

July 6, 1937.

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2,085,952

ARTIFICIAL NETWORK

Filed Dec. 29, 1933

2 Sheets-Sheet 1

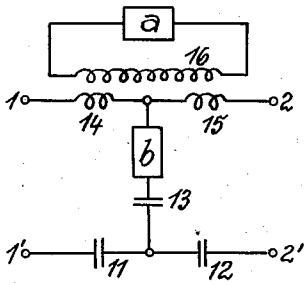


Fig. 1.

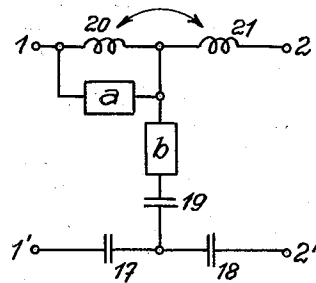


Fig. 2.

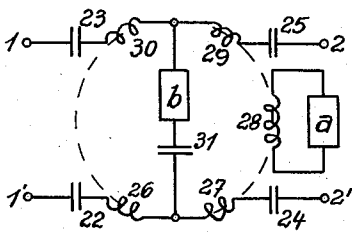


Fig. 3.

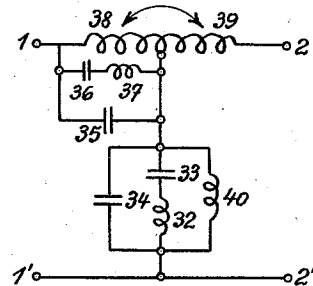


Fig. 4.

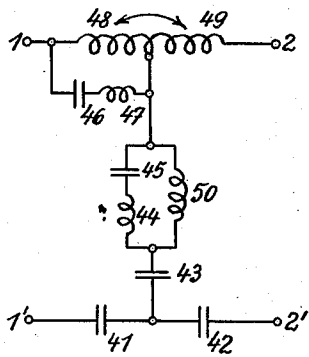


Fig. 5.

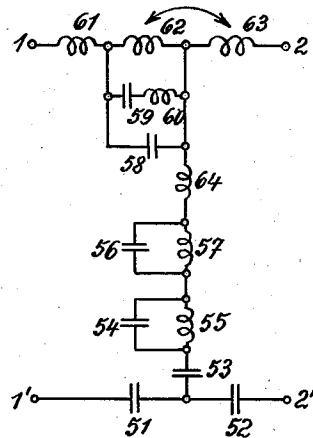


Fig. 6.

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2 Sheets-Sheet 2

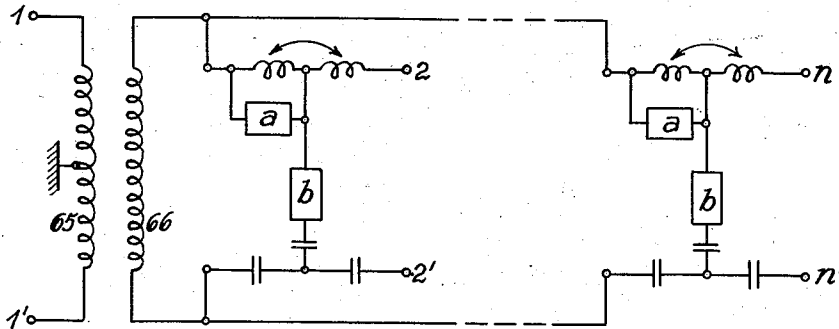


Fig. 7.

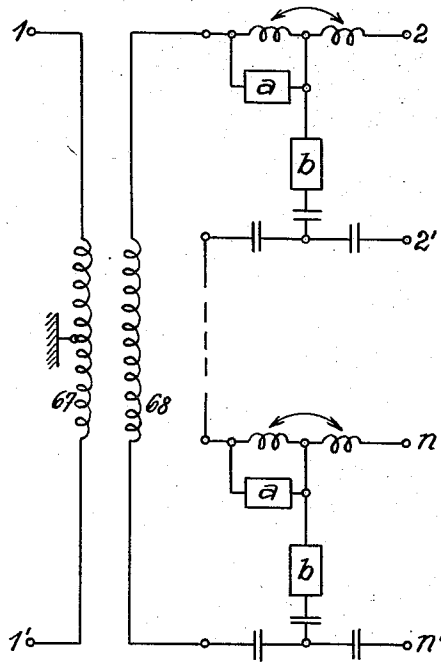


Fig. 8.

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# UNITED STATES PATENT OFFICE

2,085,952

## ARTIFICIAL NETWORK

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Application December 29, 1933, Serial No. 704,460  
In Germany January 23, 1933

3 Claims. (Cl. 178-44)

The present invention relates to electrical-impedance or artificial networks, such as are used for attaining or approximating to predetermined frequency characteristics.

5 A network having impedance that approximates to the frequency characteristics of a telephone line or a combination of telephone lines, for example, is an impedance or artificial network. An attenuation or phase-distortion-correction network is also an impedance or artificial network because it produces the desired attenuation or phase correction as a function of frequency. Wave filters and retarding networks are further such examples.

15 An object of the present invention is to provide new and improved impedance or artificial networks.

In *Siebschaltungen*, V. D. I. Verlag, 1931, Wilhelm Cauer, there is disclosed, in Fig. 4, for example, an artificial network having comparatively many ordinary transformers, constituting the equivalent of a symmetrical, four-terminal network without mutual inductances, but that is more economical than the latter symmetrical network in that it contains fewer circuit elements.

Another object of the invention is to reduce the number of such transformers in artificial networks.

30 The employment of practically ideal transformers is often disadvantageous, and a further object of this invention, therefore, is to avoid such use.

The present invention further contemplates a new and advantageous application of mutual inductance in artificial networks. To this end, a feature of the invention resides in having the artificial network comprise two pairs of terminals and, besides other circuits, one mesh going through one pair of the terminals and another mesh going through the other pair of terminals, the two meshes having a common branch, and each containing further an additional branch that is not common, but that comprises windings coupled to constitute a transformer, the transformer being loaded by an impedance containing at least two circuit elements. Such impedance is called lumped impedance. The transformer may be loaded by direct galvanical connection or by tight or loose coupling by a special winding. The loading impedance should be such that it is different from zero at frequency zero, even if resistances are neglected. The loading impedance, furthermore, should not lie in either of the said two meshes. The inductances of the windings

are of about the same value as the other circuit elements of the network. In special cases, where the coupling is tight, the windings may be wound bifilar. In some special cases, where the loading impedance shunts both the windings, the general idea of the invention leads to a network of the known bridged-T type.

The reason for the various conditions set out in the foregoing paragraph and the rules how to apply the invention to a given problem will become clear after a discussion of several examples.

It can be mathematically demonstrated and will be illustrated hereinafter in connection with Figs. 4 to 6 that, especially for each symmetrical-reactance, four-terminal network, a network without superfluous circuit elements may be obtained by applying mutual inductance, according to the invention, at but a single place, and this constitutes another object of the present invention. The resulting economy of construction of artificial networks is obvious. The invention is not, however, restricted to artificial networks of this character, and is applicable to other four-terminal networks.

In the accompanying drawings, Figs. 1 to 3 are diagrammatic views illustrating artificial networks embodying the invention; Figs. 4 to 6 are similar views of wave-filters, constructed in accordance with the present invention; and Figs. 7 and 8 are similar views illustrating the invention as applied to separating filters.

In all the figures of the drawings, a pair of input terminals of the network is shown at 1, 1' and a pair of output terminals at 2, 2'. In Figs. 7 and 8, an additional pair of output terminals is indicated at  $n, n'$ , and there may be as many additional pairs of output terminals as desired. The input terminals may, of course, be employed as the output terminals of the network, in which case the output terminals shown would be used as the input terminals.

Two-terminal impedances, each having at least two circuit elements, are shown at  $a$ . These two-terminal impedances are assumed to have a value different from zero at zero frequency, even if resistances are neglected, but they are not restricted in character, except to this extent.

The impedances of the two-terminal networks indicated at  $b$  have no restrictions whatever.

In all the figures, except Fig. 4, there is shown a star of capacities, such as the capacities 11, 12 and 13 in Fig. 1. These are necessary in order that the networks may be suitable, without exception, for use as symmetrical wave filters. In spe-

cial cases, of which the network illustrated in Fig. 4 is an example, these capacities become infinite.

Of the two before-mentioned meshes, referring first to Fig. 1, one extends from terminal 1, through a coil 14, the two-terminal network  $b$  and the capacities 13 and 11, to the terminal 1'. The other mesh extends from terminal 2, through a coil 15, the two-terminal network  $b$  and the capacities 13 and 12, to the terminal 2'. The common branch thus contains the two-terminal network  $b$  and the capacity 13. The branches that are not common contain the coils 14 and 15, which are of finite inductance, but which are coupled inductively to form a transformer. This transformer is loaded by coupling the coils 14 and 15 to a winding 16, and closing the winding 16 through the two-terminal network  $a$ . The impedance network  $a$  is thus formed of at least two circuit elements and is infinite for direct current and does not belong to one of the two meshes.

In Fig. 2, one of the meshes extends from the terminal 1, through a coil 20, the two-terminal network  $b$  and the capacities 19 and 17, to the terminal 1'. The other mesh extends from the terminal 2, through the coil 21, the two-terminal network  $b$  and the capacities 19 and 18, to the terminal 2'. The common branch contains the two-terminal network  $b$  and the capacity 19. The branches that are not common contain the coils 20 and 21, of finite inductance, but coupled inductively to form a transformer. This transformer is loaded by connecting the two-terminal network galvanically with the ends of the winding 20, in the manner of an autotransformer.

Fig. 3 represents a balanced form of the network of Fig. 1. The common branch of both the meshes contains the two-terminal network  $b$  and the capacity 31. One mesh extends from the terminal 1, through a condenser 23, a coil 30, this common branch  $b$ , 31, a coil 26 and a condenser 22, to the terminal 1'. The other mesh extends from the terminal 2, through a condenser 25, a coil 29, the common branch  $b$ , 31, a coil 27 and a condenser 24, to the terminal 2. The inductively coupled branches that are not common may be assumed, according to the invention, to be those with the coils 26 and 27 or those which the coils 29 and 30. The transformer formed by the coils is in each case loaded by the two-terminal network  $a$  by connecting it in circuit with a winding 28 that is coupled to the coils. The condensers 22 and 23 and the condensers 24 and 25 have, in pairs, equal values of capacity.

In Fig. 4, there is illustrated a symmetrical wave-filter of the Cauer class 3b (see Cauer, "New Theory and Design of Wave Filters", Physics, vol. 2, No. 4, 1932, pages 242 to 268, and other Cauer publications there cited, but embodying the invention according to Fig. 2. The coils 38 and 39 form a transformer, as described in connection with the coils 20 and 21 of Fig. 2. These coils have the same, essentially finite inductance, and are tightly coupled. Such a transformer may be constituted, in practice, for example, by a double-wound transformer with a closed iron core. This transformer is shown loaded by a two-terminal network  $a$  formed by two condensers 35 and 36 in parallel to each other and to the coil 38, and one coil 37 in series with the condenser 36. The common branch of the meshes comprises a coil 32 and a condenser

33 in series, with a coil 40 and a condenser 34 in shunt thereto and to each other. At zero frequency, the two-terminal network  $a$  has infinite impedance. The advantage of this invention is shown by a comparison thereof with a known, equivalent network, without superfluous elements, containing two non-ideal transformers, such as is shown in Fig. 13 of the before-mentioned "Siebschaltungen."

Reference has been made above to a Cauer class 3b. Though this nomenclature is now understood by persons skilled in the art, it may be stated, for greater clearness, that a filter belongs to this class 3b, if it is equivalent to a lattice section (see, for example, Fig. 1 of the "Siebschaltungen" or Cauer's said article in Physics, Fig. 3) where the two-terminal networks opposite to each other are equal in pairs and have the impedance functions

$$Z_1 = \frac{\mu\lambda(\lambda^2 + \omega_-^2)}{m(\lambda^2 + \omega_{-1}^2)(\lambda^2 + \omega_a^2)}$$

$$Z_2 = \frac{m\mu\lambda(\lambda^2 + \omega_a^2)}{(\lambda^2 + \omega_{-a}^2)(\lambda^2 + \omega_1^2)}$$

where  $\omega_1$  and  $\omega_{-1}$  are the cut-off frequencies,  $m$ ,  $\omega_a$  and  $\omega_{-a}$  are parameters and  $\lambda = i\omega$ , where  $\omega$  is the pulsance.

In Fig. 5, the invention is shown applied, according to Fig. 2, to a symmetrical wave-filter of the Cauer class 3b\*. The transformer is formed by the tightly coupled coils 48 and 49 that, like the coils 20 and 21 of Fig. 2, and 38 and 39 of Fig. 3, have the same, essentially finite inductance. This transformer is loaded by a two-terminal network  $a$ , formed by a series-connected condenser 46 and coil 47 connected across the coil 48. The impedance  $b$ , in this case, is shown as a coil 50, shunted by a series connected coil 44 and condenser 45. A zero frequency, the two-terminal network  $a$  has infinite impedance. This figure especially shows the advantage of the invention; for filters of class 3b\* have heretofore been constructed by W. Cauer (see "Siebschaltungen", Figs. 10 and 11) by means of two and four transformers.

The examples above deal with symmetrical, four-terminal networks. Rules will now be given for applying the invention to symmetrical quadripoles.

A network of lattice type, equivalent to any such network for all frequencies, can be designed, as is known in the art—see, for example, the above-mentioned article in "Physics". Using the same notation as in the said article, one pair of equal, opposite, lumped impedances of the lattice may have the value  $Z_1$ , the other pair the value  $Z_2$ . The further discussion will be restricted to the case where the symmetrical quadripole is composed of reactances and, therefore,  $Z_1$  and  $Z_2$  are reactance functions. The above example of a filter of class 3b is a special case of the nature of the reactance functions  $Z_1$  and  $Z_2$ . More generally, it is shown in the Siebschaltungen how to design the functions and impedances  $Z_1$  and  $Z_2$  to obtain a filter with prescribed characteristics. By known theorems, a given reactance function  $Z_1$  or  $Z_2$  can be realized by different structures (R. M. Foster, "A Reactance Theorem", Bell Syst. Techn. Journ., vol. III, No. 2, April 1924, and W. Cauer, "Die Verwirklichung von Wechselstromwiderständen vorgeschriebener Frequenzabhängigkeit", Archiv f. Elektrotechnik,

vol. XVII, No. 4, 1926). For example, the reactance function

$$\frac{Z_1}{2}$$

where  $Z_1$  is the above function for class 3b, is realized by a structure shown in Fig. 4 containing the coils 32 and 40 and the capacities 33 and 34. Similarly, in the case of class 3b,

$$\frac{Z_2}{2}$$

is realized by the structure containing the coils 37 and 38 and the capacities 35 and 36. In general, any lattice with lumped impedances (reactances)  $Z_1$  and  $Z_2$  can be replaced by the equivalent quadripole of structure Fig. 2, where the impedance structures for  $Z_1$  and  $Z_2$  only appear once instead of twice in the lattice. If at least one of the  $Z_1$  and  $Z_2$ , say  $Z_1$ , is zero for direct currents, the capacities 17, 18 and 19 are infinite (or capacity 19 may be included in the impedance  $b$ , as the case may be), and

$$\frac{Z_1}{2}$$

is realized by a structure *a* shunted by the coil 20 and

$$\frac{Z_2}{2}$$

is realized by a structure *b*. If coil 21 is then made equal to coil 20, and both are coupled tightly, the network of Fig. 2 is equivalent to the lattice with pairs of impedances  $Z_1$  and  $Z_2$ . If, however,  $Z_1$  and  $Z_2$  are not zero for direct currents, a capacity of impedance value

$$D_{17}\lambda^{-1} = D_{18}\lambda^{-1}$$

can be separated from  $Z_1$  and another capacity of impedance value

$$(2D_{19} + D_{17})\lambda^{-1}$$

can be separated from  $Z_2$  so that the remaining part of

$$\frac{Z_1}{2}$$

$$\frac{Z_1}{2} - \frac{1}{2}D_{17}\lambda^{-1} = \frac{\alpha L_{20}}{\alpha + L_{20}}$$

and of

$$\frac{Z_2}{2}$$

$$\frac{Z_2}{2} - \left(D_{19} + \frac{1}{2}D_{17}\right)\lambda^{-1} = b$$

is zero for direct currents and can be realized as before. If necessary, an interchange of  $Z_1$  and  $Z_2$ ,—which does not affect the characteristics of the quadripole except a phase change of  $\pi$  radians,—takes care of the condition of physical realizability that  $D_{19} \geq 0$ . As well as capacities, inductances might be separated from

$$\frac{Z_1}{2} \text{ and } \frac{Z_2}{2}$$

before realizing the rest as before. This is shown by the example of a filter of class 3d, which is shown in Fig. 6.

In Fig. 6, there is shown, according to the invention, for carrier telephony, a filter network of the Cauer class 3d, with loose coupling between the coils 62 and 63. These coils 62 and 63 and a coil 61 are connected between the terminals 1 and 2. The condensers 58 and 59 and coil 60 are connected like the condensers 35 and 36 and the coil 37 of Fig. 4. The impedance  $b$

is constituted of coils 55, 57 and 64 in series, the coils 55 and 57 being respectively shunted by condensers 54 and 56. The condensers 51, 52 and 53 are connected like the condensers 11, 12, 13 of Fig. 1.

The said separated coils are 61, 64 and a coil of the same value as coil 61, which is joined with coil 21 in the notation of Fig. 2, and is part of the coil 63. It follows that the coils 62 and 63 are coupled loosely, which might be an advantage in the case of higher frequencies. The separating of a coil 61 from  $Z_1$  has the further advantage that the remaining impedance (namely, the elements 58, 59, 60 and 62), between the terminal at the junction of the elements 61 and 62, and the terminal at the junction of the elements 58 and 64 is zero at infinite frequency and, therefore, contains a capacity 58 in parallel, which might be adjusted to compensate the undesired inter-winding capacity of the coil 62.

In Figs. 7 and 8, the invention is shown applied to separating filters such, for example, as are used for carrier telegraphy. In Fig. 7, it is assumed that there are  $n-1$  filters with different pass-bands, each constructed as in Fig. 2, and shunted with one side 66 of the transformer 65, 66. The coil 65 of the transformer is connected between the terminals 1, 1', with the open-air wire or the cable. Here the network becomes balanced by earthing of the middle of the coil 65. At the receiver end, a similar network will be used. If, at the terminals 2, 2' . . . n, n',  $n-1$  carrier telegrams are sent, they may be heard at the receiver end at the corresponding terminals of the receiving network.

The same effect may be obtained with the  $n-1$  several filters of Fig. 2 connected in series, as illustrated in Fig. 8. The coils 67 and 68 are connected like the coils 65 and 66 of Fig. 7. The Fig. 2 filters are not assumed to have any special position. The several filters may be designed as well according to Fig. 1, or to Fig. 3.

In particular, the partial filters of the separating filter of Fig. 7 may be chosen according to Fig. 5, as a filter of the class 3b\*; or, in Fig. 8, the partial filters may be chosen as filters of class 3b, according to Fig. 4.

Although the couplings of Figs. 4 and 5 were described as tight, it may be useful, in connection with carrier telephony, for example, to use mutual inductances, according to this invention, in the form of loose couplings, with coils without iron, as before described in connection with Fig. 6.

It is obviously impossible to describe in detail all the special applications of the present invention. They will be understood by persons skilled in the art without further description. It is therefore desired that the appended claims be broadly construed, unlimited except insofar as limitations may be necessary to be imposed by the state of the prior art.

What is claimed is:

1. A separating filter having two input terminals and a plurality of pairs of output terminals and comprising two or more four-terminal networks connected with the input terminals, each network attaining or approximating to prescribed frequency characteristics, but the different networks being designed to pass different bands of frequencies, at least one of the four-terminal networks having only a pair of input terminals and only a pair of output terminals without any additional free terminals and being provided with two meshes respectively connected

with the corresponding input terminals and the output terminals, the two meshes having a common branch, each mesh having a branch that is not common and that is provided with a winding, the windings being coupled together to constitute a transformer, the inductances of the windings being of about the same value as the other circuit elements of the network, the primary winding of the transformer being shunted by a loading reactance that is of infinite value for direct currents, the secondary winding of the transformer and the windings as a unit not being shunted, and the different networks being designed to coact to produce an efficient separating filter, notwithstanding that some or all of the said different networks are individually not efficient filters.

2. A separating filter comprising a connection in series of two or more filters of the Cauer class 3b, each filter comprising a four-terminal, electrical-impedance network attaining or approximating to prescribed frequency characteristics, but the different networks being designed to pass different bands of frequencies, each network having a pair of input terminals and a pair of output terminals and being provided with two meshes respectively connected with the input terminals and the output terminals, the two meshes having a common branch, each mesh having a branch that is not common and that is provided with a winding, the windings being coupled together to constitute a transformer, the inductances of the windings being of about the same value as the other circuit elements of the network, the primary winding of the transformer being shunted by a loading lumped impedance that is of infinite value for direct currents, the

secondary winding of the transformer and the windings as a unit not being shunted, the elements of the different networks having different values, and the different networks being designed to coact to produce an efficient separating filter, notwithstanding that some or all of the said networks are individually not efficient filters.

3. A separating filter comprising a parallel connection of two or more filters of the Cauer class 3b\*, each filter comprising a four-terminal, electrical-impedance network attaining or approximating to prescribed frequency characteristics, but the different networks being designed to pass different bands of frequencies, each network having a pair of input terminals and a pair of output terminals and being provided with two meshes respectively connected with the input terminals and the output terminals, the two meshes having a common branch, each mesh having a branch that is not common and that is provided with a winding, the windings being coupled together to constitute a transformer, the inductances of the windings being of about the same value as the other circuit elements of the network, the primary winding of the transformer being shunted by a loading lumped impedance that is of infinite value for direct currents, the secondary winding of the transformer and the windings as a unit not being shunted, the elements of the different networks having different values, and the different networks being designed to coact to produce an efficient separating filter, notwithstanding that some or all of the said networks are individually not efficient filters.

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