May 29, 1962 C. L. RUTHROFF 3,037,173

HYBRID NETWORK

Filed Jan. 23, 1959

FIG. 1

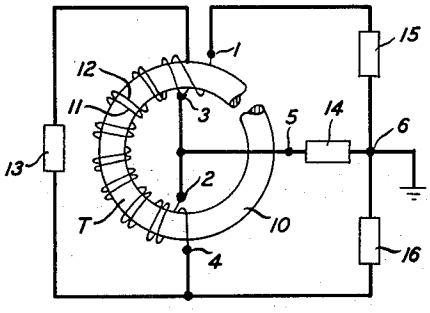


FIG. 2

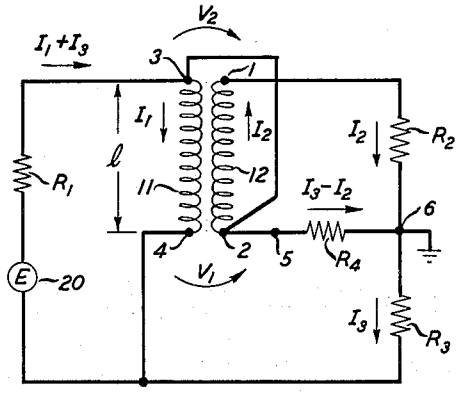


FIG. 3

($R_2=R_3=2R_4=\frac{1}{2}R_1$)

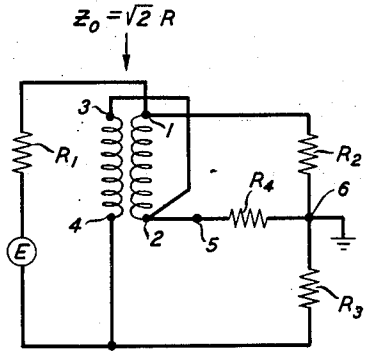
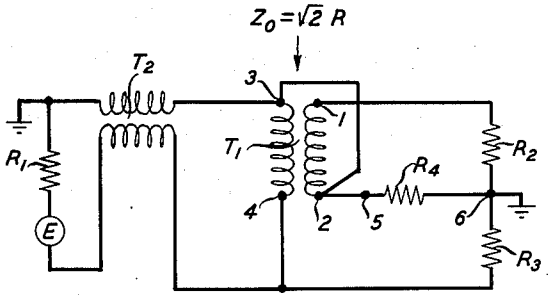


FIG. 4

($R_2=R_3=2R_4=2R_1$)



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HYBRID NETWORK

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5 Claims. (Cl. 333—11)

This invention relates to wave transmission systems, and, in particular, to broad-band coupling arrangements commonly known as hybrid networks for use in such systems.

One of the more useful circuit arrangements employed in communications networks is the so-called hybrid network. This type of network is of particular importance in that it makes possible the two-way operation of a telephone line. However, because of its nature, the ordinary hybrid coil is not adaptable to the higher frequencies. Thus, as the range of operating frequencies is extended, as is the current trend, the problems of distortion and unbalance in hybrid networks have become more acute. For example, in order to supply gain and to transmit pulses of millimicrosecond duration, amplifiers and coupling networks with bandwidths of hundreds of megacycles are needed. While the problem of extending the frequency range of hybrid networks has received the attention of many investigators, current circuit arrangements still fall far short of fulfilling the bandwidth requirements presently encountered in the communications art.

In my copending application Serial No. 734,751, filed May 12, 1958, broad-band bifilar wound transformers are described which have bandwidth ratios as high as 20,000 to 1 in the frequency range of a few tens of kilocycles to over a thousand megacycles. It is therein indicated that the frequency limitations in a conventional transformer of a type which might be used in a hybrid network are in great part due to the series self-inductance and parasitic interwinding capacitance of the transformer windings themselves. For example, in a conventionally wound transformer, the upper end of the pass-band is generally determined by the large interwinding capacity which resonates at some relatively low frequency, while the low frequency end of the pass-band is limited by a relatively small coil inductance which appears as a low impedance in parallel with the signal source. While these limitations have been somewhat overcome by the use of miniature construction and new and improved magnetic core materials, this type of approach to the problem has enjoyed only limited success.

It is, therefore, an object of this invention to produce broad-band hybrid network arrangements using a single bifilar wound coil.

By applying transmission line theory to the transformer art, broad-band transformers of the type described in my copending application are now available. It has been recognized in accordance with the present invention that bifilar transformers of this type may be adapted and utilized to produce broad-band hybrid networks by the appropriate interconnection of the bifilar transformers and the external utilization networks. As will be shown hereinafter, transformers utilized in this manner preserve their broad-band characteristics and produce hybrid coupling properties.

A broad-band hybrid network constructed in accordance with the invention comprises a pair of insulated conductive wires, uniformly spaced from each other and wound together in a substantially helical form. A coil so wound has the distributed properties of a uniform transmission line and the corresponding broad-band capabilities when used as a transformer. The two coils thus formed are serially connected by joining one end of one of them to

the other end of the second coil, that is, by joining nonadjacent ends of the two coils. Utilizing means are connected from each of the remaining free ends and from the interconnection to a common terminal. Additional utilizing means are connected either between the free ends or between the interconnection and one of the free ends, depending upon the impedance match desired.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 shows diagrammatically a hybrid network connected in accordance with the principles of the invention;

FIG. 2 is a schematic illustration of the network of FIG. 1;

FIG. 3 is a schematic illustration of a hybrid network modified for impedance matching purposes, and

FIG. 4 is a schematic illustration of a hybrid network modified to accommodate single ended utilization means.

Referring to the accompanying drawings, and more specifically to FIG. 1, there is diagrammatically shown a first embodiment of a broad-band hybrid network connected in accordance with the present invention. The transformer T comprises a pair of insulated conductive filaments **11** and **12**, wound together in a substantially helical form over coil form **10**. Insulated filaments **11** and **12** are arranged so that their insulated coverings are in close juxtaposition substantially throughout their entire lengths. The juxtaposition or contiguous arrangement of these two wires is such as to produce substantially unity coupling between the two windings and, in addition, to produce the equivalent of a uniform parallel wire transmission line from one end of the coil to the other end thereof. The double threaded spiral or helical coils described above are known in the art as bifilar coils and will be referred to as such hereinafter. The actual spacing of the conductive portions of members **11** and **12**, and the diameter of said conductors, will be considered in greater detail below.

The bifilar coil is mounted upon a coil form **10** which may be composed of any suitable high permeability, low-loss core material. For example, a number of transformers using nickel-zinc ferrite cores have been constructed and have given very satisfactory results. While coil form **10** has been shown as a toroidal member, it may assume any convenient shape consistent with the electrical requirements of the transformer windings.

Coils **11** and **12** are serially connected by joining nonadjacent ends **2** and **3** to form an internal interconnection. The latter is brought out as terminal **5**.

Connected to coils **11** and **12** are the two pairs of conjugate impedances **13** and **14** and **15** and **16**. One pair of conjugate impedances **15** and **16** connects between terminals **1** and **4**, respectively, and the common terminal **6**. Impedance **14**, of the second pair of conjugate impedances **13** and **14**, connects between the common junction **6** and the interconnection **5**. The other impedance, **13**, is connected across terminals **3** and **4**.

In FIG. 2 there is shown a schematic diagram of the network of FIG. 1 in which impedance **13** of FIG. 1 more specifically comprises a signal generator **20** and its equivalent internal impedance R_1, and impedance **14** comprises a resistor R_4. The conjugate impedances **15** and **16** are represented by the two equal resistors R_2 and R_3.

The hybrid operation of the network and its frequency response, may be demonstrated by considering the currents produced as a result of a signal E impressed upon the circuit by signal generator **20**. Assuming that the reactance of each winding is much larger than the terminating resistances and that the coupling coefficient k

is equal to unity, the network equations may be written as:

$$E=R_1(I_1+I_3)-V_2+I_2R_2+R_3I_3$$
$$E=R_1(I_1+I_3)-V_2+I_2R_2-(I_3-I_2)R_4+V_1$$
$$E=R_1(I_1+I_3)+R_4(I_3-I_2)+R_3I_3$$
$$V_1=V_2\cos\beta l+jI_2Z_0\sin\beta l$$
$$I_1=I_2\cos\beta l+j\frac{V_2}{Z_0}\sin\beta l$$

where l is the equivalent length of transmission line formed by the bifilar windings **11** and **12**, β is the phase constant of this line, and Z_0 is the characteristic impedance of the line. Solving for the currents gives

$$I_1=\frac{E}{\Delta}\left\{R_4+(R_3+R_4)\cos\beta l+j\frac{\sin\beta l}{Z_0}(R_2R_3+R_2R_4+R_3R_4)\right\}$$

$$I_2=\frac{E}{\Delta}\{R_3+R_4(1+\cos\beta l)\}$$

$$I_3=\frac{E}{\Delta}\{R_4(1+\cos\beta l)+R_2\cos\beta l+jZ_0\sin\beta l\}$$

where

$$\Delta=2R_1R_4+[R_3R_4+R_1R_2+R_2R_3+R_2R_4+2R_1R_4+R_1R_3]\cos\beta l+jZ_0\sin\beta l[R_1+R_3+R_4]+j\frac{\sin\beta l}{Z_0}[R_1R_2R_4+R_1R_2R_3+R_1R_3R_4]$$

For balanced loads and matched conditions,

$$R_1=R_4=R \text{ and } R_2=R_3=2R$$

Under these conditions, the currents can be written as

$$I_1=\frac{ER}{\Delta}\left[1+3\cos\beta l+j\frac{8R}{Z_0}\sin\beta l\right]$$

$$I_2=\frac{ER}{\Delta}[3+\cos\beta l]$$

$$I_3=\frac{E}{\Delta}[R(1+3\cos\beta l)+jZ_0\sin\beta l]$$

where

$$\Delta=2R^2\left[1+7\cos\beta l+j2\sin\beta l\left(\frac{Z_0}{R}+\frac{2R}{Z_0}\right)\right]$$

Ideally, the current in R_4 should be zero. Actually, this current is

$$(I_3-I_2)=\frac{E}{\Delta}\{2R[\cos\beta l-1]+jZ_0\sin\beta l\}$$

However, at low frequencies, when the wavelength is large compared to the winding length, βl is small and the current (I_3-I_2) approaches zero in amplitude.

The transmission T is given as the power delivered to the load resistors R_2 and R_3, divided by the available power,

$$\frac{E^2}{4R}$$

For load resistor R_2,

$$T_2=\frac{|I_2|^2\times 2R}{\frac{E^2}{4R}}$$

or

$$T_2=\frac{2(3+\cos\beta l)^2}{(1+7\cos\beta l)^2+4\sin^2\beta l\left(\frac{Z_0}{R}+\frac{2R}{Z_0}\right)^2}$$

The transmission is a maximum when the coefficient of $\sin^2\beta l$ is a minimum or where

$$\frac{d}{dZ_0}\left(\frac{Z_0}{R}+\frac{2R}{Z_0}\right)^2=0$$

Solving for Z_0, the characteristic impedance of the transformer, gives

$$Z_0=\sqrt{2R}$$

The transmission T_3 to load R_3 may also be calculated and is found to be

$$T_3=\frac{|I_3|^2\times 2R}{\frac{E^2}{4R}}=\frac{2\{(1+3\cos\beta l)\}^2+\left(\frac{Z_0}{R}\right)^2\sin^2\beta l}{(1+7\cos\beta l)^2+4\sin^2\beta l\left[\frac{Z_0}{R}+\frac{2R}{Z_0}\right]^2}$$

It will be noted that both T_2 and T_3 at low frequencies ($\beta l\approx 0$) are equal to ½, as expected.

Letting $Z_0=\sqrt{2R}$ and solving for the ratio of the transmission to loads R_2 and R_3, gives

$$\frac{T_2}{T_3}=\frac{(3+\cos\beta l)^2}{(1+3\cos\beta l)^2+2\sin^2\beta l}$$

At low frequencies $\beta l=0$ and $T_2/T_3=1$, or, equal power is delivered to each of the load resistors R_2 and R_3. At $\beta l=\pi/4$, or at a frequency for which the transformer has an equivalent length equal to one-quarter wavelength, the ratio of the power delivered to the two load resistors R_2 and R_3 is 1.28, or the power split is unequal by about 1 decibel. At half a wavelength, the ratio of power delivered to the two resistors is 3:1.

The ratio of power delivered to the conjugate resistor R_4 to the available power is given as

$$T_4=\frac{4(\cos\beta l-1)^2+2\sin^2\beta l}{(1+7\cos\beta l)^2+32\sin^2\beta l}$$

At $\beta l=0$, T_4 is equal to zero. At $\beta l=\pi/4$, $T_4=.0332$ or or the insertion loss from R_1 to R_4 is about 30 decibels. Ideally, of course, the insertion loss should be infinite at all frequencies or T_4 should equal zero.

In the embodiment of FIG. 1 and FIG. 2, the conjugate resistors R_1 and R_4 are equal. In some applications, however, these resistors are more conveniently made unequal. In particular, for those applications in which $R_1=4R_4$, the circuit is modified as shown in FIG. 3, wherein resistor R_1 is connected across both of the serially connected coils **11** and **12**. As shown, resistor R_1 connects from the terminal **1** to terminal **4**, all other connections being the same as in FIG. 1.

In either arrangement, however, the characteristic impedance of the transmission line formed by the bifilar wound coils **11** and **12** is given as $Z_0=\sqrt{2R}$. In terms of the wire size and spacing,

$$Z_0=\sqrt{2R}=\frac{\sqrt{\frac{\mu}{\epsilon}}}{\pi}\cosh^{-1}\left(\frac{b}{a}\right)$$

where
μ is the effective permeability;
ϵ is the effective dielectric constant;
b is the distance between wire centers, and
a is the wire diameter.

An examination of the hybrid networks shown in FIGS. 1 and 3, discloses that at best only three of the four loads can be grounded simultaneously. In FIG. 2, the common terminal **6** for resistors R_2, R_3 and R_4 is grounded, whereas the generator, **20**, is double-ended, or balanced with respect to ground. This arrangement may be modified, and all four load resistors operated single-ended, by using an additional bifilar transformer as shown in FIG. 4. In FIG. 4, generator **20** and resistor R_1 are connected to transformer T_1 through the second transformer T_2 which acts as a simple balanced-to-unbalanced transformer. Because of the broad-band properties of this type of transformer there is no appreciable degradation in frequency response. The characteristic impedance of transformer T_2 is either R or 4R depending upon whether the arrangement of FIG. 1 or FIG. 3 is used. In either arrangement, however, all four loads may be operated single-ended, with

the grounds as shown in FIG. 4 as a typical arrangement.

In all cases it is understood that the above-described arrangements are illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, a two-element transmission line having a characteristic impedance Z_0 comprising two insulated conductive wires wound together in a substantially helical form to form a pair of coils, said wires being contiguous and parallel from the first end of each to the second end of each, said coils being serially interconnected with said first end of one being connected directly to the second end of the other, first and second external circuits each having an impedance 2R connected from each of the remaining free ends of said coils to a common terminal, a third external circuit having an impedance R connected from said interconnection to said common terminal, and a fourth external circuit connected between a pair of ends of said coils wherein said characteristic impedance and said external circuit impedances are related by $Z_0=\sqrt{2R}$.

2. The combination according to claim 1 wherein said fourth circuit is connected between said free ends and has an impedance 4R.

3. The combination according to claim 1 wherein said fourth circuit is connected between one of said free ends and said interconnection and has an impedance R.

4. The combination according to claim 1 wherein said common terminal is grounded and said fourth circuit is balanced with respect to ground.

5. The combination according to claim 1 wherein said common terminal is grounded and said fourth circuit comprises an unbalanced-to-balanced transformer and a load which is unbalanced with respect to ground.

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