **10** may, for example, comprise a transmission line which is energized by a remote voice-frequency transmitter and load **12** may comprise the input or output of a repeater circuit which amplifies the transmission of signals through that transmission line. In transmission line-repeater systems of this type, a transformer such as transformer **14** is desirable to electrically isolate the repeater circuit from the transmission line and vice-versa.

In the present embodiment, transformer **14** comprises a suitable magnetic core **14***a* around which are disposed a primary winding **14***b*, a secondary winding **14***c* and a tertiary or auxiliary winding **14***d*. Because core **14***a* has magnetic properties, transformer **14** exhibits a magnetizing impedance which is a function of frequency. This magnetizing impedance results from the presence of magnetizing inductance in transformer **14,** the latter being a quantity which is best visualized in the context of the familiar transformer equivalent

circuit shown in FIG. 1*a*. The effect of this magnetizing impedance is to cause the flow of a frequency dependent component of current in primary winding **14***b* which gives rise to no similar component of current in secondary winding **14***c*. The magnitude of this magnetizing impedance is ordinarily so large in the high and middle frequency regions of the voice-frequency band, that the effect thereof may be neglected. At the low end of the voice-frequency band, however, this magnetizing impedance is substantially lower, preventing an appreciable portion of low frequency components of the primary winding current from affecting load **12.** This condition is manifested as an excessive attenuation of the low frequency components of the voice-frequency signal and results in a noticeable signal distortion.

To the end that the signal distorting effect of the magnetizing impedance of transformer **14** may be substantially reduced or eliminated, particularly at the lower end of the voice-frequency band, there is provided a correction circuit **16** which, in the present embodiment, is coupled to core **14***a* through tertiary winding **14***d*. As will be described more fully presently, correction circuit **16** serves to establish at terminals **16***a* and **16***b* thereof, voltages and currents which alter the response of core **14***a* and thereby substantially cancel the effect of the magnetizing inductance thereof. As a result, correction circuit **16** allows voice-frequency transmission from source **10** to load **12** to proceed as if transformer **14** had no magnetizing inductance and thereby greatly improves the low frequency response of transformer **14.**

In accordance with one feature of the present invention, the desired inductance cancellation is produced by simulating between terminals **16***a* and **16***b* the presence of a negative inductance having a magnitude determined by the magnetizing inductance of transformer **14** and the number of turns on winding **14***d*. The result of coupling this synthesized negative inductance to transformer **14** is that the negative inductance combines in parallel with the existing magnetizing inductance, according to the usual parallel combination rules, to generate an equivalent combined inductance having a value which approaches infinity. The latter condition effectively prevents transformer **14** from affecting signal transmission from source **10** to load **12.**

To the end that correction network **16** may establish an effective negative inductance between terminals **16***a* and **16***b*, network **16** includes, in the present embodiment, an operational amplifier **18** having an inverting input **18***a*, a non-inverting input **18***b* and an output **18***c*. Correction network **16** also includes feedback means which here takes the form of a negative feedback impedance comprising a capacitor **20** connected between amplifier output **18***c* and inverting input **18***a*, a positive feedback impedance comprising a resistor **22** connected between amplifier output **18** c and non-inverting input **18***b*, and an input feedback impedance comprising a resistor **24** connected between network input terminal **16**a and inverting input **18***a*. The relationship governing the magnitude of the impedance looking into terminals **16***a* and **16***b* is given by the formula $Z_{in} = -Z2 \cdot Z3/Z_1$ where Z_{in} is the impedance looking into terminals **16***a* and **16***b*, Z1 is the negative feedback impedance, Z2 is the input feedback impedance and Z3 is the positive feedback impedance. This relationship allows the magnitudes of capacitor **20** and resistors **22** and **24** to be selected so that the input impedance of network **16** establishes the desired cancelling value of negative inductance.

It will be understood that other correction networks utilizing different amplifier and feedback impedance connections may be utilized to simulate the required negative inductance at terminals **16***a* and **16***b*. The particular amplifier and feedback impedance connections shown in FIG. **1,** however, have the advantages of simplicity, economy and expandibility, that is, the ability to utilize additional feedback elements for the purpose of providing increasingly sophisticated forms of transformer correction.

For example, if the series resistance of winding **14***d* is sufficiently large that it prevents precise magnetizing inductance cancellation via terminals **16***a* and **16***b*, the series resistance of windings **14***d* may be effectively cancelled by connecting a suitable resistor **26** in parallel with feedback capacitor **20.** This result follows because a positive resistance which is connected in parallel with feedback capacitor **20** causes a simulated negative resistance to appear in series with the existing simulated negative inductance between terminals **16***a* and **16***b*. This simulated negative resistance, in turn, cancels the effect of the series resistance of winding **14***d* so that the simulated negative inductance may be applied more directly in parallel with the magnetizing inductance and thereby afford more precise inductance cancellation.

A still further degree of transformer correction may be provided by effectively cancelling the equivalent shunt resistance of transformer **14,** the latter being a quantity which is utilized to represent the core losses of a transformer and which is often represented as being in parallel with the magnetizing inductance of the transformer, as shown in FIG. 1*a*. This shunt resistance may be cancelled along with the magnetizing inductance by connecting a suitable resistor in series with capacitor **20.** This result follows because the insertion of a resistor in series with capacitor **20** causes an effective negative resistance to appear in parallel with the existing effective negative inductance between terminals **16***a* and **16***b*. The effect of cancelling this equivalent shunt resistance is to render transformer **14** effectively free of core losses.

In view of the foregoing, it will be seen that the utilization of correction network **16** to simulate the negative inductance required for magnetizing inductance cancellation, to simulate the series negative resistance required to cancel the series resistance of winding **14***d*, and to simulate the shunt negative resistance to cancel the equivalent shunt resistance of transformer **14,** causes transformer **14** to act as an ideal transformer, that is, a transformer which exhibits substantially no loss and substantially no magnetizing inductance.

In the event that it is desirable to utilize transformers which do not have a tertiary winding as, for example, in the case where it is desirable to add to the correction circuit of the invention to existing two-winding transformers, this may be accomplished by connecting correction circuit **16** to an existing two-winding transformer in the manner shown in FIGS. **2** and **3.** The circuits of FIGS. **2** and **3** are generally similar to that of FIG. **1** and like functioning parts are similarly numbered. It will be understood however, that the capacitance and resistance values of the capacitors and resistors shown in FIGS. **2** and **3** are not necessarily the

same as those of the capacitors and resistors shown in FIG. 1.

As shown in FIG. 2, correction circuit 16 is connected across primary winding 14*b* of transformer 14. In this position, correction circuit 16 operates in generally the same manner as that described in connection with FIG. 1 to substantially cancel the magnetizing inductance of transformer 14. The correction provided by network 16 in the circuit of FIG. 2 is, however, not as complete as the correction provided in the circuit of FIG. 1. This lesser degree of correction results from the connection of the correction circuit across the primary winding and the resulting connection of the simulated negative inductance to the magnetizing inductance through the leakage inductance and series resistance of the primary winding, as shown in FIG. 1 a. However, because this series resistance and leakage inductance is generally small, particularly at the low frequencies of concern in connection with magnetizing inductance cancellation, the degree of improvement in transformer response provided by connecting correction circuit 16 in the manner shown in FIG. 2 is more than sufficient to justify the expense thereof.

Referring to FIG. 3, there is shown a correction circuit configuration in which correction network 16 is connected across the secondary winding of transformer 14. In this position circuit 16 operates in generally the same manner as that described in connection with FIG. 1 to substantially cancel the magnetizing inductance of transformer 14. As in the case of the circuit of FIG. 2, however, this correction is not as complete as that provided by the circuit of FIG. 1, due to the fact that in the circuit of FIG. 3, correction circuit 16 makes its effect felt through the series resistance and leakage inductance of secondary winding 14*c*. The degree of correction is, however, more than sufficient to justify the expense of correction network 16.

The magnetizing inductance compensating circuits shown in FIGS. 1, 2 and 3 are premised upon the utilization of a transformer in which the magnetizing impedance is substantially constant as a function of current. This constancy in the magnitude of the magnetizing inductance allows the utilization of correction networks having linear feedback impedances of fixed values. In the event that the material chosen for core 14*a* causes the magnetizing inductance of transformer 14 to be a non-linear function of current, the utilization of linear feedback impedances of fixed values in correction network 16 will produce a correction error as the transformer current varies from its maximum to its minimum value.

To the end that the desired magnetizing inductance correction may be provided in non-linear transformers, there are provided non-linear correction circuits 16' which may be connected to the transformers to be corrected as shown in FIGS. 4, 5 and 6. In the embodiment of FIG. 4, correction network 16' includes an operational amplifier 18 of the type described previously in connection with FIGS. 1, 2 and 3. Correction network 16' also includes a positive feedback impedance which here takes the form of a resistor 28, a negative feedback impedance which here takes the form of a resistor 30 and an input feedback impedance 32 which here takes the form of an inductor having a core made out of the same material as core 14*a*. Inductor 32 is arranged so that the operating point of the flux density thereof is the same as the operating point of the flux density of core 14*a*. This flux density condition flows quite naturally from the configuration of the correction circuit since the low voltage across inputs 18a and 18*b* of amplifier 18 causes the voltage across and current through inductor 32 to be proportional to the primary voltage and current of transformer 14. The result of this flux density condition is to assure that as the magnetizing inductance of transformer 14 varies with the current through that transformer, similar variations occur in the inductance of inductor 32. Thus, the impedance of inductor 32 tracks variations in the magnetizing impedance of transformer 14.

When the impedances of resistors 28 and 30 and the nonlinear impedance of inductor 32 are substituted into the previously described equation for Z_{in}, it is apparent that the impedance looking into terminals 16*a*' and 16*b*' of correction network 16' comprises an effective non-linear negative impedance which is proportional to the magnetizing impedance of transformer 14. Accordingly, it will be seen that however non-linear the magnetizing impedance of transformer 14 is, the correction provided by network 16' is correspondingly non-linear to provide a variable correction which, for suitable values of resistors 28 and 30, automatically and fully cancels the non-linear magnetizing impedance of transformer 14. Thus, the circuit of FIG. 4 not only eliminates the distortion which is due to the mere presence of magnetizing impedance but also the distortion which is due to the non-linear character of that magnetizing impedance.

It will be understood that inductor 32 need not be of the same size as transformer 14 so long as the flux density operating points of the core of inductor 32 and the core of transformer 14 are the same. Inductor 32 may, for example, consist of a small sample of the core material of transformer 14 around which a coil of wire of a suitable number of turns is wound. This smaller sized core will be satisfactory because inductor 32 serves merely as a non-linear reference inductance for imparting the desired non-linearity to the negative inductance simulated by correction network 16'.

As in the case of FIGS. 2 and 3, correction network 16' need not be coupled to transformer 14 through tertiary winding 14*d* as shown in FIG. 4. Correction network 16' may, for example, be connected across primary winding 14*b* as shown in FIG. 5 or may be connected across secondary winding 14*c*, as shown in FIG. 6. The adoption of the correction network configurations shown in FIGS. 5 and 6 do, however, result in somewhat less accurate magnetizing inductance corrections than the adoption of the correction configuration shown in FIG. 4, due to the coupling of correction network 16' to core 14*a* through the series resistance and leakage inductance of primary winding 14*b* or secondary winding 14*c*. Thus, correction network 16' may be utilized with existing two-winding, non-linear transformers as well as with three-winding, non-linear transformers which have been designed with the presence of correction network 16' in mind.

In view of the foregoing, it will be seen that a transformer compensating circuit constructed in accordance with the invention is adapted to cancel the effect of magnetizing impedance on the transmission of a signal from a source to a load through a transformer, both in the presence of linear magnetic core characteristics and in the presence of non-linear magnetic core characteristics. In this manner the circuit of the invention

reduces the distortion which has degraded the quality of voice-frequency voltage and current transformations, particularly at the low end of the voice-frequency band.

It will be understood that the above described embodiments are for illustrative purposes only and may be changed or modified without departing from the spirit and scope of the appended claims.

What is claimed is:

1. A transformer circuit which provides an uninterrupted path for the flow of primary and secondary current and which compensates for the frequency dependent attenuation of transformer signals that is introduced by the magnetizing inductance of the transformer comprising, in combination, a magnetic core, primary, secondary and tertiary windings disposed on said core, an impedance simulating network including feedback circuitry for establishing voltages and currents which affect the circuitry to which said voltages and currents are applied as if a negative inductance were connected to said circuitry, said negative inductance having a magnitude proportional to the magnetizing inductance of said transformer, and means for connecting said impedance simulating network to said tertiary winding to effectively cancel the magnetizing inductance of said transformer.

2. A transformer circuit as set forth in claim **1** wherein the impedance simulating network includes means for establishing, in parallel with said negative inductance, a negative resistance having a magnitude that is proportional to the equivalent shunt resistance of said transformer.

3. A transformer circuit as set forth in claim **1** wherein the impedance simulating network includes means for establishing, in series with said negative inductance, a negative resistance having a magnitude substantially equal to the series resistance of said tertiary winding.

4. A transformer circuit as set forth in claim **3** wherein the impedance simulating network includes means for establishing, in parallel with said negative inductance, a negative resistance having a magnitude that is substantially proportional to the equivalent shunt resistance of said transformer.

5. A transformer circuit as set forth in claim **1** wherein said magnetic core has a non-linear magnetizing characteristic which causes the magnetizing inductance of the transformer to be non-linear, and wherein said impedance simulating network establishes a negative inductance which is similarly non-linear.

6. A transformer circuit as set forth in claim **5** wherein said impedance simulating network includes a second magnetic core made up of the same material as the magnetic core of said transformer, said second core being arranged to operate about the same flux density operating point as the magnetic core of said transformer.

7. A transformer circuit as set forth in claim **5** wherein the impedance simulating network includes means for establishing, in series with said negative inductance, a negative resistance having a magnitude substantially equal to the series resistance of said tertiary winding.

8. A transformer circuit as set forth in claim **7** wherein the impedance simulating network includes means for establishing, in parallel with said negative inductance, a negative resistance having a magnitude that is substantially proportional to the equivalent shunt resistance of said transformer.

9. A transformer circuit as set forth in claim **1** wherein said impedance simulating network includes: an operational amplifier having an inverting input, a non-inverting input and an output, a positive feedback impedance connected between the output and non-inverting input of said amplifier, a negative feedback impedance connected between the output and inverting input of said amplifier, an input feedback impedance connected between said tertiary winding and one of the inputs of said amplifier.

10. A transformer circuit as set forth in claim **9** in which said negative feedback means includes a capacitor.

11. A transformer circuit as set forth in claim **10** including a resistor in parallel with said capacitor.

12. A transformer circuit as set forth in claim **10** including a resistor is series with said capacitor.

13. A transformer circuit as set forth in claim **10** including a first resistor in parallel with said capacitor and a second resistor in series with said capacitor.

14. A transformer circuit as set forth in claim **9** in which said input feedback impedance includes a second magnetic core, said second magnetic core being operated about the same flux density operating point as the magnetic core of said transformer.

15. A transformer circuit as set forth in claim **14** in which said positive and negative feedback impedances comprise resistors.

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