

May 9, 1944.

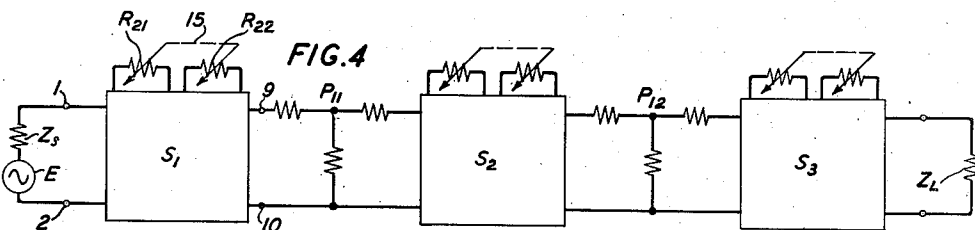
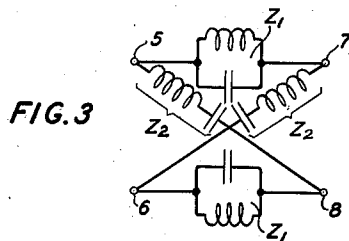
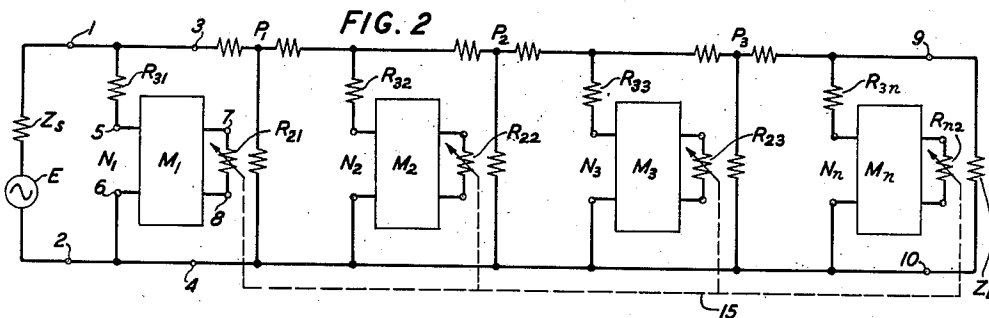
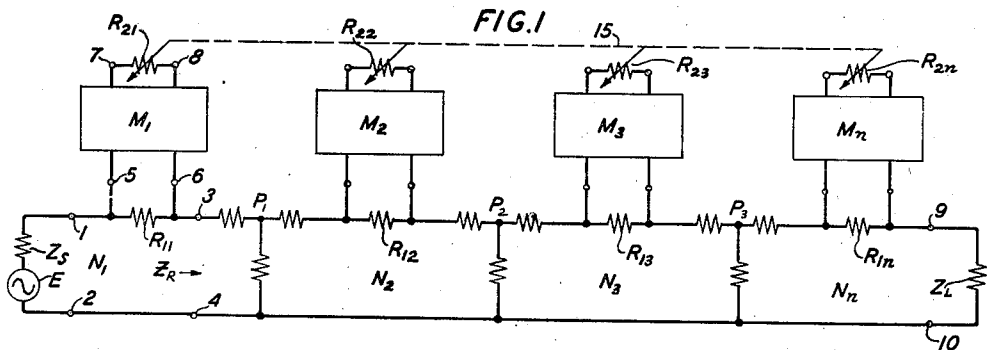
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2,348,572

VARIABLE ATTENUATION NETWORK

Filed Feb. 20, 1943

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

FIG. 5

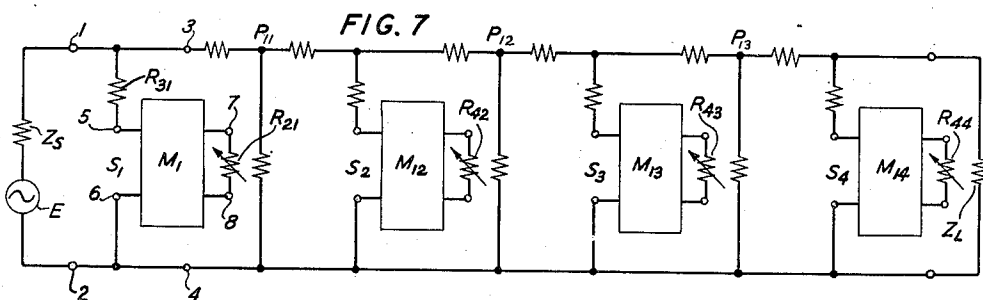
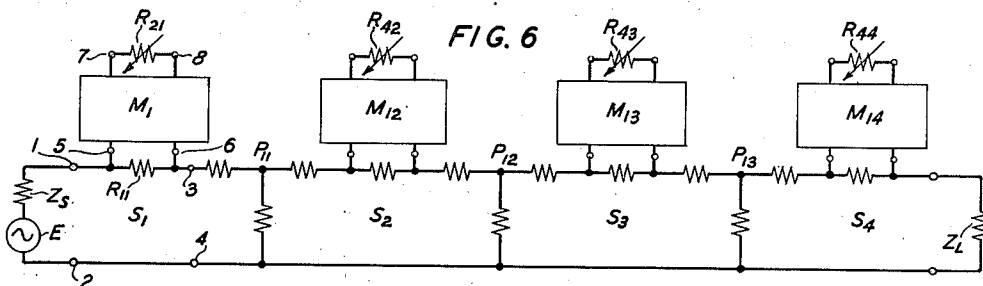
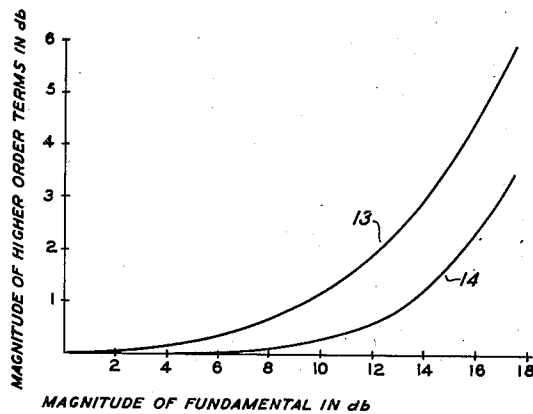
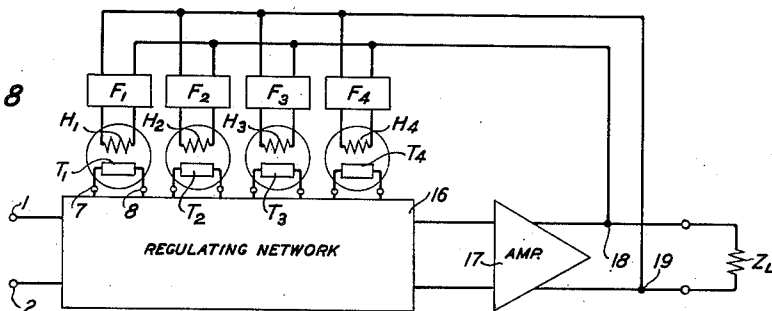


FIG. 8



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2,348,572

VARIABLE ATTENUATION NETWORK

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Application February 20, 1943, Serial No. 476,512

13 Claims. (Cl. 178-44)

This invention relates to attenuation equalizing networks and more particularly to variable equalizers having a plurality of controls for the compensation of transmission lines subject to variation in attenuation.

An object of the invention is to maintain close attenuation regulation for a transmission line, the attenuation of which changes.

Another object is to provide, over a finite frequency range, a variable attenuation characteristic which may be made to simulate any given curve as closely as desired.

A feature of the invention is a variable attenuation network having a number of controls each of which independently controls an insertion loss characteristic corresponding to one term of a Fourier series.

It is known that any curve, over a limited range, may be analyzed on the basis of a Fourier series, and that if a sufficient number of terms are employed the curve may be simulated to any desired degree of closeness. In accordance with the present invention there is provided a variable attenuation network comprising a number of associated but independently controlled units each of which furnishes an insertion loss characteristic corresponding to one term of a Fourier series. If enough such units are provided it is obvious that any attenuation characteristic may be simulated as closely as desired over a finite frequency range. In practice it will usually be found that only a few units will give the required simulation.

Each of the units is made up of one or more tandem connected variable attenuation equalizer sections of the type disclosed in United States Patent 2,096,027, issued October 19, 1937, to H. W. Bode. Each of these sections comprises a pair of terminal impedances between which is interposed a variable impedance constituted by a fixed resistor in combination with a subsidiary four-terminal network terminated by a variable resistor. The fixed resistor may be connected either in series or in parallel with the associated terminal impedances. Each subsidiary network has an image impedance which is a constant resistance and an image transfer constant the attenuation constant of which is independent of frequency and the phase constant of which, over the frequency range to be covered, is proportional to frequency. All of the subsidiary networks have phase constants which are integrally related to each other. To provide a characteristic which, when referred to a constant loss, is a cosine curve, the required ratios of these phase

constants are 1:3:5: . . . : (2n-1). Additional units are similarly designed to provide second, third and higher harmonic curves. The number of units required depends upon the accuracy with

which the desired insertion loss characteristic is to be simulated. The various units are connected in tandem and coupled in such a way as to reduce interaction between them. Resistance pads may, for example, be used for coupling. Alternatively, the units may be located at different points along a transmission line, separated by sections of the line.

In some practical applications each unit may comprise only one equalizer section. One such application is in a regulating network for compensating attenuation distortion in long telephone circuits caused, for example, by changes in temperature. The number of such units to be used will, of course, depend upon the closeness of regulation required. The phase constants of the auxiliary networks may, in this case, have the ratios 1:2:3: . . . : n. In order to make the regulation automatic the variable resistors may be of the type having non-linear resistance-temperature characteristics, each under the control of a pilot current of suitable frequency, the amplitude of which reflects the variation of the line attenuation. Perfect compensation is attained at each pilot frequency, and if sufficient units are employed and the pilot frequencies are properly distributed any desired limits of regulation throughout the band may be achieved.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings in which like reference characters refer to similar or corresponding parts and in which:

Fig. 1 is a schematic circuit, partly in block diagram, of one form of a variable attenuation unit, in accordance with the invention, comprising n component equalizer sections and having an insertion loss characteristic corresponding to one term of a Fourier series;

Fig. 2 shows another form of attenuation unit, similar to the one of Fig. 1 except that the fixed resistors of the component sections are connected, respectively, in parallel with their terminal impedances instead of in series therewith;

Fig. 3 is a schematic circuit of a subsidiary four-terminal network suitable for use in the component equalizer sections shown in Figs. 1 and 2;

Fig. 4 shows three units of the type shown in Fig. 1 or Fig. 2, each comprising two equalizer sections, coupled in tandem by resistance pads

to provide a variable attenuation network the over-all insertion loss characteristic of which corresponds to three terms of a Fourier series;

Fig. 5 shows curves which give an indication of how much the insertion loss characteristic of the network of Fig. 1 or Fig. 2, referred to a constant loss, departs from a pure cosine curve when only one or two component equalizer sections are used;

Fig. 6 shows four units of the type shown in Fig. 1, each comprising a single section, which will provide an insertion loss characteristic corresponding to four terms of a Fourier series;

Fig. 7 shows a variable attenuation network similar to the one of Fig. 6 except that each of the units comprises a single section of the type shown in Fig. 2; and

Fig. 8 is a schematic circuit, partly in block diagram, of an automatic regulating network employing a variable attenuation network of the type shown in Fig. 6 or Fig. 7 and having four controls actuated by individual pilot currents.

Taking up the figures in more detail, Fig. 1 shows one form of the variable attenuation unit in accordance with the invention which may be so designed that its insertion loss characteristic, when referred to a constant loss, corresponds to one term of a Fourier series. This term may be the fundamental or any of the higher harmonics. The unit has a pair of input terminals 1, 2 to which are connected a wave source of impedance Z_s and voltage E and a pair of output terminals 9, 10 to which the load impedance Z_L is connected. Between the input and output terminals are shown n variable attenuation equalizer sections N_1, N_2, N_3 and N_n , connected in tandem and coupled together in a manner to reduce interaction between the sections. As shown, the coupling means may be the T-type resistance pads P_1, P_2 and P_3 . Other means of coupling the sections may, however, be employed. Each of the equalizer sections N_1 to N_n is of the type shown in Fig. 11 of the above-mentioned Bode patent. The section N_1 , for example, comprises a variable impedance branch connected in series between the input impedance Z_s and an output impedance Z_R , which is the impedance looking into the pad P_1 at the terminals 3, 4. This series impedance branch comprises a fixed resistor R_{11} to the terminals of which are connected the terminals 5, 6 of a four-terminal subsidiary network M_1 which has a constant resistance image impedance and is terminated at its other terminals 7, 8 in a variable resistor R_{21} of value R . The equalizer sections N_2, N_3 and N_n have similarly arranged fixed series resistors R_{12}, R_{13} and R_{1n} , respectively, and subsidiary networks M_2, M_3 and M_n which are terminated, respectively, in the variable resistors R_{22}, R_{23} and R_{2n} .

Equation 23 of the above-mentioned Bode patent shows that, for transmission between terminal impedances Z_s and Z_R , the insertion factor e^{θ} for an equalizer section such as N_1 may be expressed as

$$e^{\theta} = e^{\alpha} \frac{1+x \frac{e^{\psi} + \tanh \Psi}{1+e^{\psi} \tanh \Psi}}{x + \frac{e^{\psi} + \tanh \Psi}{1+e^{\psi} \tanh \Psi}} \quad (1)$$

where x is the ratio of the terminating resistance R to the image impedance R_0 of the subsidiary network M_1 , Ψ is the image transfer constant for the network M_1 , φ is a constant and is equal to θ_0 and e^{φ} is the insertion factor for the

section when x is unity. It may be shown from Equation 1 that

$$\tanh \frac{\theta}{2} = \frac{x-1}{x+1} \tanh \frac{\theta_0}{2} e^{-\varphi} \quad (2)$$

now, letting

$$U = \frac{x-1}{x+1} \quad (3)$$

and

$$K = \tanh \frac{\theta_0}{2} \quad (4)$$

and substituting in Equation 2 gives

$$\tanh \frac{\theta}{2} = UK e^{-\varphi} \quad (5)$$

from which

$$\theta = 2 \tanh^{-1} UK e^{-\varphi} \quad (6)$$

Expanding this expression for θ in a well-known series gives

$$\theta = 2UK e^{-\varphi} + \frac{(2UK)^3 e^{-3\varphi}}{12} + \frac{(2UK)^5 e^{-5\varphi}}{80} + \dots \quad (7)$$

for the first three terms. Now introducing the relation that

$$\Psi = \alpha + j\beta \quad (8)$$

where α is the attenuation constant and β is the phase constant of the image transfer constant Ψ gives

$$\theta = (2UK e^{-2\alpha}) e^{-j2\beta} + \frac{(2UK e^{-2\alpha})^3 e^{-j6\beta}}{12} + \frac{(2UK e^{-2\alpha})^5 e^{-j10\beta}}{80} + \dots \quad (9)$$

The quantity $2UK e^{-2\alpha}$ in parenthesis, which will be denoted by C , will be independent of frequency if α is independent of frequency. The magnitude of C , however, is proportional to U , which it is seen from Equation 3 can take on all values from -1 to $+1$, assuming that the variable terminating resistance R may be varied from zero to infinity. Substituting C for the quantity $2UK e^{-2\alpha}$ in Equation 9 the series becomes

$$\theta = C e^{-j2\beta} + \frac{C^3}{12} e^{-j6\beta} + \frac{C^5}{80} e^{-j10\beta} + \dots \quad (10)$$

from which it is found that the insertion loss A_n in nepers for the section N_1 is

$$A_n = C \cos 2\beta + \frac{C^3}{12} \cos 6\beta + \frac{C^5}{80} \cos 10\beta + \dots \quad (11)$$

and the phase shift B_r in radians is

$$B_r = C \sin 2\beta + \frac{C^3}{12} \sin 6\beta + \frac{C^5}{80} \sin 10\beta + \dots \quad (12)$$

If, now, it is assumed that the phase constant β is proportional to the frequency f , that is,

$$\beta = kf \quad (13)$$

where k is a numerical constant, the insertion loss A_d in decibels is given by

$$A_d = 8.686 \left(C \cos 2kf + \frac{C^3}{12} \cos 6kf + \frac{C^5}{80} \cos 10kf + \dots \right) \quad (14)$$

and the phase shift B_d in degrees is given by

$$B_d = 57.3 \left(C \sin 2kf + \frac{C^3}{12} \sin 6kf + \frac{C^5}{80} \sin 10kf + \dots \right) \quad (15)$$

Equation 14 shows that, for the conditions assumed, the insertion loss for a single section such as N_1 of Fig. 1, referred to a constant loss, is the

sum of a pure cosine curve and the odd harmonics thereof. The harmonics, however, have considerably less amplitude than the fundamental, and their amplitude decreases rapidly as the order increases. In Fig. 5 curve 13 gives the magnitude of the third harmonic in decibels and curve 14 that of the fifth harmonic, as a function of the magnitude of the fundamental.

In order to obtain a more nearly pure cosine characteristic additional equalizer sections, such as N_2 , N_3 and N_n of Fig. 1, may be added in tandem. Each section is so designed that its insertion loss, when referred to a constant loss, is equal in magnitude but opposite in sign to one of the higher order terms of Equation 14. Each added section will, therefore, annul the contribution of one of these terms, thus making the over-all characteristic, referred to a constant loss, more nearly a pure cosine curve. The section N_2 may, for example, be designed to have a loss characteristic which, referred to a constant loss, will be equal in magnitude, but opposite in sign, to the second term

$$\frac{C^2}{12} \cos 6kf$$

In order to do this the phase constant β_2 of the subsidiary network M_2 must be three times as large as β over the frequency range of interest. That is,

$$\beta_2 = 3\beta = 3kf \quad (16)$$

In like manner the network N_3 is designed to annul the contribution of the third term,

$$\frac{C^3}{80} \cos 10kf$$

and the subsidiary network M_3 will have a phase constant β_3 equal to

$$\beta_3 = 5\beta = 5kf \quad (17)$$

The number n of sections to be employed will depend upon the allowable deviation from a pure cosine curve for the over-all characteristic. The variable terminating resistors R_{21} , R_{22} , R_{23} and R_{2n} may be arranged for unitary control, if desired, as indicated by the dashed line 15.

Fig. 3 is a schematic circuit of a network which is suitable for use as the subsidiary four-terminal network M_1 . It is a constant resistance, all-pass, lattice structure of the type shown, for example, as network 14 in Appendix IV of the paper by O. J. Zobel in the Bell System Technical Journal for July, 1928, pages 438 to 534. It comprises two equal series impedance branches Z_1 and two equal lattice impedance branches Z_2 which have the relationship

$$Z_1 Z_2 = R_0^2 \quad (18)$$

where R_0 is the image impedance and is a constant resistance. It may be so designed that its phase constant β is substantially proportional to frequency over the range of interest. Since the phase constant β_2 of the network M_2 must be equal to 3β , three lattice structures of the type shown in Fig. 3 connected in tandem may be used for this network. Likewise, five such lattices may be used for the network M_3 , and $(2n-1)$ for the network M_n .

Fig. 2 shows another form of the variable attenuation unit, similar to the one of Fig. 1 except that each of the equalizer sections N_1 , N_2 , N_3 and N_n is of the type shown in Figs. 12 and 27 of the above-mentioned Bode patent. In this case the variable impedance branch is connected

in parallel with the input impedance Z_s and the output impedance Z_L . In the section N_1 , for example, this shunt branch comprises a fixed resistor R_{21} having one terminal connected to terminal 5 of the subsidiary four-terminal network M_1 which is terminated at its other end in the variable resistor R_{21} . In a similar manner in the other sections the fixed resistors R_{22} , R_{23} and R_{2n} are associated, respectively, with the auxiliary networks M_2 , M_3 and M_n . The tandem connected sections are coupled by means of the resistance pads P_1 , P_2 and P_3 , as in Fig. 1. By following the design procedure outlined above the unit shown in Fig. 2 may be designed to provide the same type of over-all loss characteristic as that obtainable with the unit of Fig. 1. For a cosine curve the auxiliary networks M_1 , M_2 , M_3 and M_n will have phase constants which are related in the ratios of odd integers.

Fig. 4 is a schematic circuit, partly in block diagram, of three variable units, S_1 , S_2 and S_3 , each of the type shown in Fig. 1 or Fig. 2, connected in tandem between the input impedance Z_s and the load impedance Z_L and coupled in such a way as to reduce interaction between the units. The coupling means may be the resistance pads P_{11} and P_{12} , as shown, or, as already mentioned, the units may be located at different points along a transmission line, separated by sections of the line. Each unit comprises two sections, such as N_1 and N_2 , and therefore has two controls, such as R_{21} and R_{22} . Each unit may, of course, comprise any number of sections, with a corresponding number of controls. One of the units, say S_1 , is designed to have a loss characteristic which, when referred to a constant loss, is a cosine curve. The unit S_2 is designed to furnish the second harmonic curve, and the unit S_3 the third harmonic curve. Additional units may, of course, be employed if higher harmonics are required. The desired characteristic is analyzed on the basis of a Fourier series of cosine terms. By employing a sufficient number of units, each with a sufficient number of controls, and by properly setting the controls the desired characteristic may be simulated to any required degree.

Fig. 6 shows a variable attenuation network similar to the one of Fig. 4 except that it is made up of four units, S_1 to S_4 , and each unit comprises only a single equalizer section, of the type of N_1 of Fig. 1, employing a fixed resistor R_{11} in a series branch. The section S_1 is designed to supply the fundamental cosine curve and the sections S_2 , S_3 and S_4 , respectively, the second, third and fourth harmonics. The phase constants of the auxiliary networks M_1 , M_{12} , M_{13} and M_{14} will, therefore, have the ratios 1:2:3:4. Each of the variable resistors R_{21} , R_{22} , R_{23} and R_{24} controls the magnitude and sign of the term furnished by the unit with which the resistor is associated. Since the unit S_1 has only a single section, the second and all higher terms in its loss characteristic, as given by Equation 14, are neglected. It will be noted, however, that the second term, involving cosine $6kf$, is of the form of the third harmonic. Therefore, the unit S_3 , which supplies the third harmonic term, may be adjusted to correct for the first neglected term in the fundamental furnished by the unit S_1 .

Fig. 7 shows a variable network similar to the one of Fig. 6 except that the sections are of the type of N_1 of Fig. 2, in which the fixed resistor R_{21} is in a shunt branch.

Fig. 8 shows a regulating system for automatically equalizing the attenuation distortion caused, for example, by temperature changes in a long telephone circuit. The distorted signal is impressed upon the input terminals 1, 2 of the regulating network 16, which provides the equalization, amplified in the amplifier 17 and delivered to the load Z_L . The network 16 is of the type shown in Fig. 6 or Fig. 7 but the variable resistors R_{21} , R_{42} , R_{43} and R_{44} , which individually control the fundamental and higher order terms, are replaced, respectively, by the thermistors T_1 , T_2 , T_3 and T_4 , associated, respectively, with the heaters H_1 , H_2 , H_3 and H_4 . These heaters are under the control of individual pilot currents which are taken off at the points 18, 19 on the output side of the amplifier 17 and separated by means of the band-pass filters F_1 , F_2 , F_3 and F_4 . The pilot frequencies are spaced throughout the range to be equalized and each pilot is preferably located in a region where the component characteristic controlled by it makes its maximum contribution to the over-all loss characteristic.

As already pointed out in connection with Fig. 4, the different units of the regulating network may be located at different points along the transmission line, say one at each repeater point. One unit may, for example, be designed to compensate for the slope distortion and placed at one repeater point, a second unit, at a second repeater point, may be designed to correct the so-called bulge distortion, and other units, at other repeater points, may be designed to compensate for higher order distortion effects. Any required number of units, either greater or less than four, may, of course, be employed.

What is claimed is:

1. In combination, a plurality of tandem connected variable attenuation equalizer sections each comprising terminal impedances and an interposed variable impedance, each of said interposed impedances comprising a fixed resistor in combination with a subsidiary four-terminal network terminated by a variable resistor of value R , said subsidiary network having an image impedance R_0 which is a constant resistance and an image transfer constant Ψ the attenuation constant of which is independent of frequency and the phase constant of which is proportional to frequency, in each of said equalizer sections the component impedances being so proportioned with respect to each other that the insertion factor e^0 for transmission between said terminal impedances may be expressed by the equation

$$e^0 = e^{e^0} \frac{1 + x \frac{e^{e^0} + \tanh \Psi}{1 + e^{e^0} \tanh \Psi}}{x + \frac{e^{e^0} + \tanh \Psi}{1 + e^{e^0} \tanh \Psi}}$$

wherein x is the ratio of R to R_0 and e^{e^0} is the insertion factor for said equalizer when x is unity and said phase constants of said subsidiary networks being integrally related to each other.

2. The combination in accordance with claim 1 in which said phase constants are related to each other in the ratios of odd integers.

3. The combination in accordance with claim 1 in which said phase constants are related to each other in the ratios of 1:2:3: . . . : n , where n is an integer.

4. The combination in accordance with claim 1 in which said phase constants are related to each other in the ratios of 1:3:5: . . . : $(2n-1)$ where n is an integer.

5. The combination in accordance with claim 1 in which said interposed variable impedance is connected in series with said terminal impedances.

6. The combination in accordance with claim 1 in which said interposed variable impedance is connected in parallel with said terminal impedances.

7. The combination in accordance with claim 1 in which said fixed resistor is connected in series with said terminal impedances and a pair of terminals of said auxiliary network are connected, respectively, to the terminals of said fixed resistor.

8. The combination in accordance with claim 1 in which one terminal of said fixed resistor is connected to one terminal of each of said terminal impedances, the other terminal of said fixed resistor is connected to one terminal of a pair of terminals of said auxiliary network and the other terminal of said pair is connected to each of the other terminals of said terminal impedances.

9. The combination in accordance with claim 1 in which all of said variable resistors are under unitary control.

10. The combination in accordance with claim 1 in which said sections are coupled together by means which reduce the interaction between said sections.

11. The combination in accordance with claim 1 in which said sections are coupled together by resistance pads.

12. The combination in accordance with claim 1 in which said variable resistors are thermistors.

13. The combination in accordance with claim 1 in which said sections are coupled together by means which reduce the interaction between said sections and in which all of said variable resistors are under unitary control.

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