Feb. 2, 1960 J. L. FLANAGAN **2,923,784**

ARTIFICIAL TRANSFORMER

Filed Dec. 30, 1957 2 Sheets-Sheet 1

FIG. 1

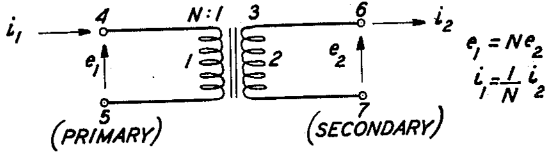


FIG. 2

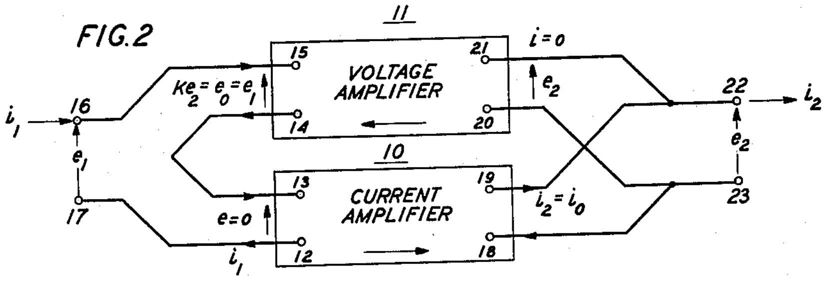


FIG. 3

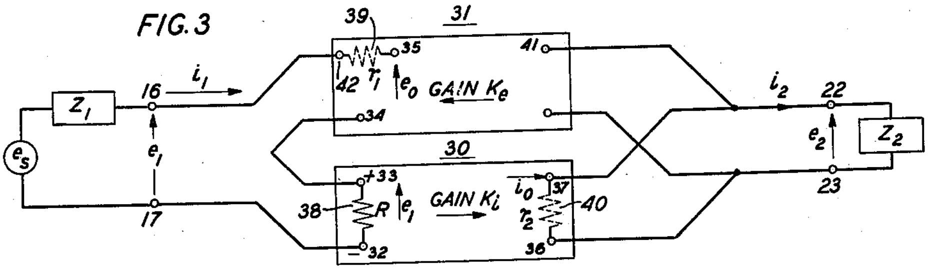
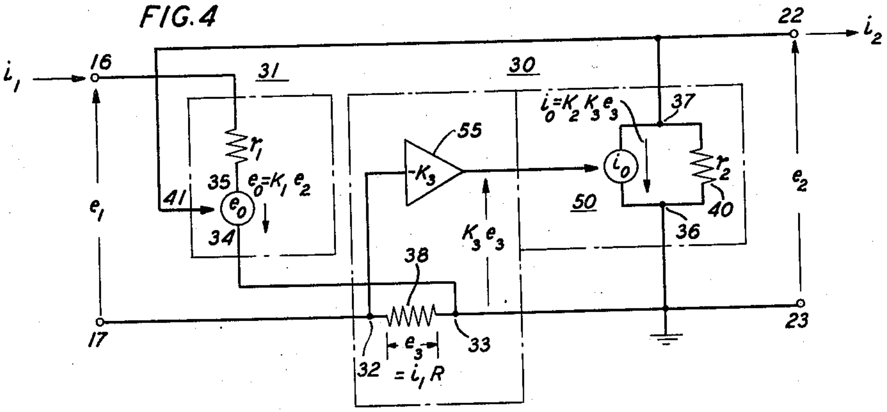


FIG. 4



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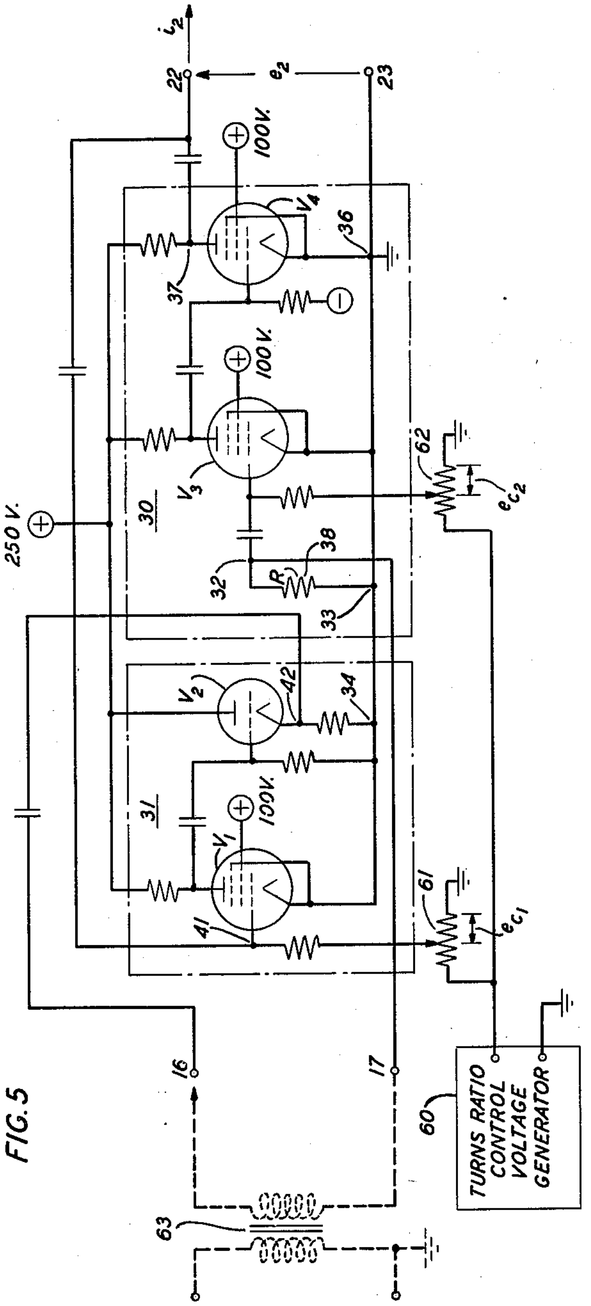

FIG. 5

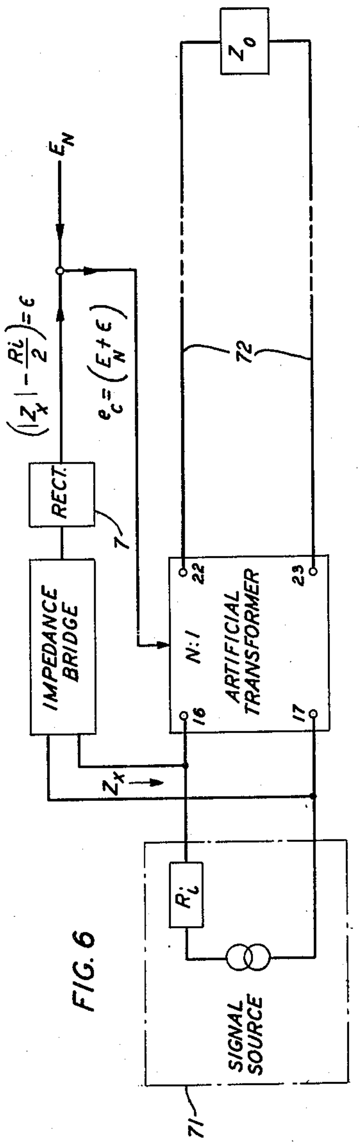

FIG. 6

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ARTIFICIAL TRANSFORMER

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Application December 30, 1957, Serial No. 705,998

15 Claims. (Cl. 330—85)

This invention relates generally to the coupling of a source of electric signals to a load and to the continuous maintenance of prescribed conditions of impedance match between them despite variations of the self impedance of either one.

In an ideal close-coupled transformer, the ratio of primary to secondary voltage is directly proportional to the ratio (N:1) of the number of turns in the primary winding to the number in the secondary winding. Similarly, the ratio of primary to secondary current is inversely proportional to the turns-ratio, (N:1). The impedance presented at the primary terminals of the transformer is equal to the impedance of the secondary circuit multiplied by the square of the turns-ratio (N^2). Uses of such transformers are manifold.

Variable transformers wherein the effective turns-ratio is altered in discrete steps by sliding contacts are well known; however, such transformers typically are usable only over a restricted range of frequencies and are characterized by noise generated as the tap is moved discontinuously from turn to turn. Moreover, servo-mechanisms to effect dynamic variations of the position of the movable tap are complex and cumbersome. A transformer designed for use at very low frequencies requires a bulky and heavy iron core to obtain the necessary self-inductance to permit linear operation at such low frequencies. For many laboratory uses such an iron core transformer is prohibitively expensive, and an unacceptable time delay in development work may attend the fabrication of such special units.

It is an object of this invention to provide a compact, lightweight unit which will simulate in external characteristics an ideal transformer with continuously variable turns-ratio, which can be adapted to operate over a range of frequencies from the very lowest frequencies to the megacycle range.

Another object of this invention is to provide an artificial transformer by which the apparent impedance of a passive network may be altered without destroying its desired frequency response characteristics.

Another object of this invention is to provide an artificial transformer with a control by which the varying impedance of a load may be continuously matched to that of a generator.

Another object of this invention is to provide a device that will transform the sign as well as the magnitude of a passive impedance (for example, a positive resistance can be made to appear as a negative resistance of arbitrary magnitude, or an inductive reactance can be made to appear as a capacitive reactance of arbitrary magnitude).

To these ends, the invention consists of certain novel connections of a voltage amplifier and a current amplifier; namely, that each amplifier is connected in a feedback relation to the other to form the functional equivalent of a magnetic transformer with effective turns-ratio responsive to a controlled variation of the amplifier gains.

The principles governing the fabrication and use of

such artificial transformers, together with further objects and advantages thereof, will best be comprehended by reference to the following description of illustrative embodiments thereof, taken in connection with the accompanying drawings, in which:

Fig. 1 is a circuit diagram of an ordinary close-coupled magnetic transformer which transforms a primary voltage e_1 and a primary current i_1 into a secondary voltage e_2 and a secondary current i_2 in accordance with a turns-ratio N:1;

Fig. 2 is a block diagram of an ideal artificial transformer device constructed in accordance with this invention;

Fig. 3 is a more detailed block diagram representative of a practical embodiment of the invention;

Fig. 4 is a partial schematic diagram showing substantially the same circuit shown in Fig. 3 with the elements further broken down and grouped in a functional manner;

Fig. 5 is a schematic diagram representative of a specific embodiment of the invention which has been found to be useful in the laboratory; and

Fig. 6 is a schematic diagram of a simple transmission system incorporating the invention.

Referring now to the drawings, Fig. 1 represents a conventional close-coupled magnetic transformer having a primary winding **1** and a secondary winding **2**. Both windings link a common core **3**. The turns-ratio, N, of the number of primary winding turns around the core to the number of secondary turns determines the voltage and current ratios of the transformer.

Externally, the transformer presents four terminals, two input terminals **4** and **5** connected to the primary winding and two output terminals **6** and **7** connected to the secondary winding. The input current, i_1, and the input voltage, e_1, are related to the output current i_2 and output voltage e_2 through the turns-ratio. Thus

$$\frac{i_2}{i_1}=N \qquad (1)$$

and

$$\frac{e_2}{e_1}=\frac{1}{N} \qquad (2)$$

Further, a secondary load impedance, Z_2, "viewed" from the primary is multiplied by the square of the turns-ratio, i.e.:

$$\frac{e_1}{i_1}=N^2Z_2 \qquad (2a)$$

and conversely, for a primary impedance Z_1, viewed from the secondary side:

$$\frac{e_2}{i_2}=\frac{Z_1}{N^2} \qquad (2b)$$

These equations describe an "ideal" close-coupled transformer. They quite accurately define the performance of a conventional close-coupled iron cored transformer over a band of frequencies. For a well designed transformer these relations can be made to hold for about seven octaves in frequency.

Consider now the circuit of Fig. 2. In it an ideal current amplifier **10**, connected to transfer signals from left to right, is interconnected with an ideal voltage amplifier **11**, connected to transfer signals from right to left. The input terminals **12** and **13** of the current amplifier **10** are connected in series with the output terminals **14** and **15** of the voltage amplifier **11** and with the input terminals **16** and **17** of the circuit. The output terminals **18** and **19** of the current amplifier **10** and the input terminals **20** and **21** of the voltage amplifier **11** are connected in parallel with the output terminals **22** and **23** of the circuit. In other words, the amplifiers are connected together in the specified manner to form a feedback loop. In consequence, the input current i_1 of the circuit is equal to the input current of the current amplifier **10**, and the input voltage of the amplifier **11** is the output voltage e_2 of the device. The ideal current amplifier **10** has a constant ratio K_1 of output current i_0 to input current i_1, i.e.:

$$\frac{i_0}{i_1}=K_1 \qquad (3)$$

An ideal current amplifier has a zero input resistance so that its insertion in the circuit does not affect the current to be measured and the output current is dependent solely upon the input current. Since, by hypothesis, the output current i_0 depends only on input current, i_1, it is independent of output voltage, e_2, that is,

$$\left(\frac{\partial i_0}{\partial e_2}\right)_{i_1=\text{constant}}$$

vanishes, and its reciprocal, the output impedance

$$\left(\frac{\partial e_2}{\partial i_0}\right)_{i_1=\text{constant}}$$

is infinite. Accordingly, the ideal current amplifier **10** may be characterized by a zero input impedance, an infinite output impedance, and a constant gain factor. By itself it is both asymmetrical and unidirectional; a current applied to the output does not generate a current at the input.

Similarly, the ideal voltage amplifier **11** has a constant ratio K_e of output voltage e_0 to input voltage e_2, i.e.:

$$\frac{e_0}{e_2}=K_e \qquad (4)$$

Since output voltage e_0 depends only on input voltage e_2, the output impedance

$$\left(\frac{\partial e_0}{\partial i_1}\right)_{e_2=\text{constant}}$$

vanishes. Additionally, since a voltage amplifier preferably should not load the source of input voltage, its input impedance is preferably infinite. Accordingly, the ideal voltage amplifier **11** is characterized by an infinite input impedance, a zero output impedance, and a constant gain factor. It is also asymmetrical and unidirectional. These characteristics of ideal amplifiers must hold whether the gain factors are greater or less than unity. Thus, as used in this specification, and in the appended claims, the input and output terminals of voltage amplifiers and of current amplifiers are designated with respect to impedance levels rather than signal levels.

It will be apparent that in Fig. 2 the output current i_0 of the current amplifier **10** is the total output current i_2 of the device, i.e.:

$$i_0 \equiv i_2 \qquad (5)$$

and the output voltage e_0 of the voltage amplifier **11** is equal to the voltage input e_1 of the device, i.e.:

$$e_0 \equiv e_1 \qquad (6)$$

Accordingly, the device of Fig. 2 is governed by the following relations:

$$\frac{e_2}{e_1}=\frac{1}{K_e} \qquad (7)$$

$$\frac{i_2}{i_1}=K_i \qquad (8)$$

and

$$\frac{e_1}{i_1}=K_eK_i\frac{e_2}{i_2} \qquad (9)$$

K_i and K_e, being gain constants of the amplifiers, may be selected as a matter of design choice and made variable by well known expedients. Four cases are of interest:

Case 1.—If $K_e=K_i=N=$a positive and real constant, then the circuit functions as an ideal, close-coupled transformer. The transformer neither consumes nor generates power. Then

$$e_1=Ne_2,\ i_2=Ni_1 \qquad (10)$$

and

$$\frac{e_1}{i_1}=N^2\frac{e_2}{i_2} \qquad (11)$$

moreover, instantaneous power in=

$$e_1i_1=\frac{1}{N}e_1\cdot Ni_1=e_2i_2 \qquad (12)$$

=instantaneous power out.

Case 2.—If $K_e \neq K_i$, but both are positive and real, the general terminal Relations 7, 8 and 9 still hold out:

$$\text{instantaneous power in}=e_1i_1=K_ee_2\frac{i_2}{K_1}=\frac{K_e}{K_1}e_2i_2$$

$$=\left(\frac{K_e}{K_i}\right)(\text{power out}) \qquad (13)$$

and power out may be greater or less than power in, depending upon the ratio K_e/K_i; the transformer may consume power or act as a source of power.

Case 3.—If K_i and K_e are real, and either (but not both) is negative, then the transformer functions as a negative, impedance converter, transforming a positive load impedance at one set of terminals into a negative impedance at the other pair of terminals; i.e., the transformer changes the sign of a given impedance $R \rightarrow -R$ for resistive loads; and $(r+jx) \rightarrow -(r+jx)$ for reactive loads. In this case the transformer circuit supplies power to the driving source.

Case 4.—If K_i and K_e are complex quantities; i.e., if the amplifiers exhibit phase shift, then

$$K_i=|K_i|\epsilon^{j\theta_i} \qquad (14)$$

$$K_e=|K_e|\epsilon^{j\theta_e} \qquad (15)$$

and the complex voltages, currents and impedances may be manipulated by adjusting the phase characteristics of the amplifiers. If:

$$e_1 \equiv |e_1|\epsilon^{j\theta_{e1}},e_2 \equiv |e_2|\epsilon^{j\theta_{e2}}$$

$$i_1 \equiv |i_1|\epsilon^{j\theta_{i1}},i_2 \equiv |i_2|\epsilon^{j\theta_{i2}} \qquad (16)$$

then

$$e_1=|K_e|\epsilon^{j\theta_e}|e_2|\epsilon^{j\theta_{e2}}=|K_e||e_2|\epsilon^{j(\theta+\theta_{e2})} \qquad (17)$$

similarly,

$$i_2=|K_i|\epsilon^{j\theta_i}|i_1|\epsilon^{i\theta_{e1}}=|K_i||i_1|\epsilon^{i(\theta_i+\theta_{i2})} \qquad (18)$$

and

$$e_1/i_1=|K_e||K_i|\epsilon^{j(\theta_e+\theta_i)}(e_2/i_2) \qquad (19)$$

By properly adjusting the phase characteristics of the amplifiers, various effects can be produced. The first three cases are just particular forms of this fourth and general case. For example, a complex load impedance may be made to appear as its complex conjugate at the other terminals if: $|K_i|\ |K_e|=1$ and $(\theta_e+\theta_i)=-(2\theta_2)$ where θ_2 is the phase angle of the load impedance, then

$$|Z_1|\epsilon^{j\theta_1}=|K_e||K_i|\epsilon^{j(\theta_e+\theta_i)}|Z_2|\epsilon^{j\theta_2} \qquad (20)$$

or

$$|Z_1|\epsilon^{j\theta_1}=|Z_2|\epsilon^{-j\theta_2}=\text{conjugate of }|Z_2|\epsilon^{j\theta_2} \qquad (21)$$

By this choice of phase characteristics, the sign of the imaginary or reactive term of the load impedance has been changed. A similar choice of phase can be made to change the sign of the real part (or resistive component).

Fig. 3 represents a device having output and input impedances more representative of practical amplifiers, when connected as described for the device of Fig. 2. Here the circuit is driven from a source e_s with self impedance Z_1 connected to the primary side, and a load impedance Z_2 is connected across the secondary terminals.

A resistor **38** of value R is connected between input terminals **32** and **33** of the current amplifier **30**. Resistor **39** of value r_1 is connected effectively in series with output terminals **34** and **35** of the voltage amplifier **31**, and the output resistance **40** of value r_2 shunts the output terminals **36** and **37** of the current amplifier **30**. Z_1 represents the source impedance of the circuit driving the primary with a source voltage e_s as seen from the input terminals **16** and **17** of the device. Z_2 represents a secondary circuit load impedance as seen from the output terminals **22** and **23** of the device. In Fig. 3 (where the circuit is assumed to be driven from the primary side and loaded on the secondary side), the output i_0 of the current amplifier is not exactly identical to secondary current i_2, and the output e_0 of the voltage amplifier is not exactly equal to the primary voltage e_1, but rather:

$$e_1=e_0+i_1(r_1+R) \tag{22}$$

where

$$e_0=+K_e e_2 \tag{23}$$

and

$$+K_i i_1=i_2+\frac{e_2}{r_2} \tag{24}$$

and

$$\frac{e_2}{i_2}=Z_2 \tag{25}$$

Wherefore, combining Equations 22 through 25, it follows that the input terminals present an apparent impedance given by:

$$\frac{e_1}{i_1}=\frac{K_i\left[K_e Z_2+\frac{i_1}{i_2}(r+R)\right]}{1+\frac{Z_2}{r_2}} \tag{26}$$

if

$$Z_2<<r_2 \tag{27}$$

then

$$\frac{e_2}{r_2}\ll i_2 \tag{28}$$

and

$$\frac{i_1}{i_2}\cong\frac{1}{K_1},\text{ or } i_2\cong K_i i_1 \tag{29}$$

and since

$$\frac{Z_2}{r_2}\ll 1$$

Equation 26 simplifies to:

$$\frac{e_1}{i_1}\cong K_i K_e Z_2+(r_1+R) \tag{30}$$

Further, if

$$(r_1+R)<<K_i K_e Z_2 \tag{31}$$

then

$$e_1/i_1\cong K_i K_e Z_2 \tag{32}$$

or

$$e_1\cong K_e e_2 \tag{33}$$

Essentially the same conditions apply when the circuit is driven from a source connected to the secondary terminals and a load impedance is connected to the primary terminals. Equations 27 and 31 means that the output impedance (r_2) of the current amplifier must be high compared to the impedance level of the secondary circuit, and the sum of the output impedance (r_1) of the voltage amplifier and the input impedance (R) of the current amplifier must be low compared with the impedance reflected at the primary terminals. Both of these conditions can be easily realized to a satisfactory degree in practical circuits, of which Fig. 5 is an example.

Many varieties of amplifiers may be employed in practicing the invention; but stability and the range of useful operation will depend upon the degree to which the amplifiers employed have the characteristics of ideal amplifiers.

Fig. 4 is a partial schematic diagram of an embodiment comprising a voltage amplifier **31** represented as the alternating current equivalent circuit for a triode tube, and a current amplifier **30** represented by a conventional alternating current equivalent circuit **50** for a pentode tube, together with the resistor R and a phase inverting stage 55, proportioned to provide a voltage gain $-K_3$. This circuit will be recognized as equivalent to Fig. 2 wherein K_i is replaced by the product R K_2 K_3 and K_e is replaced by K_1. To permit grounded operation of both amplifiers, the points **33** and **34** are grounded. The input to the current amplifier, appearing across the resistor R is, then, in opposite phase to the output of the voltage amplifier. Accordingly, an additional phase reversal in one of the amplifiers, as indicated by the negative sign of ($-K_3$), is necessary to correspond to the feedback arrangement of Figs. 2 and 3. Both the triode and pentode stages of Fig. 4 produce phase inversions of 180 degrees so that the net effect of the circuit is exactly identical to that of the circuit in Fig. 3.

The device exhibits the characteristics of a transformer with turns-ratio N when the factors are adjusted so that

$$K_1=K_2K_3R=N \tag{34}$$

Variations of K_1 and the other factors in a manner to preserve the Relations 34 result in a corresponding variation in equivalent turns-ratio. The control of amplifier gain factors to achieve wide variations of N may be accomplished by means well known in the art. As a practical matter there is usually no need for N to be less than unity since one may simply reverse the primary and secondary connections.

The maximum value of N that can be achieved is determined largely by stability margins of the circuit as a feedback device. N's in the range from one to ten have been attained with relatively little attention to the phase characteristics of the circuit.

Fig. 5 is a schematic diagram of an artificial transformer which has been employed to couple passive networks in connection with electrical analog studies of acoustical systems.

The voltage amplifier **31** comprises the pentode V_1 in tandem with the cathode follower V_2. The current amplifier comprises the two pentode stages V_3 and V_4 which amplify the voltage produced across the resistance, R, by the input current. As in the circuit of Fig. 3, grounded operation of the amplifiers requires that the output of the voltage amplifier and input of the current amplifier be connected series opposed rather than series aiding. The output of the current amplifier appearing at point **37** is connected through coupling capacitors to the input grid of the voltage amplifier at point **41**. Each amplifier is thus connected in feedback relation to the other as in Fig. 4 Both tubes V_1 and V_3 are of the remote cutoff type to provide a convenient means for varying the gain constants (i.e. "turns-ratio") in response to a variable bias control voltage. The transconductance of V_4 is maintained substantially constant by operating the stage in a conventional maner with fixed bias. Variation of the turns-ratio is effected by jointly varying the gain constants K_1 and K_3 by means of the bias voltages e_{c1} and e_{c2}, respectively. The circuit is designed so that the current and voltage gains are maintained equal for a reasonably wide range of N, the equivalent control functions K_e versus e_{c1} and K_i versus e_{c2} are made to "track" and by proper adjustment of the two potentiometers **61**, **62**, the biases e_{c1} and e_{c2} can be derived from the single control voltage source **60**.

The conventional fixed turns-ratio transformer **63** shown connected to the input of the device is a useful adjunct to the circuit in that it permits "grounded" operation of both primary and secondary circuits, as shown.

Fig. 6 represents a telephone-type repeated amplifier **71** feeding a long section of transmission line 72 (for example, a section of undersea cable). To optimize the power transmitted to the receiving end of the line, and to minimize objectionable reflections of energy due to impedance miscatches, it is desirable to have the impedance looking into the cable (i.e. essentially the characteristic impedance of the cable, Z_0, if it is a long section) matched in magnitude to the internal impedance, R_i, of the signal source (or repeater amplifier). This match usually is effected by a transformer having a turns-ratio equal to N where, recalling Equation 2*a*:

$$N=\left[\left|\frac{R_i}{Z_0}\right|\right]^{1/2} \tag{35}$$

Often, however, because of variations in environmental conditions (such as temperature changes caused by ocean currents) the impedance looking into the sending end of the cable may vary continuously with time. (The impedance of the source usually is constant and usually is resistive. In general Z_0 also is predominantly resistive.) If a proper impedance match, i.e. $R_i=N^2|Z_0|$, is to be maintained at all times, the turns-ratio of the transformer should be varied so that $N^2|Z_0|$ is always constant and equal to R_i. Continuous variation of the turns-ratio can only be approximated with conventional, close-coupled, tapped transformers. With the electronic transformer of the invention, however, such continuous variation of N is possible.

The circuit of Fig.6 is an illustration of how such an impedance match may be maintained constantly and automatically. The long transmission line **72** with characteristic impedance Z_0 is to be fed from the source **71** with constant resistive internal impedance, R_i. The variable transformer is used to match Z_0 to R_i. To do this, an impedance bridge continuously makes a measurement of the impedance $|Z_x|$, namely the parallel combination,

$$\frac{R_iN^2Z_0}{R_i+N^2Z_0}$$

of the source **71** and the load as seen through the transformer. The measurement is made at a frequency not used for communication, for example, in a guard band between two speech channels in a carrier transmission system. The impedance bridge is arranged to be balanced when Z_x is equal to $R_i/2$. When unbalanced, a smoothed error signal ϵ proportional to $(|Z_x|-R_i/2)$ is developed by the detector **73**. This control voltage may be additively combined with a manually set voltage E_N (set originally to give the proper match) and the sum, e_c, is used to determine the turns-ratio of the transformer. This control loop acts to maintain the proper impedance match when Z_0 varies by automatically adjusting the turns-ratio N.

The control circuit functions in the following manner. Suppose E_N is set to give the right value of N when the line is first connected, but, for some reason, Z_0 is later caused to increase appreciably. Then, recalling Equation 35, $N^2|Z_0|>R_i$ and mismatch occurs. Simultaneously, however, the parallel combination of $N^2|Z_0|$ and R_i also increases so:

$$|Z_x|>R_i/2 \tag{36}$$

and

$$\epsilon=(|Z_x|-R_i/2)>0 \tag{37}$$

The resulting increased correction voltage $(\epsilon+E_N)$ reduces the turns-ratio, N, of the transformer until $N^2|Z_0|\approx R_i$. (The preciseness with which the adjustment is made is dependent upon the gain around the control loop.)

The invention has been described above as a substitute for a simple variable coupling transformer and as applied to match impedances in a transmission system. Many other applications of these principles may be found which fall within the scope of the invention, the particular embodiments described above being ones in which the invention performs a function peculiar to its nature and produces results previously unobtainable except through the use of more complex and otherwise less satisfactory apparatus.

What is claimed is:

1. An impedance transformer comprising a voltage amplifier having two input terminals and two output terminals, a current amplifier having two input terminals and two output terminals, the input terminals of said current amplifier being connected in series relationship to the output terminals of said voltage amplifier, and the input terminals of said voltage amplifier being connected in parallel with the output terminals of said current amplifier.

2. A transformer as defined in claim 1 wherein said voltage amplifier comprises an electron tube amplifier, and wherein said current amplifier comprises an electron tube amplifier.

3. A transformer as defined in claim 2 wherein said voltage amplifier comprises a variable mu tube input stage and an output stage in cathode follower connection connected in tandem therewith, and wherein said current amplifier comprises a variable mu tube input stage and an output pentode stage connected in tandem amplifier relationship with said second named variable mu tube.

4. A transformer in accordance with claim 3 wherein said variable mu tubes are resistively connected to a voltage source arranged to alter the current and voltage amplification ratios equally and synchronously.

5. An impedance transformer comprising a voltage amplifier having an input and an output, and a current amplifier having an input and an output, said voltage amplifier input being connected in parallel with said current amplifier output, and said current amplifier input being connected in series with said voltage amplifier output.

6. An artificial transformer comprising a current amplifier having an input and output, and a voltage amplifier having an input and an output, said amplifiers having equal gain factors and the input of each amplifier being connected with the output of the other whereby each amplifier is in feedback relation to the other.

7. An artificial transformer comprising a voltage amplifier having an input and an output, a current amplifier having an input and an output, said amplifiers having the same amplification ratio, said voltage amplifier input being connected in parallel with said current amplifier output, and said current amplifier input being connected in series with said voltage amplifier output.

8. In combination, apparatus in accordance with claim 7 and unicontrol means to adjust said amplification ratio whereby the effective turns-ratio of said artificial transformer is varied.

9. Apparatus in accordance with claim 1, wherein said current amplifier and said voltage amplifier comprise electron tube amplifiers of the variable mu type, said tubes being connected to adjustable sources of bias voltage, whereby the amplification ratios of said current amplifier and said voltage amplifier may be equalized.

10. Apparatus in accordance with claim 9 wherein said sources of bias voltage are simultaneously variable thereby changing the effective turns-ratio of said transformer.

11. The apparatus in accordance with claim 10 wherein said bias sources comprise a pair of potentiometer resistors connected in parallel across a common source of variable voltage, one resistor being tapped to supply

bias for said voltage amplifier, the other resistor being tapped to supply bias for said current amplifier.

12. In combination, a source of electrical communication signals; a transmission line terminated at its distal end by substantially its characteristic impedance; a variable artificial transformer having input terminals, output terminals, and control terminals connected between said source and the proximal end of said transmission line to match the impedance of said source to that of said line; an impedance bridge connected at the common terminals of said source and said transformer to measure the apparent parallel impedance at said common terminals; and a detector converting the error signal of said bridge to a control signal connected to a control terminal of said transformer whereby the apparent turns-ratio of said transformer is adjusted to maintain a proper termination of said proximal end.

13. In combination, an artificial transformer having input terminals, output terminals, and control terminals, comprising a current amplifier and a voltage amplifier, the input of said current amplifier and the output of said voltage amplifier being in series with said input terminals, the output of said current amplifier and the input of said voltage amplifier being in parallel with said output terminals, and said control terminals being connected to control elements of said amplifiers to alter the current and voltage amplification ratios equally and synchronously; a source of electrical communication signals connected to the input of said transformer; a transmission line terminated at its distal end by substantially its characteristic impedance and at its proximal end connected to the output terminals of said transformer; an impedance bridge connected at the junction of said source and said transformer to measure the apparent parallel impedance at said juncture; and a detector converting the unbalanced signal of said bridge to a control signal connected to said control terminals whereby the apparent turns-ratio of said transformer is adjusted to maintain a proper termination of said proximal end.

14. A transformer as described in claim 2 wherein said voltage amplifier comprises a variable mu pentode electron tube and a triode tube connected in tandem therewith in cathode follower connection, and wherein said current amplifier comprises a variable mu pentode tube the control grid of which is connected to said input terminals, and an output pentode tube connected in tandem amplifier relationship with said second named variable mu pentode tube, the anode of said output tube being connected to said output terminals.

15. A transformer in accordance with claim 14 wherein said variable mu pentodes are resistively connected to a bias voltage source arranged to alter the respective current and voltage amplification ratios equally and synchronously.

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