

PATENT SPECIFICATION

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(54) IMPROVEMENTS IN OR RELATING TO CIRCUITS UTILIZING GYRATORS

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 195, Broadway, New York City, New York State, United States of America, a Corporation organised and existing under the laws of the State of New York, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to circuits utilizing gyrators.

Repeated advances in the state of the art of integrated circuits have made this circuit form an increasingly common choice over discrete component forms. Nevertheless, there are still restrictions on the kinds of circuits that may be fully integrated — circuits employing inductors being the most significant example. In those instances where only very low inductance values are required, integration may be effected by fabricating thin film coils in the form of flat spirals. Where more appreciable inductance is needed, however, conventional practice still calls for the use of discrete inductive elements.

A partial solution to the problem indicated lies in the use of special integrable networks having inductive characteristics rather than in attempts to integrate inductive devices directly. Such networks, known as gyrators, are generally described as anti-reciprocal, two-port networks and are formed from a combination of integrable active and passive circuit elements which may include, for example, transistors, capacitors and resistors. The combination, in effect, provides inductance although no coils or inductors in the conventional sense are employed. Illustrative gyrators are shown in United States Patent No. 3,001,157.

Although gyrators have been employed successfully in lieu of inductors in practical circuits such as filters, as described for example in U.S. Patent No. 3,001,157, in other areas their application has been limited to theoretical proposals. One such area is that of transformers. The basic theory of gyrator utilization to form a transformer has been described in work disclosed by B. D. H. Tellegen in an article, "The Gyrator, A New Electric Network Element". Philips Research Reports, Vol. 3, No. 2, pages 81—101, April, 1948.

Despite the seemingly very attractive advantages promised by the potential availability of transformers in integrated circuit form, no practical circuits of this type have heretofore been realized. This absence of effective implementation following the theoretical work of Tellegen appears to be due at least in part to the lack, heretofore, of a capability for controlling and tailoring the transformer characteristics in terms of both frequency response and effective turns ratio.

According to the invention a circuit for simulating a transformer includes a primary circuit including a pair of input points and a first gyrator circuit, a secondary circuit including a pair of output points and a second gyrator circuit, first means coupling said input points to said first gyrator circuit, second means coupling the output of said first gyrator circuit to the input of said second gyrator circuit, and third means coupling said second gyrator circuit to said output points, wherein each of said first, second and third means includes a parallel combination of a resistive element and a capacitive element, each said parallel combination being connected across said input points, said first gyrator output and said output points respectively.

The capacitive and resistive elements may be proportioned in magnitude to con-

form the frequency response of said circuit for simulating to the frequency response of a 1/2 dB Chebyshev filter.

The invention will now be described with reference to the accompanying drawings in which:

Fig. 1 is a schematic circuit diagram of a circuit in accordance with the invention;

Fig. 2 is a plot of output voltage/input voltage versus frequency for a theoretical Chebyshev response curve compared with an actual response curve of the circuit shown in Fig. 1 with component values tailored, however, to produce a Chebyshev response; and

Fig. 3 is a plot of the static input-output relation for a gyrator-simulated transformer in accordance with the invention.

As shown in Fig. 1, a circuit in accordance with the invention employs a first or primary gyrator G_1 connected in cascade or tandem relation with a second or secondary gyrator G_2 . These gyrators may take any one of a number of gyrator forms including, for example, the gyrator disclosed in the heretofore mentioned U.S. patent. Both the turns ratio and the frequency response of the circuit of Fig. 1 are controlled by the use of one or more of the coupling networks N_1 , N_2 and N_3 .

Each of the networks N_1 and N_3 includes a shunt capacitor C (C' in the intermediate network N_2) and a shunt resistor R (R' in the intermediate network N_2). The analysis which follows shows that with the proper proportioning of the coupling networks, desired transformed characteristics in terms of both frequency response and turns ratio may readily be achieved. In order to simplify and clarify the mathematical aspects of the analysis, it is assumed that the magnitudes of the resistors R and of the capacitors C of the networks N_1 and N_3 are identical. It is further assumed that the magnitude of the resistor R' and of the capacitor C' is equal to one-half the magnitude of the resistors R and of the capacitors C , respectively. The transmission matrix for the circuit of Fig. 1 is given by:

$$\begin{bmatrix} E_{IN} \\ I_{IN} \end{bmatrix} = \begin{bmatrix} A_t B_t \\ C_t D_t \end{bmatrix} \begin{bmatrix} E_{OUT} \\ -I_{OUT} \end{bmatrix} \quad (1)$$

where it may be shown that:

$$A_t = \left(2R_{g1}R_{g2}C^2 \right) s^2 + \left(\frac{4R_{g1}R_{g2}}{R} C \right) s + \left(\frac{2R_{g1}R_{g2}}{R} + \frac{R_{g1}}{R_{g2}} \right), \quad (2)$$

$$B_t = \left(\frac{R_{g1}R_{g2}}{R} \right) (sRC+1), \quad (3)$$

$$C_t = \frac{R_{g1}+R_{g2}}{R} (sRC+1) \times \left[\frac{R_{g1}R_{g2}}{R} \left(R^2 C^2 s^2 + 2RCs+1 \right) + 1 \right] \quad (4)$$

and

$$D_t = \frac{R_{g1}R_{g2}}{R} \left[2(sRC+1)^2 + \left(\frac{R}{R_{g1}} \right)^2 \right]. \quad (5)$$

In equations (2), (3), (4) and (5) the gyration resistance of the primary gyrator G_1 is designated by R_{g1} and the gyration resistance of the secondary gyrator G_2 is indicated by R_{g2} . The open circuit voltage transfer ratio E_{OUT}/E_{IN} for the circuit is the turns ratio n of the simulated transformer and is given by:

$$n = \frac{R_{OUT}}{R_{IN}} = \frac{1}{A_t} = \frac{(2R_{g1}R_{g2}C^2)^{-1}}{s^2 + \frac{2}{R_0}s + \left(\frac{2R_{g2}^2 + R^2}{2R_{g2}R_0C^2}\right)} \quad (6)$$

Of particular significance is the quadratic response characteristic evident from equation (6). Additionally, it should be noted that the pole locations are a function of the elements R and C.

A cascade connection of ideal gyrators corresponding to $R=\infty$ and $C=0$ simulates a transformer with turns ratio given by:

$$n = R_{g2}/R_{g1} \quad (7)$$

The nonideal transformer, however, results from including shunt R and C in the circuit and the low frequency turns ratio $n(0)$ is given by equation (6) with $C=0$, i.e.,

$$n(0) = \frac{R_{g2}}{R_{g1}} \left(\frac{1}{2 \left(\frac{R_{g2}}{R} \right)^2 + 1} \right) \quad (8)$$

which reduces to equation (7) when R becomes infinite.

The two-pole response characteristic given in equation (6) implies that the high frequency performance of the transformer can be tailored to meet a selected response shape. This implication has been substantiated and verified by testing a circuit in accordance with the invention which was designed to conform to a particular response shape, namely the well-known 1/2 dB Chebyshev response. This design was effected by conventional polynomial coefficient matching and frequency scaling. The actual circuit topology conforms to the circuit shown in Fig. 1 and was found to form the basis for an efficient wideband design.

The circuit design indicated was carried out with reference to the conventional normalized second degree 1/2 dB Chebyshev polynomial,

$$P_2(s) = s^2 + 1.4256s + 1.5162, \quad (9)$$

for which the 1/2 dB bandwidth is 1 rad/sec. The denominators of equations (6) and (10) are equated to obtain the 1/2 dB Chebyshev response shape which results in the determination of the magnitude of the resistance R as:

$$R = 1.99 R_{g2} \quad (10)$$

and which results in the magnitude of capacitance C as:

$$C = \frac{1}{.7128R} \quad (11)$$

The low frequency asymptote turns ratio (n) for the case of a 1/2 db Chebyshev response is:

$$n = \frac{R_{g2}}{1.51 R_{g1}} \quad (12)$$

In the actual gyrators employed, the magnitudes of R_{g1} and R_{g2} were found to be 15K Ω and 60K Ω , respectively. The effective turns ratio n is then found from equation (12) to be 2.67 and the magnitude of the resistance R is found from equation (10) to be 119K Ω . The final step consists of frequency scaling from 1 rad/sec to $2\pi(4 \times 10^3)$ rad/sec by

$$C = (.7128 \times 119 \times 10^3)^{-1} (8\pi \times 10^3)^{-1} = 470 \text{ pF.} \quad (13)$$

The comparison of experimental and theoretical results from the foregoing circuit design is illustrated by the plots of Fig. 2 in which it may be noted that excellent agreement is obtained throughout the frequency range of measurement.

As an additional comparison of interest, the static or D.C. input-output relation for a gyrator-simulated transformer in accordance with the invention is evaluated and illustrated by the curve of Fig. 3 for the case where $n=4$. The linear portion of the curve for $E_{IN} < 8$ volts corresponds to conventional operation. Transistor saturation and limiting duplicates the magnetization curve saturation.

The foregoing discussion has indicated how the magnitudes of each of the impedance elements in each of the three coupling networks of Fig. 1 may be determined to arrive at an effective transformer circuit with desired properties in terms of frequency response and effective turns ratio.

Thus, the effective transformer properties in terms of both effective turns ratio and frequency response are controlled by the combined characteristics of the coupling networks and gyrators, thus enabling the circuit designer to select those characteristics he desires for the application at hand.

WHAT WE CLAIM IS:—

1. A circuit for simulating a transformer, said circuit including a primary circuit including a pair of input points and a first gyrator circuit, a secondary circuit including a pair of output points and a second gyrator circuit, first means coupling said input points to said first gyrator circuit, second means coupling the output of said first gyrator circuit to the input of said second gyrator circuit, and third means coupling said second gyrator circuit to said output points, wherein each of said first, second and third means includes a parallel combination of a resistive element and a capacitive element, each said parallel combination being connected across said input points, said first gyrator output and said output points respectively.

2. A circuit as claimed in claim 1 wherein said capacitive and resistive elements are proportioned in magnitude to conform the frequency response of said circuit for simulating to the frequency response of a $1/2$ dB Chebyshev filter.

3. A circuit substantially as herein described with reference to Fig. 1 of the accompanying drawings.

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