Dec. 17, 1935. A. J. GROSSMAN 2,024,576

ELECTRICAL WAVE FILTER

Filed Dec. 29, 1933

FIG. 1

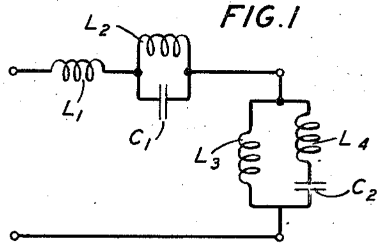


FIG. 2

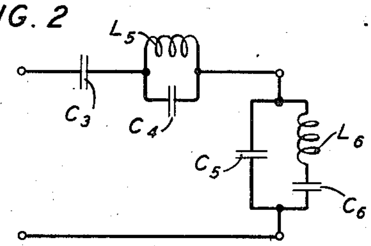


FIG. 3

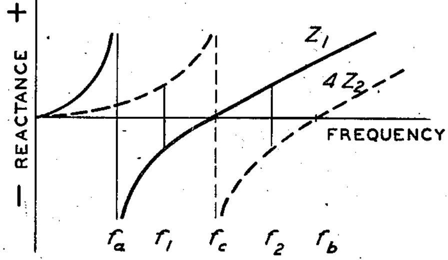


FIG. 4

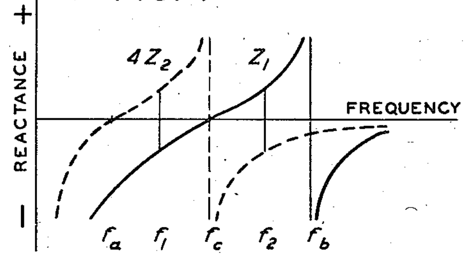


FIG. 5

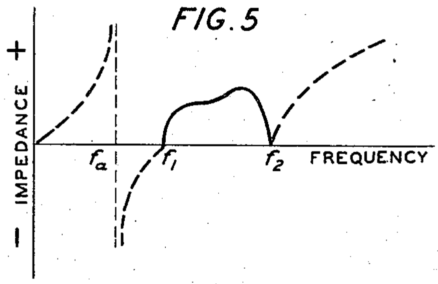


FIG. 6

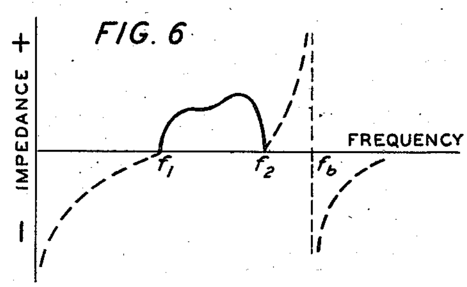


FIG. 7

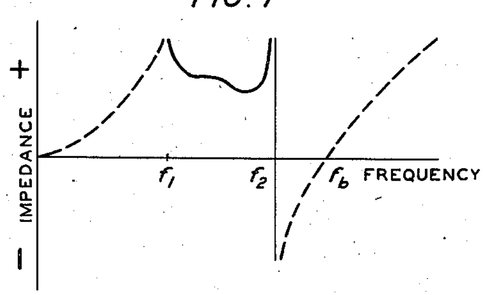


FIG. 8

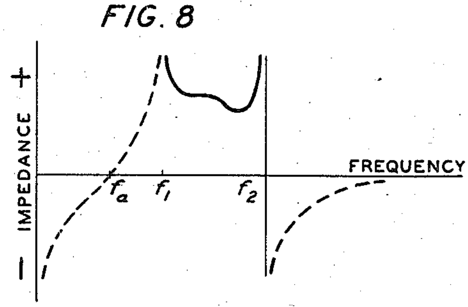
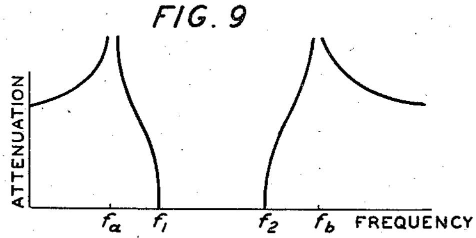


FIG. 9



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ELECTRICAL WAVE FILTER

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Application December 29, 1933, Serial No. 704,442

24 Claims. (Cl. 178—44)

This invention relates to wave transmission networks and more particularly to electrical wave filters.

An object of the invention is to reduce the number of inductors or the number of capacitors required to construct a wave filter having specified transmission characteristics.

Another object is to reduce the total number of impedance elements required for such a network.

A further object is to reduce the space requirements and the manufacturing cost of wave filters.

A feature of the invention is a wave filter of the ladder type in which each impedance branch comprises two reactances of one type and one reactance of the other type.

In designing an electrical wave filter which will give a satisfactory performance under a given set of operating conditions, it is often found that the component reactance elements of one type are more expensive to build or require more space than the reactance elements of the other type. For example, if capacitances having large magnitudes and close adjustment limits must be provided, the capacitors may cost more than the inductors. On the other hand, if large values of inductance are required with small energy dissipation at high frequencies, the inductors may be more expensive than the capacitors. Or, where space considerations are paramount, it may be found that the overall size of the network may be reduced by resorting to a filter design having a minimum number of inductances. Also, the effective electrostatic and electromagnetic shielding of the filter is considerably simplified by reducing the number of inductors used. Then too, as a rule, both the size and cost of a filter are reduced by a reduction in the total number of reactance elements required for its construction.

These objects are achieved, in accordance with the present invention, by the provision of two new filter sections of the ladder type in which each series and each shunt impedance branch comprises two reactance elements of one type and one reactance element of the other type. Thus, a single full section of the unbalanced type will consist either of six inductors and three capacitors, or of six capacitors and three inductors. The same attenuation characteristic may be provided as that obtainable with previously known single sections of the ladder type which require five inductors and five capacitors, thus effecting a saving of one element and thereby reducing the size and cost of the filter. The new sections have the further advantage that the number of capacitors may be reduced from five to three, or the number of inductors may be reduced in like proportion, as compared with the prior art filters referred to above. The selection of the section to be used in any particular instance is generally dictated by a consideration of the relative costs of the two types of reactance elements.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawing, of which

Figs. 1 and 2 show schematically the full series and full shunt impedance branches of the two filter sections of the invention;

Figs. 3 and 4 represent the reactance characteristics of the impedance branches comprising the networks of Figs. 1 and 2;

Figs. 5 and 6 give symbolically the mid-series characteristic impedance of the filter sections of Figs. 1 and 2, respectively;

Figs. 7 and 8 are symbolic representations of the mid-shunt characteristic impedance of the filters shown in Figs. 1 and 2, respectively; and

Fig. 9 is a typical attenuation characteristic which may be obtained from the networks of Figs. 1 and 2.

The filter sections of the invention are of the well known ladder type, comprising lumped impedances Z_1 connected in series with the line and alternately disposed lumped impedances Z_2 in shunt with the line. Each impedance branch comprises one reactance element of one type and two reactance elements of the other type, the reactance characteristic of each branch exhibiting one resonance frequency and one frequency of anti-resonance.

In the filter section represented schematically by Fig. 1 each impedance branch comprises two inductances and one capacitance. Typical reactance characteristics of these branches are shown in Fig. 3, in which the solid line curve represents the reactance of the full series branch Z_1 and dotted line curve represents four times the reactance of the full shunt branch Z_2. In each branch the anti-resonance occurs at a lower frequency than the resonance, and it will be noted that the resonance frequency of Z_1 coincides with the anti-resonance of Z_2, both occurring at the frequency f_c. The filter is of the band-pass variety, having two attenuation peaks, one on each side of the transmission band, as shown by the attenuation characteristic of Fig.

9. The two cut-off frequencies f_1, f_2 occur at the frequencies where the reactances Z_1 and 4 Z_2 are equal in magnitude but opposite in sign, and may be located graphically on the diagram of Fig. 3, as indicated. The lower attenuation peak occurs at the frequency f_a where Z_1 is anti-resonant, and the upper peak occurs at the resonance frequency f_b of Z_2. The mid-series characteristic impedance of the filter is shown in Fig. 5 and the mid-shunt characteristic impedance in Fig. 6, the resistance being shown by the solid line curve and the reactance by the dotted line curve.

Assuming that non-dissipative elements are used, the impedance of the filter throughout the transmission band is a pure resistance, varying with frequency. In order to reduce reflection losses, it is customary to match the load impedance connected to the terminals of the filter with the characteristic impedance at the mid-band frequency f_m, which is equal to

$$\sqrt{f_1 f_2}.$$

The design of the filter section shown in Fig. 1 involves the determination of the values of the four inductances L_1, L_2, L_3, L_4 and the two capacitances C_1, C_2. Since there are six independent constants to be determined it follows that any six properties of the filter, dependent upon the values of the reactance elements but independent of each other, may be chosen at will. Two of these may be taken as the cut-off frequencies f_1, f_2, thus defining the range of free transmission, two more as the frequencies of maximum attenuation f_a, f_b, the fifth as the characteristic impedance R of the filter at the mid-band frequency f_m, and the sixth is determined by the fact that the resonance in the series branch and the anti-resonance in the shunt branch both occur at the same frequency, f_c.

The general equations for the propagation constant P, the mid-series characteristic impedance K_1 and the mid-shunt characteristic impedance K_2 of any ladder type network, in terms of the full series branch impedance Z_1 and the full shunt branch impedance Z_2 are the following:

$$\cosh P = 1 + \frac{Z_1}{2Z_2} \tag{1}$$

$$K_1 = \sqrt{Z_1 Z_2 + \frac{Z_1^2}{4}} \tag{2}$$

$$K_2 = \frac{Z_1 Z_2}{K_1} \tag{3}$$

When the conditions mentioned above are imposed the following formulæ may be evolved for the determination of the required inductances in henries and the capacitances in farads, in terms of the frequencies f_1, f_2, f_a and f_b and the characteristic impedance R of the filter at the mid-band frequency f_m.

$$L_1 = \frac{(F^2 + M_1 M_2)(F+1)R'}{\pi f_2 (F^2 - M_1^2)(M_1 + M_2)} \tag{4}$$

$$L_2 = \frac{M_1(F^2 - 1)(F+1)R'}{\pi f_2 (F^2 - M_1^2)(1 - M_1^2)} \tag{5}$$

$$L_3 = \frac{(M_2^2 - 1)(F+1)R'}{4\pi f_2 (M_1 + M_2)(1 + M_1 M_2)} \tag{6}$$

$$L_4 = \frac{(M_2^2 - F^2)(M_2^2 - 1)R'}{4\pi f_2 M_2 (F-1)(M_1 + M_2)^2} \tag{7}$$

$$C_1 = \frac{(F^2 - M_1^2)^2}{4\pi f_2 M_1 (F+1)(F^2 - 1)R'} \tag{8}$$

$$C_2 = \frac{M_2(F-1)(M_1 + M_2)^2}{\pi f_2 (M_2^2 - 1)^2 R'} \tag{9}$$

In the above equations, the symbols F, M_1, M_2 and R′ are evaluated in accordance with the following equations:

$$F = \frac{f_2}{f_1} \tag{10}$$

$$M_1 = \sqrt{\frac{1 - \frac{(f_a)^2}{(f_1)}}{1 - \frac{(f_a)^2}{(f_2)}}} \tag{11}$$

$$M_2 = \sqrt{\frac{1 - \frac{(f_b)^2}{(f_1)}}{1 - \frac{(f_b)^2}{(f_2)}}} \tag{12}$$

When the filter is terminated mid-series,

$$R' = \frac{R(F + M_1^2)}{F+1} \tag{13}$$

and when the filter is terminated mid-shunt,

$$R' = \frac{RF(M_1 + M_2)^2}{(F+1)(M_2^2 + F)} \tag{14}$$

It will be found desirable to make R substantially equal to the impedance of the load which is to be connected to the filter terminals, in order to reduce reflection losses at the point of juncture.

The other filter section of the invention is shown schematically in Fig. 2, in which each impedance branch comprises two capacitances and one inductance. The branches will have the reactance characteristics shown in Fig. 4, in which the solid line curve represents the reactance of Z_1 and the dotted line curve represents four times the reactance of Z_2. In each branch the resonance occurs at a lower frequency than the anti-resonance, and it will also be observed that the resonant frequency of Z_1 coincides with the anti-resonance frequency of Z_2, both occurring at the frequency f_c. The attenuation characteristic, shown in Fig. 9, is the same as that for the filter of Fig. 1, the criteria for cut-off frequencies and attenuation peaks also being the same for the two filters. The mid-series and the mid-shunt characteristic impedances are shown, respectively, in Figs. 6 and 8. The formulæ required for the determination of the four capacitances C_3, C_4, C_5, C_6 and the two inductances L_5, L_6 are the following:

$$C_3 = \frac{(M_2^2 - 1)(F+1)}{4\pi f_2 (M_1 + M_2)(1 + M_1 M_2)R''} \tag{15}$$

$$C_4 = \frac{(M_2^2 - F^2)(M_2^2 - 1)}{4\pi f_2 M_2 (M_1 + M_2)^2 (F-1)R''} \tag{16}$$

$$C_5 = \frac{(F^2 + M_1 M_2)(F+1)}{\pi f_2 (M_1 + M_2)(F^2 - M_1^2)R''} \tag{17}$$

$$C_6 = \frac{M_1(F^2 - 1)(F+1)}{\pi f_2 (1 - M_1^2)(F^2 - M_1^2)R''} \tag{18}$$

$$L_5 = \frac{M_2(M_1 + M_2)^2 (F-1)R''}{\pi f_2 (M_2^2 - 1)^2} \tag{19}$$

$$L_6 = \frac{(F^2 - M_1^2)^2 R''}{4\pi f_2 M_1 (F+1)(F^2 - 1)} \tag{20}$$

In the above equations the symbols F, M_1 and M_2 have the values given, respectively, by Equations (10), (11) and (12). When the filter is terminated mid-series,

$$R'' = \frac{R(F+1)(M_2^2 + F)}{F(M_1 + M_2)^2} \tag{21}$$

and when the filter is terminated mid-shunt,

$$R'' = \frac{R(F+1)}{F + M_1^2} \tag{22}$$

The formulæ given above for the determination of the reactance elements apply to full series and full shunt impedance branches. If the filter is terminated mid-series, each reactance of the terminating series impedance branch should have only half the impedance indicated, that is, each inductance should be made only half the magnitude and each capacitance should be made twice the magnitude given by the formulæ. Likewise, if the filter is terminated mid-shunt, each element of the terminating shunt branch should be made to have twice the indicated impedance, each inductance being of twice the value and each capacitance only half the value given by the formulæ.

In a filter having the impedance branches shown in Fig. 1, the total inductance of a branch of the type of Z_2 is greater than that of a mesh of the type of Z_1, and the capacitance is smaller. However, the shunt branch may be transformed into a mesh having the configuration of the series branch, or if desired the series branch may be transformed into the configuration of the shunt branch. Also, in a filter in which the branch impedances are of the form shown in Fig. 2, the sum of the capacitances comprising a branch of the type of Z_1 is greater than that of a mesh having the form of Z_2, and the inductance is smaller. But either the series or the shunt branch of the filter may be transformed into the configuration of the other branch, if it is found advantageous to do so in any particular design. The method of making these transformations is well known in the art, being shown, for example, on pages 270 and 271 of K. S. Johnson's "Transmission Circuits for Telephonic Communication", published by D. Van Nostrand Company, Inc.

It will be noted that the attenuation characteristic of the filter sections as shown in Fig. 9 is of the same type as that provided by the six-element sections shown in Figs. 18 and 19 of U. S. Patent No. 1,644,004, to O. J. Zobel, issued October 4, 1927. However, only nine reactance elements are required for a single full section of the filter of the present invention, whether terminated mid-series or mid-shunt, whereas a single full section of the filter shown in Fig. 18 of the above mentioned patent requires ten elements when mid-shunt terminations are used, and the filter shown in Fig. 19 of the same patent also requires ten elements when mid-series terminations are employed. Under these circumstances, it is therefore possible to save one reactance element, as compared with the previously known filter sections, by using the filter sections of the present invention. As stated above, the attenuation characteristics may be made identical in both cases. If a multi-section filter is to be built, six additional reactance elements are required for each unbalanced full section added. The filter is, therefore, known as the six-element type.

A further marked advantage of the filter sections here presented is that the designer has the choice of a section which employs a preponderance of inductances or a preponderance of capacitances, in the ratio of two to one, and therefore he may select the section which uses the greater number of the elements which, under the given operating conditions, are the cheaper to build.

What is claimed is:

1. A ladder type wave filter section in which each impedance branch comprises a plurality of reactance elements, a majority of said reactance elements in each of said branches being of the same type as the majority of said reactance elements in each of the remaining branches.

2. A ladder type wave filter section in which each impedance branch comprises a plurality of reactance elements, a majority of said reactance elements in each of said branches being positive inductances.

3. A ladder type wave filter section in which each impedance branch comprises a plurality of reactance elements, a majority of said reactance elements in each of said branches being capacitances.

4. A six-element ladder type wave filter in which a majority of the component reactance elements are of one type.

5. A six-element ladder type wave filter section comprising an impedance branch in series with the line and an impedance branch in shunt with the line, a majority of the reactance elements comprising said section being of the same type.

6. A six-element ladder type wave filter in which a majority of the component reactance elements are inductances.

7. A six-element ladder type wave filter in which a majority of the component reactance elements are capacitances.

8. A six-element ladder type wave filter section comprising an impedance branch in series with the line and an impedance branch in shunt with the line, a majority of the reactance elements in each of said branches being of the same type.

9. A ladder type wave filter section having an attenuation peak on each side of the transmission band, a majority of the component reactance elements comprising said section being of one type.

10. A ladder-type wave filter section having an attenuation peak on each side of the transmission band, a majority of the component reactance elements comprising said section being inductances.

11. A ladder type wave filter section having an attenuation peak on each side of the transmission band, a majority of the component reactance elements comprising said section being capacitances.

12. A ladder type wave filter section having an attenuation peak on each side of the transmission band, a majority of the reactance elements in each impedance branch being of the same type.

13. A ladder type wave filter section having an attenuation peak on each side of the transmission band, a majority of the reactance elements in each impedance branch being inductances.

14. A ladder type wave filter section having an attenuation peak on each side of the transmission band, a majority of the reactance elements in each impedance branch being capacitances.

15. A ladder type wave filter comprising an impedance branch in series with the line and an impedance branch in shunt with the line, each of said branches having the same number of reactance elements and a majority of the reactance elements comprising said filter being of the same type.

16. A ladder type wave filter comprising an impedance branch in series with the line and an impedance branch in shunt with the line, each of said branches having the same number of reactance elements and a majority of the reactance elements in each of said branches being of the same type.

17. A ladder type wave filter in which each impedance branch comprises three reactance elements, a majority of said elements being of the same type.

18. A ladder type wave filter in which each impedance branch comprises three reactance elements, two of said elements being of one type and one of said elements being of the other type.

19. A six-element ladder type wave filter section having a peak of attenuation on each side of the transmission band, a majority of the component reactance elements comprising said section being of one type.

20. A six-element ladder type wave filter section comprising an impedance branch in series with the line and an impedance branch in shunt with the line, said section having an attenuation peak on each side of the transmission band, and a majority of the reactance elements in each of said branches being of the same type.

21. A six-element ladder type wave filter section in which each impedance branch has the same type of reactance characteristic.

22. A six-element ladder type wave filter section in which each impedance branch has the same type of reactance characteristic, a resonance frequency in one of said branches occurring at an anti-resonance frequency in the other of said branches.

23. A ladder type wave filter section in which the reactance characteristic of each impedance branch has a finite resonance frequency other than zero and a finite anti-resonance frequency, said resonance frequency occurring at a lower frequency than said anti-resonance frequency.

24. A ladder type wave filter section in which the reactance characteristic of each impedance branch has a finite anti-resonance frequency other than zero and a finite resonance frequency, said anti-resonance frequency occurring at a lower frequency than said resonance frequency.

ALEXANDER J. GROSSMAN.