Dec. 20, 1960 R. W. DE MONTE 2,965,859

SIMULATION NETWORK

Filed Feb. 27, 1959 2 Sheets-Sheet 1

FIG. 1

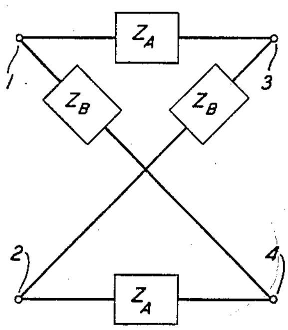

FIG. 2

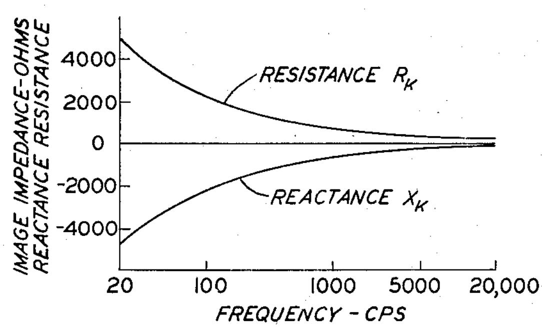

FIG. 4

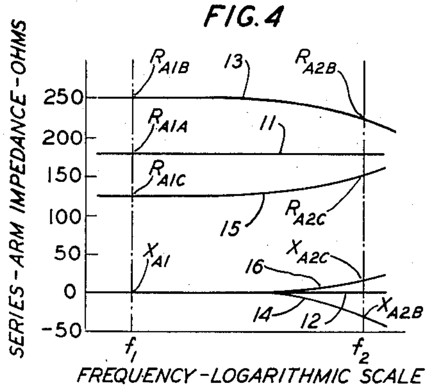

FIG. 3

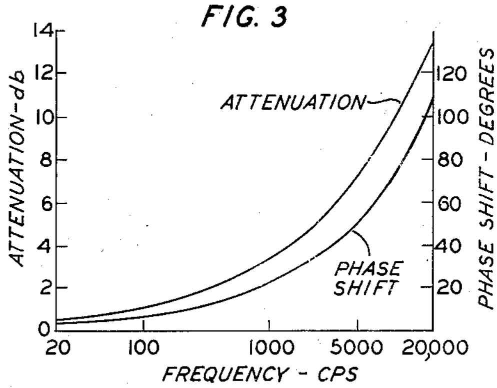

FIG. 5

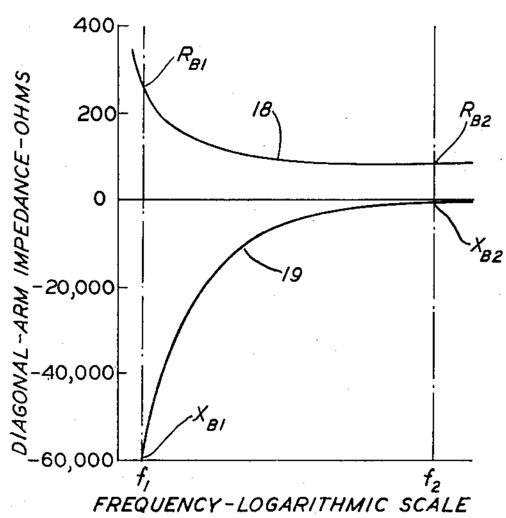

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FIG. 6

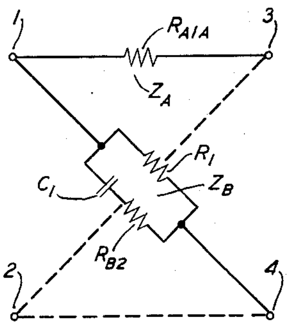


FIG. 7

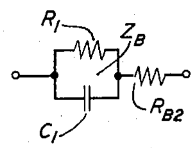


FIG. 8

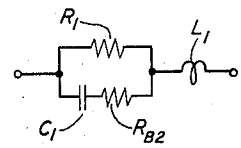


FIG. 9

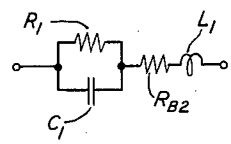


FIG. 10

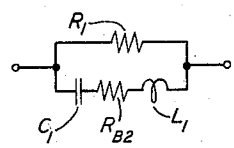


FIG. 12

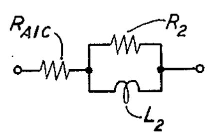


FIG. 11

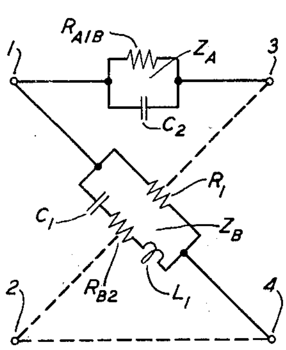
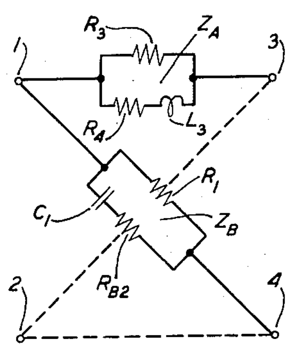


FIG. 13



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SIMULATION NETWORK

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4 Claims. (Cl. 333—23)

This invention relates to wave transmission networks and more particularly to a simulation network or artificial line.

The object of the invention is to simulate a length of smooth transmission line in both image impedance and propagation over a wide band of frequencies. Related objects are to simplify the structure, increase the precision, and widen the band of a simulation network.

In many wave transmission systems, the need often arises for a simple, easily designed network which will closely simulate the image impedance and propagation characteristics of a section of smooth transmission line over a wide band of frequencies. Such networks are especially useful in telephone, telegraph, and data transmission systems, and in test circuits for such systems.

The network of the present invention fulfills these requirements in a symmetrical lattice structure adapted to simulate any fractional part of a loading section of smooth transmission line. The branches of the lattice may be synthesized directly from impedance and transmission measurements made on a half section of the line at frequencies near the edges of the band. For a critical length of section, each series branch of the lattice comprises only a resistor. For longer sections, a parallel capacitor is added. For shorter sections, a second resistor and an inductor are included. Each diagonal branch is the equivalent of a resistor in series with the parallel combination of a second resistor and a capacitor. In some cases, a series inductor is desirable in the diagonal branch.

With these comparatively simple simulation networks, a frequency band of more than two decades may be covered with a design error of less than 0.5 percent in both the real and the imaginary parts of the image impedance and the propagation constant of the line section. The design method is perfectly straightforward and avoids any cut-and-try procedure. With the aid of suitable loading coils, the networks may be used to simulate the transmission characteristics of any type of loaded line or cable having any fractional length of end section.

The nature of the invention and its various objects, features, and advantages will appear more fully in the following detailed description of the typical embodiments illustrated in the accompanying drawing, of which:

Fig. 1 is a generalized schematic circuit of a simulation network in accordance with the invention;

Fig. 2 is a graph of the resistive and reactive components of the image impedance of a typical section of smooth transmission line over the frequency band of interest;

Fig. 3 is a graph of the attenuation and phase shift per 6000 feet of the line over the band;

Fig. 4 shows three typical impedance characteristics of the series branches of lattice networks for simulating sections of line which are, respectively, equal to, shorter than, or longer than the critical length;

Fig. 5 shows a typical impedance characteristic of the diagonal branch of a lattice network for simulating a section of line of any length;

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Fig. 6 is a schematic circuit of a simulation network in accordance with the invention for a line of critical length;

Fig. 7 shows an equivalent circuit of the diagonal branch of Fig. 6;

Figs. 8, 9, and 10 show equivalent circuits of the diagonal branch when an inductor is included;

Figs. 11 and 13 are schematic circuits of simulation networks in accordance with the invention for line sections with lengths, respectively, longer and shorter than critical; and

Fig. 12 shows an equivalent circuit of the series branch of Fig. 13.

As shown in Fig. 1, the simulation network in accordance with the present invention is a symmetrical lattice structure comprising two equal series impedance branches Z_A and two equal diagonal branches Z_B connected between a pair of input terminals 1, 2 and a pair of output terminals 3, 4.

Fig. 2 shows the resistive component R_K and the reactive component X_K of the image impedance Z_K of a typical transmission line to be simulated. A logarithmic scale is used for the frequency, which covers a range of 20 to 20,000 cycles per second. The impedance shown is that of a cable using 26-gauge copper wire. This impedance may be computed from the primary constants of the line, or it may be found by measuring the open-circuit impedance Z_{OC} and the short-circuit impedance Z_{SC} of the section at frequencies throughout the range of interest and using the formula

$$Z_K=\sqrt{Z_{OC}Z_{SC}}=R_K+jX_K \qquad (1)$$

Fig. 3 gives the attenuation in decibels and the phase shift in degrees of a 6000-foot section of this cable.

The lattice network shown in Fig. 1 will exactly simulate a section of smooth line of length S if the branch impedances Z_A and Z_B are equal, respectively, to the short- and open-circuit impedances of a half section having a length of S/2. Fig. 4 shows the required resistance and reactance characteristics of the series branch Z_A for three typical cases which will be designated A, B, and C. Case A is for a section of line of critical length S_A, case B for a longer length S_B, and case C for a shorter length S_C. The frequencies f_1 and f_2 are located at or near the limits of the band of interest. For case A, the resistive component **11** is substantially constant over the band and the reactive component **12** is substantially zero. For case B, the resistive component **13** is falling and the reactive component **14** is negative and increasing in magnitude at the higher frequencies. For case C, the resistive component **15** is rising and the reactive component **16** is positive and rising in the vicinity of f_2. All of these curves are smooth and monotonic between f_1 and f_2.

In Fig. 5, the curve **18** shows the resistive component and the curve **19** the reactive component of a typical impedance Z_B required for each of the diagonal branches of the lattice. The resistance falls monotonically and the reactance is negative, decreases monotonically, and approaches zero at the higher frequencies. These curves are of this form for all three cases A, B, and C.

The next step is to synthesize impedance branches Z_A and Z_B which will give the required simulation over the band with the least number of elements. In accordance with the invention, the synthesis is based upon the required resistance and reactance values at only the two frequencies f_1 and f_2, which are 100 and 10,000 cycles per second in the following examples. The simplest structure is required for case A, where the line to be simulated has a critical length S_A of 4229 feet in the example chosen. The lattice circuit is shown in Fig. 6.

Only one series branch Z_A and one diagonal branch Z_B are shown. The omitted branches are represented by the broken lines between the terminals **2, 3** and **2, 4.** Each impedance Z_A is constituted by a resistor having a value equal to the short-circuit resistance of a half section of the line with a length equal to $S_A/2$, at the frequency f_1. As read from the curve **11** of Fig. 4, this value is R_{A1A}.

Each diagonal branch Z_B comprises a resistor R_1 shunted by the series combination of a resistor R_{B2} and a capacitor C_1. The resistor R_{B2} has a value equal to the open-circuit resistance of the half section at the frequency f_2, as is indicated in Fig. 5. The value of the resistor R_1 is equal to the reciprocal of the open-circuit conductance G_{B1} of the half section at f_1. In terms of the resistance R_{B1} and the reactance X_{B1} shown on Fig. 5,

$$R_1=\frac{1}{G_{B1}}=\frac{R_{B1}^2+X_{B1}^2}{R_{B1}} \quad (2)$$

The capacitor C_1 has a value equal to the open-circuit susceptance B_{B1} of the half section at f_1 divided by $2\pi f_1$. The formula is

$$C_1=\frac{B_{B1}}{2\pi f_1}=\frac{X_{B1}}{2\pi f_1(R_{B1}^2+X_{B1}^2)} \quad (3)$$

In the present example of case A, the component elements have the following values:

R_1	ohms	14,000,000
R_{A1A}	do	177.2
R_{B2}	do	62.0
C_1	microfarad	0.03172

As shown in Fig. 7, the resistor R_1 in the diagonal branch Z_B may be shunted across the capacitor C_1 only, if desired. Since R_1 is so large, the value of the impedance branch is substantially unchanged.

When the band between f_1 and f_2 is extremely wide, or when f_2 is high, a series inductor L_1 may be added to the diagonal branch Z_B to improve the simulation at the higher frequencies. The reactance of L_1 is made equal to the difference between the reactance of C_1 and the desired reactance X_{B2} at f_2. Thus, the inductance of L_1 is

$$L_1=\frac{1/2\pi f_2 C_1-X_{B2}}{2\pi f_2} \quad (4)$$

Figs. 8, 9, and 10 show substantially equivalent circuits for Z_B with L_1 added. In the present example of case A, L_1 is so small that it may be omitted.

Fig. 11 is a schematic circuit of a typical example of a case B network, to simulate a section of line of length S_B equal to 6000 feet. Each diagonal branch Z_B is the same as the one shown in Fig. 10. The component elements are evaluated as described above except that the open- and short-circuit impedances apply to a half section of length $S_B/2$ instead of $S_A/2$.

The series branch Z_A comprises a resistor R_{A1B} and a capactior C_2 connected in parallel. The value of the resistor is equal to the short-circuit resistance of the half section at f_1, as found on the curve **13** in Fig. 4. The capacitor C_2 has a value equal to the short-circuit susceptance B_{A2B} of the half section at f_2 divided by $2\pi f_2$. The formula is

$$C_2=\frac{B_{A2B}}{2\pi f_2}=\frac{X_{A2B}}{2\pi f_2(R_{A2B}^2+X_{A2B}^2)} \quad (10)$$

The elements in the example of case B shown in Fig. 11 have the following values:

R_1	ohms	14,300,000
R_{A1B}	do	250.0
R_{B2}	do	86.2
C_1	microfarad	0.04484
C_2	do	0.00752
L_1	henry	0.000071

Fig. 12 shows the series branch Z_A for case C, in which the section to be simulated has a length S_C shorter than S_A. The branch comprises a resistor R_{A1C} in series with the parallel combination of a second resistor R_2 and an inductor L_2. As in th other cases, R_{A1C} has a value equal to the short-circuit resistance of a half section of line of length $S_C/2$ at f_1. The value is shown on the curve **15** in Fig. 4. The elements R_2 and L_2 are added to take care of the rising character of the curves **15** and **16.** Their values depend upon the difference between the short-circuit resistances R_{A2C} and R_{A1C} and the difference between the short-circuit reactances X_{A2C} and X_{A1} at the frequencies f_2 and f_1, as shown in Fig. 4. The element values are found from the formulas

$$R_2=\frac{(R_{A2C}-R_{A1C})^2+(X_{A2C}-X_{A1})^2}{R_{A2C}-R_{A1C}} \quad (5)$$

$$L_2=\frac{(R_{A2C}-R_{A1C})^2+(X_{A2C}-X_{A1})^2}{2\pi f_2(X_{A2C}-X_{A1})} \quad (6)$$

It is sometimes desirable to transform the series branch Z_A of Fig. 12 into the equivalent branch shown in Fig. 13. Here, Z_A comprises a resistor R_3 shunted by the series combination of a resistor R_4 and an inductor L_3. The conversion formulas are the following:

$$R_3=R_2+R_{A1C} \quad (7)$$

$$R_4=R_{A1C}+\frac{R_{A1C}^2}{R_2} \quad (8)$$

$$L_3=L_1\left(1+\frac{R_{A1C}}{R_2}\right)^2 \quad (9)$$

In this circuit, the value of R_4 may be reduced to allow for the inherent resistance associated with L_3.

The diagonal branch Z_B in Fig. 13 is the same as the one shown in Fig. 6 except that the elements are evaluated from the open-circuit impedance of a half section of length $S_C/2$.

As an example of case C, a network to simulate a line 3000 feet long will have the following element values:

R_1	ohms	34,700,000
R_3	do	167.36
R_4	do	493.0
R_{B2}	do	46.0
C_1	microfarad	0.02245
L_3	henry	0.00910

It is to be understood that the above-described arrangements are only illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A symmetrical lattice network for simulating a section of smooth transmission line over a band extending between a frequency f_1 and a higher frequency f_2, each series branch of the lattice having an equivalent circuit which includes a resistor of value R_{A1} and each diagonal branch being the equivalet of a resistor of value R_{B2} in series with the parallel combination of a resistor of value $1/G_{B1}$ and a capacitor of value $B_1/2\pi f_1$, where R_{A1} is the short-circuit resistance of a half section of the line at f_1, R_{B2} is its open-circuit resistance at f_2, G_{B1} its open-circuit conductance at f_1, and B_{B1} its open-circuit susceptance at f_1.

2. A symmetrical lattice network for simulating a section or transmission line over a band extending between a frequency f_1 and a higher frequency f_2, each series branch of the lattice having at f_1 a resistance approximately equal to the short-circuit resistance of a half section of the line at f_1, and each diagonal branch being equivalent to the series combination of a resistor of value R_{B2}, an inductor of value $D/2\pi f_2$, and the parallel combination of a resistor of value $1/G_{B1}$ and a capacitor of

value $B_{B1}/2\pi f_1$, where R_{B2} is the open-circuit resistance of the half section at f_2, G_{B1} its open-circuit conductance at f_1, B_{B1} its open-circuit susceptance at f_1, and D the difference between the reactance of the capacitor and the open-circuit reactance of the half section at f_2.

3. A symmetrical lattice network for simulating a section of smooth transmission line over a band of frequencies extending between a frequency f_1 and a higher frequency f_2, each series branch of the lattice including the parallel combination of a resistor of value R_{A1} and a capacitor of value $B_{A2}/2\pi f_2$ and each diagonal branch being the equivalent of a resistor of value R_{B2} in series with the parallel combination of a resistor of value $1/G_{B1}$ and a capacitor of value $B_{B1}/2\pi f_1$, where R_{A1} is the short-circuit resistance of a half section of the line at f_1, B_{A2} is its short-circuit susceptance at f_2, R_{B2} its open-circuit resistance at f_2, G_{B1} its open-circuit conductance at f_1, and B_{B1} its open-circuit susceptance at f_1.

4. A symmetrical lattice network for simulating a section of smooth transmission line over a band extending between a frequency f_1 and a higher frequency f_2, each series branch of the lattice being the equivalent of a resistor of value R_{A1} in series with the parallel combination of a resistor of value $(D_R^2+D_X^2)/D_R$ and an inductor of value $(D_R^2+D_X^2)/2\pi f_2 D_X$ and each diagonal branch being the equivalent of a resistor of value R_{B2} in series with the parallel combination of a resistor of value $1/G_{B1}$ and a capacitor of value $B_{B1}/2\pi f_1$, where R_{A1} is the short-circuit resistance of a half section of the line at f_1, D_R the difference between its short-circuit resistances at f_2 and f_1, D_X the difference between its short-circuit reactances at f_2 and f_1, R_{B2} its open-circuit resistance at f_2, G_{B1} its open-circuit conductance at f_1, and B_{B1} its open-circuit susceptance at f_1.

References Cited in the file of this patent

UNITED STATES PATENTS

1,760,973 Zobel ------------------ June 3, 1930

OTHER REFERENCES

Weinberg: A General RLC Synthesis Procedure; Proceedings of the IRE, February 1954, vol. 42, No. 2, pages 427–437.