July 4, 1939. A. ALFORD 2,165,087

APERIODIC TRANSFORMER SYSTEM

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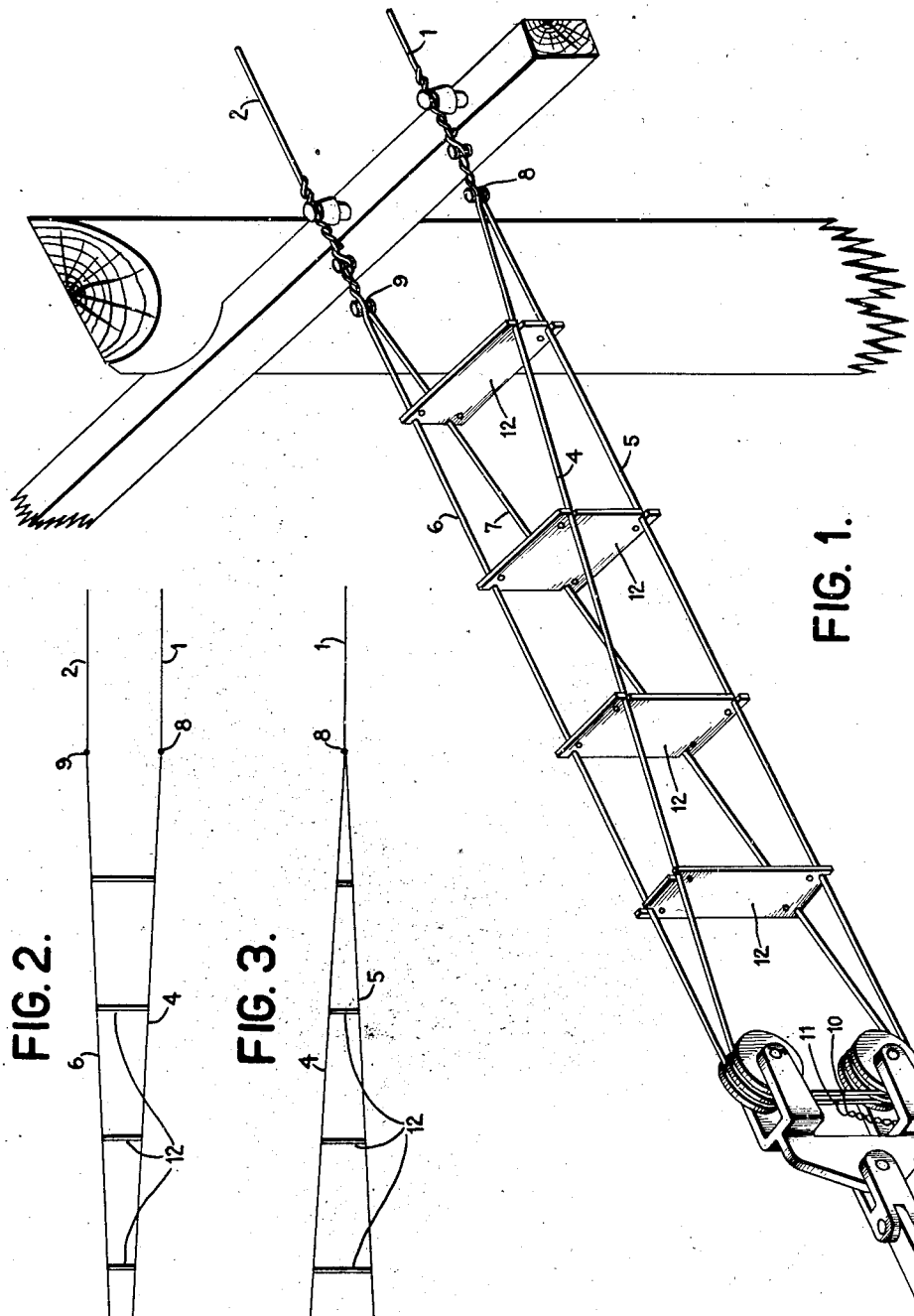


FIG. 1.

FIG. 2.

FIG. 3.

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APERIODIC TRANSFORMER SYSTEM

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FIG. 4.

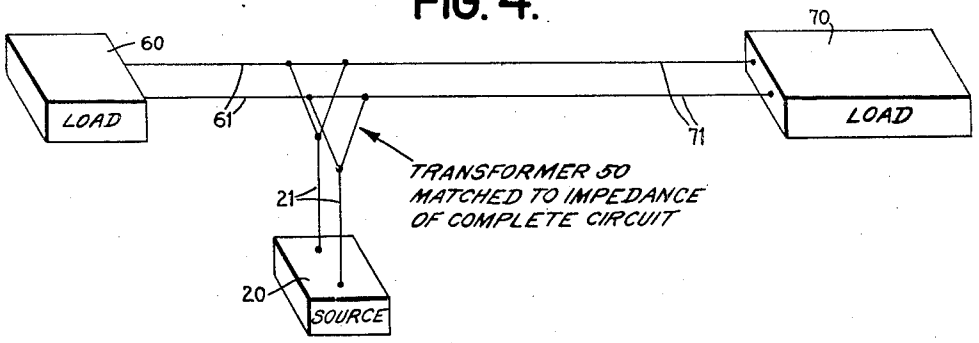


FIG. 5.

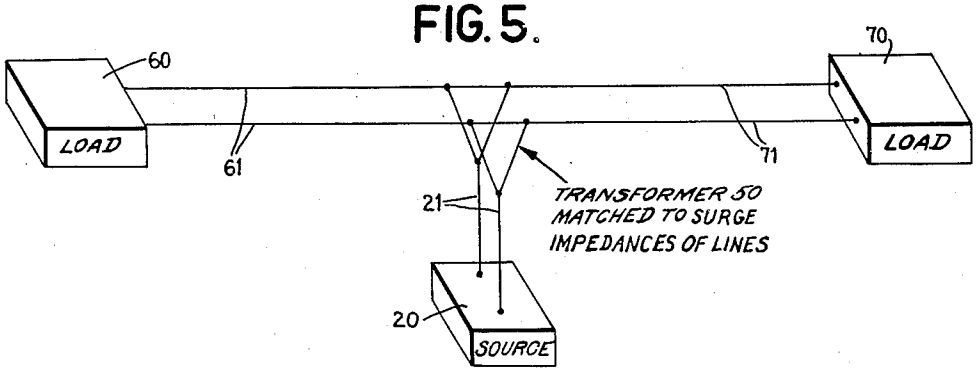
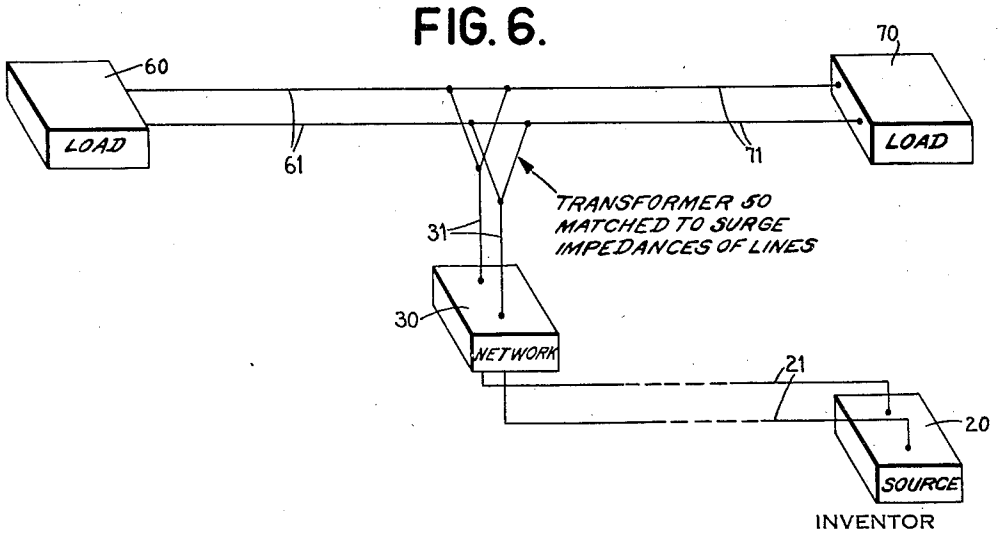


FIG. 6.



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FIG. 7.

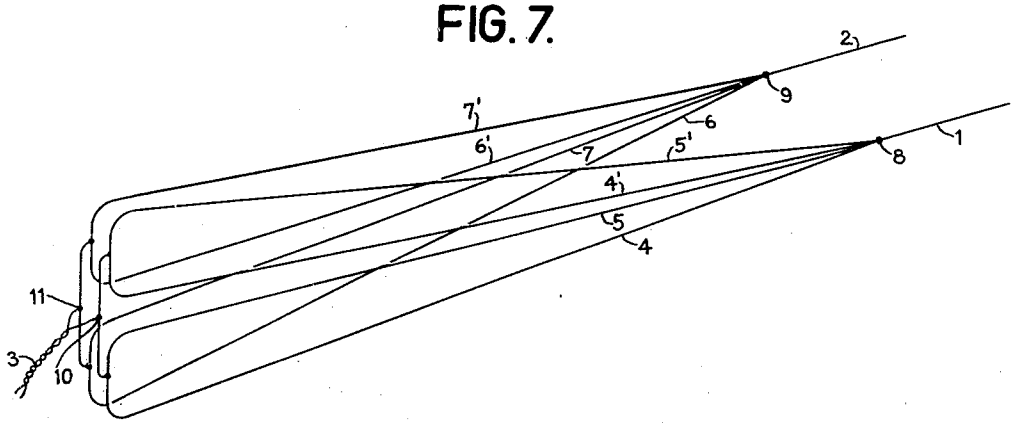
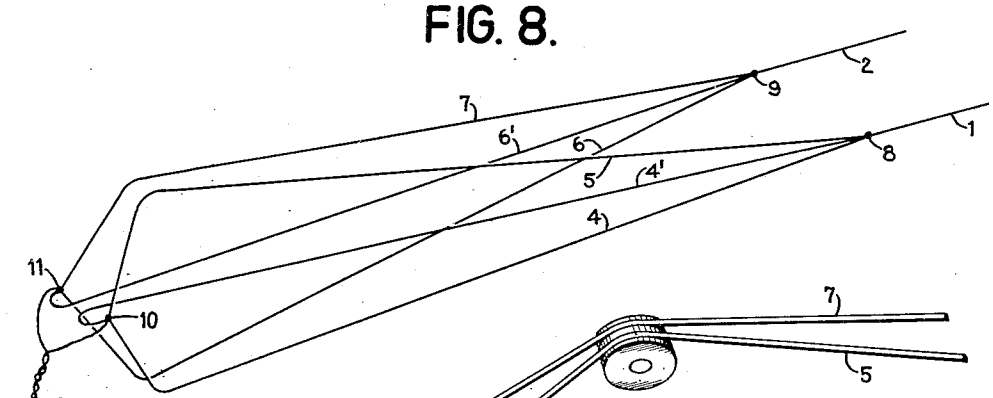


FIG. 8.



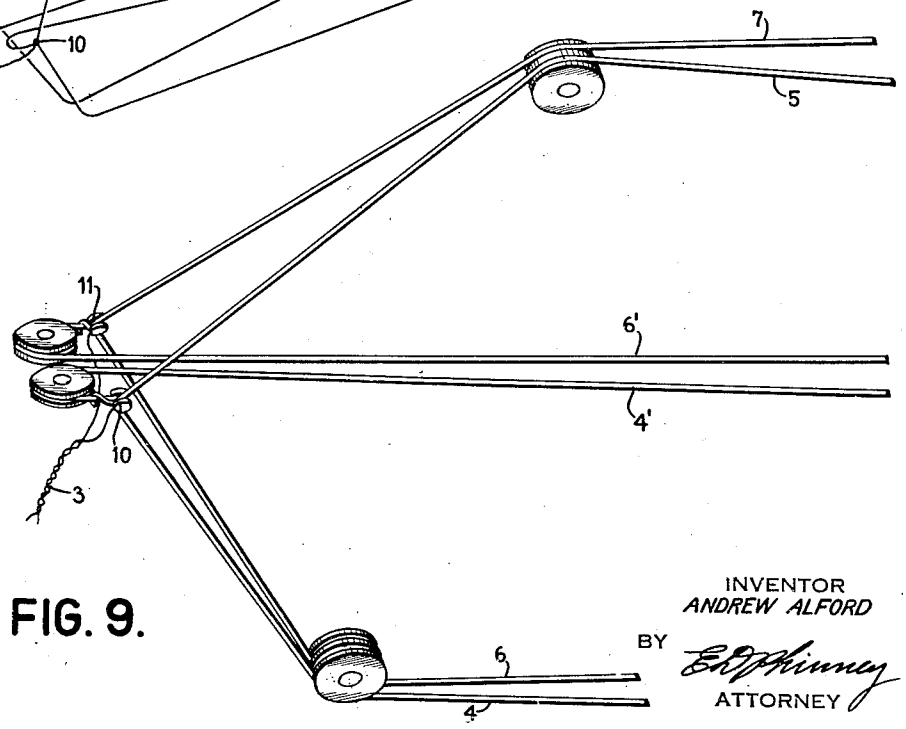


FIG. 9.

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UNITED STATES PATENT OFFICE

2,165,087

APERIODIC TRANSFORMER SYSTEM

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Application October 9, 1937, Serial No. 168,223

12 Claims. (Cl. 178—44)

The present invention relates to high frequency transformers and more particularly to substantially aperiodic transformers which are useful at all frequencies within a given range.

It is an object of the present invention to provide such an aperiodic high frequency transformer which may be cheaply and easily constructed. It is a further object to provide such a transformer which is especially adapted for incorporation in transmission lines of ordinary construction and which can readily be erected by construction crews engaged in erecting transmission lines and antenna structures.

It is a further object of the invention to provide a transformer whose dimensions shall be of practical size when designed for the ranges of frequency and transformation ratios ordinarily required at the junctions of transmission circuits for commercial short-wave frequencies. More particularly it is an object to provide a transformer whose length can be reduced to less than a wavelength without causing appreciable reflection of waves even when the transformation ratio corresponds to an impedance ratio of more than 3 to 1. In accordance with the simplest form of my invention, a transformer is provided which can practicably be given a transformation ratio of 2.45 to 1, although it is preferred to use this form of my invention for applications where the required transformation ratio is between 1.2 to 1 and 1.9 to 1. For comparison with other impedance matching systems, it may be noted that a transformation ratio of 1.9 to 1 is sufficient to match two impedances which are in the proportion of 3½ to 1.

According to other forms of my invention still greater transformation ratios can be obtained in an aperiodic high-frequency transformer of practical size and shape. Furthermore even for use in applications where the required transformation ratios are attainable by means of "tapered" transmission lines, the present invention provides a transformer of much smaller dimensions for any given requirement of reflection-free transformation.

In all the forms of my invention the required transformation ratio may be obtained without necessitating impracticably close spacing between conductors of opposite polarity.

Furthermore, the maximum spacing between conductors is not so great as to be inconvenient or unwieldy.

An important feature of the present invention is the provision of a transformer whose characteristics and dimensions can readily be precomputed so that transformer can be constructed to meet various requirements without endless experimentation. Another feature of the present invention is the provision of a transformer which is essentially constructed of simple wires so that the expense of producing wires of tapered diameter or special cross-section is obviated.

The invention can best be understood from the following description taken in conjunction with the attached drawings, in which

Fig. 1 is a perspective view of a transformer constructed in accordance with the simplest form of my invention;

Fig. 2 and Fig. 3 are, respectively, a plan and an elevation of the essential conductor members shown in Fig. 1;

Fig. 4 is a schematic perspective view of a system embodying a transformer like that in Fig. 1;

Figs. 5 and 6 represent two further kinds of systems embodying transformers like that in Fig. 1;

Fig. 7 is a schematic representation of another form of transformer similar to the form shown in Fig. 1 but having eight conductors instead of four conductors;

Fig. 8 is a schematic representation of still another form of transformer having six wires;

Fig. 9 is a perspective view of the low impedance end of the transformer schematically represented in Fig. 8.

Referring more particularly to Fig. 1, 1—2 is an ordinary open wire transmission line for carrying a high frequency signal from a receiving antenna to the point of reception. Line 3 is a twisted pair transmission line of lower impedance than open wire line 1—2, which serves to carry the high frequency signals into the building where the receiving equipment is located and then through a telegraph type plug and jack distributing board to the receiving set. It will be assumed that the conductors of line 1—2 are ordinary hard-drawn copper wires of #10 AWG, having a diameter of approximately .10 inches. The spacing between these wires will be assumed to be 4 inches. Upon the basis of these assumed dimensions, line 1—2 will have a surge impedance of approximately

$$276 \log_{10} \frac{8}{.1} \text{ ohms}$$

The low impedance twisted pair transmission line 3 is assumed to have a surge impedance of 150 ohms. The signals to be carried over line 1—2 and line 3 are assumed to lie in the frequency range between 5 and 30 megacycles.

In accordance with the present invention, line 1—2 is connected to line 3 by means of an aperiodic transformer which may be roughly described as consisting of two transmission lines, each having tapered characteristics and disposed with respect to each other so that they mutually interact in a tapered manner. As shown in Fig. 1 this transformer comprises assentially four conductors, 4, 5, 6 and 7, of which the conductors 4 and 5 are connected together and joined to line con-

ductor 1, while the conductors 6 and 7 are similarly joined together and connected to line conductor 2. The two upper conductors, 4 and 6, constitute a special kind of transmission line having tapered characteristics. These two conductors, 4 and 6, are spaced from each other the same distance as conductors 1 and 2, that is to say, 4 inches, at the junction points 8 and 9, but at points progressively more remote from these junction points the two conductors, 4 and 6, approach each other more and more closely. Transformer conductors 5 and 7 are likewise spaced 4 inches apart at junction points 8 and 9, and likewise progressively approach each other at points removed from these junctions. The transmission line constituted by conductors 4 and 6 is not independent of the line constituted by conductors 5 and 7 but these two transmission lines mutually interact in a manner which varies from the high impedance end 8—9 to the low impedance end 10—11 of the transformer. The variation of the mutual interaction between transmission line 4—6 and transmission line 5—7 results not only from the variable width spacing of each of these transmission lines but also from a varying spacing between the whole tranmission line 4—6 and the transmission line 5—7. As clearly shown in Fig. 1 the transmission line 4—6 is immediately adjacent to the transmission line 5—7 at the end 8—9. At points progressively removed from this end 8—9, however, the transmission line 4—6 is progressively farther from the transmission line 5—7. For convenience in illustration, the conductors 4, 5, 6 and 7 have been shown in Fig. 1 as if each of these conductors were perfectly straight, so that the two conductors of one transmission line, as for example, conductors 4 and 6 or conductors 5 and 7, approach each other in a taper that is perfectly uniform, while at the same time the two whole transmission lines, 4—6 and 5—7, diverge from each other in a taper that is also perfectly uniform. Ordinarily, however, in actual construction the convergence of the two conductors of each transmission line, or the divergence of the two transmission lines, or both of these variations in spacing will be non-uniform in accordance with the definite rule of spacing more fully set forth below. The curvatures of conductors 4, 5, 6 and 7, which are required in order to attain the non-uniform divergences or convergences, or both, are obtained by means of spreader insulators 12 which may be proportioned and spaced so as to support the conductors 4, 5, 6 and 7 in the required curves. Although only four of these insulators have been illustrated in Fig. 1, it will be understood that a greater number may be used if it is desired to cause the conductors 4, 5, 6 and 7 to conform more accurately to the theoretical curvatures derived in accordance with the rules hereafter set forth. On the other hand, it is also evident that a smaller number of insulating spreaders may be used in those cases where a less close conformity with the theoretical curvatures is required.

The four conductors 4, 5, 6 and 7 as illustrated in Fig. 1, may be of the same diameter as the open line wires 1—2. In such a case it is convenient to make conductors 4—5 of the same continuous piece of wire as line wire 1, the line wire 1 merely extending beyond junction point 9 to form conductor 5 and then being looped around through supporting structure 13 to return as conductor 4. The end of conductor 4 is then connected to the line wire 1 at junction 8 by twisting the wires together and clamping them with suitable screw clamping means as shown. A preferred clamping device is that type generally known as a "Kearny Clip". The same type of construction is employed for conductors 6—7 which are similarly integral with line wire 2. For very accurate design of the transformer, however, it may be desired to have conductors 4, 5, 6 and 7 of smaller diameter than line wires 1 and 2 in the ratio more fully set forth hereafter. For such design of the transformer, therefore, the conductors 4—5 may be one single piece of wire but must both be connected at junction 9 to line wire 1; similarly conductors 6—7 will be a separate piece of wire from line wire 2. In either case, whether conductors 4, 5, 6 and 7 are integral with line wires 1 and 2 or not, it is convenient to employ such a supporting arrangement as 13 at the low impedance end of the transformer, so that conductors 4—5 may consist of a single piece of wire and likewise conductors 6—7 may consist of a single piece of wire. Preferably the supporting structure 13 should be arranged so that the tensions in conductors 4—5 can equalize themselves approximately.

Referring now more particularly to Figs. 2 and 3, which show the four conductors, 4, 5, 6 and 7, in plan view and elevation, respectively, it will be noted that the two conductors of any one transmission line, as for example, 4 and 6, approach each other in a uniform straight taper. The rate of divergence between the two transmission lines, however, is not uniform but is determined in accordance with the following formula:

$$138[N^{\frac{1}{2}}X - M^{\frac{1}{2}}X + M^{\frac{1}{2}}]^2[A+B]=1 \qquad (1)$$

X is the distance from the point of measurement to the high impedance end of the transformer, that is to junction points 8—9, expressed as a fraction of the whole length of the transformer M and N are, respectively, the conductances in mhos of the high and low terminal impedance values for which the transformer is designed; in other words M and N are the reciprocals of the impedances which the transformer is intended to match. W is the width spacing between centers of the two conductors of one transmission line, such as between 4 and 6 or 5 and 7. H is the height separation between two successive transmission lines; that is the distance between centers of two wires of like potential, such as 4 and 5 or 6 and 7. r is the radius of the transformer wires. A, B, C and D are convenient designations, used in the above formula and later formulae, and represent the following functions of W, H and r:

$$A=\log\frac{W}{r};\quad B=\tfrac{1}{2}\log\left(\frac{W^2}{H^2}+1\right);$$

$$C=\tfrac{1}{2}\log\left(\frac{W^2}{4H^2}+1\right);\quad D=\tfrac{1}{2}\log\left(\frac{W^2}{9H^2}+1\right)$$

In the system shown in Fig. 1, in which the transformer is connected between a high impedance line 1—2 and a low impedance line 3 for matching their surge impedances, M will represent the reciprocal of the surge impedance of line 1—2, while N will similarly represent the reciprocal of the surge impedance of the low impedance line 3.

It is evident that in following the above formula for determining the width spacing W between wires of unlike polarity such as 4 and 6 or 5 and 7, and for determining the height spacing H be-

tween wires of like polarity, such as 4 and 5 or 6 and 7, ratio

$$\frac{H}{r}$$

cannot practically be made smaller than 2 since two round wires cannot be brought closer together than twice their radius.

In case it is desired to connect the high impedance end of the transformer directly to an open wire line such as 1—2, and to accurately match the impedance of this end of the transformer to the surge impedance of the open wire line 1—2, it may be convenient to have the width spacing W of the transformer equal to the spacing of the open line 1—2 at the position 8—9 where the transformer is connected to the line. In order to make W equal to the spacing of line 1—2 at this position, while still maintaining an accurate matching between the transformer and the open wire line, the conductors may be selected to be of smaller diameter than the line wires 1 and 2. Assuming that the transformer is constructed so that at points 8—9 its height ratio

$$\frac{H}{r}$$

is equal to 2, the diameter of the transformer conductors 4, 5, 6 and 7 should be about .7 times the diameter of the line wires 1 and 2. The exact formula for

$$\frac{r}{R}$$

being

$$\sqrt[4]{\frac{1+\left(\frac{2r}{W}\right)^2}{4}}$$

where R is the radius of the line wire and r is the radius of the transformer wire.

If, on the other hand, it is desired to make the transformer conductors of the same wire as the line wires 1 and 2, while still accurately matching the input impedance of the transformer to the impedance of the open line 1—2, this may be done in accordance with the Formula (1) given above, but in this case the width dimension W of the transformer at points 8—9 will be approximately 40% greater than the spacing between the open line wires 1 and 2. The line wires may be connected to the end of the transformer either by abruptly diverging the line wires or by abruptly converging the endmost portion of the transformer, but in either case the convergence or divergence should be comparatively abrupt so that the region of this convergence or divergence will occupy only a very small fraction of a wavelength.

In actual practice it is ordinarily not necessary to construct the transformer so as to match the line absolutely accurately. In most cases, therefore, the line wires and transformer conductors may be of the same diameter and, at the same time, the width dimension of the transformer at its high impedance terminals 8—9 may be equal to the spacing of the open wire line 1—2. Fig. 1 illustrates the preferred construction for such a case. The ratio of mismatch between the open wire line and the high impedance end of the transformer in such a case, is only approximately 1.08 to 1, which is ordinarily not detrimental.

In designing the varying spacing of the four transformer conductors in accordance with Formula (1) given above, it is preferred to let the width dimension W decrease according to a uniform straight taper from the high impedance end of the transformer to the low impedance end, and then to compute the corresponding non-uniform divergence of the height dimension H from the high impedance end of the transformer 8—9 to the low impedance end of the transformer. The procedure, however, may be reversed by taking the divergence of dimension H to be uniform and then computing the corresponding non-uniform convergence of dimension W, or, if desired, both dimensions may be varied in a non-uniform manner. The transformation ratio which can be attained with a four conductor transformer constructed in accordance with my invention theoretically depends both upon the minimum spacing between conductors of unlike polarity at the low impedance end and upon the maximum values of the dimensions W and H which are attained at the low impedance and high impedance ends of the transformer, respectively. If, however, the maximum width W at the high impedance end of the transformer is assumed to be as much as twenty times the wire diameter of conductors 4, 5, 6 and 7, and if the wires of like polarity are brought directly into contact at this high impedance end of the transformer, so that the dimension H has the value $2r$ at this end, it will be observed from Formula (1) that an increase of the width dimension W has comparatively little effect upon the input impedance of the transformer. In fact, the high-end impedance varies by only approximately twenty percent when the high-end width of the transformer is doubled under these conditions. Similarly at the low impedance end of the transformer if the height H is as much as three times the width W, further increases in H cannot alter the impedance at this end of the transformer by more than about eight percent no matter how much this dimension H is increased and even if W at this end is only two times r. For practical purposes, therefore, the most significant dimension in determining the transformation ratio is the minimum value of the width ratio W/r at the low impedance end of the transformer. If the lowest practicable limit of the width ratio W/r is taken as 4, which represents a spacing of two diameters between the centers of the adjacent conductors, a transformation ratio of about 2.45 to 1, corresponding to an impedance ratio of approximately 6 to 1, can be realized. Even if the minimum width ratio is limited to not less than 10, which represents a spacing of five diameters between the centers of the conductors, a transformation ratio of almost 1.9 to 1 can be realized, which corresponds to an impedance ratio of 3½ to 1.

Where the practical limitations of the minimum width spacing W render it impossible or inconvenient to attain the required transformation ratio by means of a transformer such as shown in Fig. 1, or where for any other reason such a transformer does not conveniently provide a sufficient transformation ratio or a sufficiently low characteristic impedance at its low impedance end, the modified form of my invention shown in Figs. 7, 8 and 9 may be employed. Fig. 7 schematically represents a transformer similar in its general construction to the transformer shown in Fig. 1, but having four pairs of wires instead of only two pairs. The four wires, 4, 5, 4′ and 5′, which include one wire from each of the four pairs, are connected together at the point 8 in the same way that the two wires 4 and 5 were connected together at point 8 in Fig. 1. At the other end the four wires 4, 5, 4′ and 5′, are con-

nected together by joining wires 4 and 5 and joining wires 4' and 5', and then joining these junctions at point 10 as shown in Fig. 7. It is obvious that other arrangements for joining the ends of these four wires might be employed, but in any case, the junction must be so arranged that the paths from point 10 to each of the four wires are equal. Wires 6, 7, 6' and 7', which include the other wires of the four pairs, are similarly arranged and connected as shown in Fig. 6.

Upon the assumption that the four wires of one polarity are equally spaced, that is, that the distance from conductor 4 to conductor 5 is the same as the distance from conductor 5 to 4' and also the same as the distance from conductor 4' to conductor 5' at every position along the length of the transformer as shown in Fig. 7, the formula for determining W and H at every point along the length of the transformer is as follows:

$$138[N^{\frac{1}{2}}X-M^{\frac{1}{2}}X+M^{\frac{1}{2}}]^2\left[\frac{(A+B)(A+D)-(B+C)^2}{2A-B-2C+D}\right]=1 \quad (2)$$

W represents the separation between wires of opposite polarity, as for example, between conductor 5' and conductor 7', or between conductor 4 and conductor 6; H represents the uniform spacing dimension between successive wires of like polarity, as for example, between conductors 4 and 5; X, r, M, N, A, B, C and D have the same significance as explained in connection with Formula (1).

Fig. 8 schematically represents a transformer of the general type shown in Figs. 1, 2, 3 or 7, but having three pairs of wires, 4—6, 4'—6' and 5—7, instead of two pairs or four pairs of wires. The arrangement and connection of the six conductors of Fig. 8 is generally similar to the arrangement and connection of the eight conductors of Fig. 7. The junction arrangement at the low impedance end of the transformer of Fig. 8, however, is somewhat different from the arrangement in Fig. 7 or the arrangement in Fig. 1. It is necessary in the case of Fig. 8 to bring together three wires by means of electrical paths which are of equal length. Fig. 9 more clearly shows how the low impedance junctions of Fig. 8 are arranged, and also illustrates how insulators of pulley form may be employed for supporting this low impedance end of the transformer. The use of insulators of such type not only provides an equalization of the tensions in the three wires of each polarity but also permits the connections from the three wires to the common point to be adjusted to electrical equality by adjusting the wires where they are clamped together at point 8. The formula applicable to the form of transformer illustrated in Figs. 8 and 9 is as follows:

$$[138N^{\frac{1}{2}}X-M^{\frac{1}{2}}X+M^{\frac{1}{2}}]^2\left[\frac{A(A+C)-2B^2}{3A-4B+C}\right]=1 \quad (3)$$

The transformation ratio which may be obtained by means of a transformer constructed in accordance with Figs. 7, 8 or 9 is dependent not only upon the minimum tolerable value of W, but also upon the maximum values of W and H. Just as in the case of the transformer of Fig. 1, however, the minimum value of W is the chief factor in determining the transformation ratio provided the maximum value of W is large in comparison with the wire diameter and the maximum value of H is large in comparison with the minimum value of W.

In case still greater impedance ratios are required, transformers may be constructed with more than four pairs of wires. The wires which are to be joined together may be directly brought to a common junction at the high impedance end just as in the case of the 6-wire and 8-wire transformers illustrated in Figs. 7 and 8. At the low impedance end of the transformer the junction may be made either by bringing the wires directly together as in the arrangements of Figs. 9 and 8, or by combining the wires in pairs and then connecting these pairs as in the case of Fig. 7. The latter arrangement is preferably employed only when the total number of conductors in the transformer is even.

In accordance with the present invention, a transformer constructed of four or more wires spaced from each other in accordance with the formulae given above, may be employed not only for connecting two transmission lines of different surge impedance but generally for connecting two loads of any type. One useful system embodying such a transformer is illustrated in Fig. 4, in which a source 20 is coupled to two loads 60 and 70 by means of a transformer constructed according to Fig. 1. The transformer which is designated generally by 50 is designed so that the impedance of its input terminals matches the impedance of source 20 as viewed through transmission line 21, while the impedance of the output terminals of the transformer matches the combination of the impedances of load 60 as viewed through line 61 considered in parallel with the impedance of load 70 as viewed through line 71.

Although the transformer 50 shown in Fig. 4 is aperiodic in its characteristics, the complete system is in general not aperiodic unless the impedances of the source and loads are matched to the impedances of lines 21, 61 and 71, respectively, or unless these lines have sufficient attenuation so that the reflected waves resulting from the mismatch of the terminating loads or source are substantially extinguished before returning to transformer 50. This system, however, represents a useful application of transformer 50 even if the system is not aperiodic. It will be understood that the transformer 50 may be reversed in position so that its high impedance end is connected to the junction of lines 61 and 71, while its low impedance end is connected to line 21, if the combined impedance of the two loads as viewed through lines 61 and 71 is higher than the impedance of source 20 as viewed through line 21. It will also be understood that one load or three loads or any other number of loads may be employed, and also that a plurality of sources may be employed if desired.

In addition to the novel form of aperiodic transformer whose nature and construction has been above disclosed and whose manner of use has been explained in conjunction with the transmission system of Fig. 4, my invention also comprises a novel transmission system more fully described below in conjunction with Figs. 5 and 6. This transmission system includes an aperiodic transformer connected to transmission circuits and proportioned with respect to such circuits according to a novel rule whereby the transformer cooperates with the rest of the system in a fundamentally new manner to produce an effect of an entirely novel kind. It is preferred to construct this novel system with an aperiodic transformer of the new and improved type above disclosed, but it is within the scope of my invention to construct the novel transmission system with any

other available type of aperiodic or semi-aperiodic transformer. Where the expression aperiodic transformer is used in connection with this novel transmission system, therefore, it should be understood to include aperiodic and semi-aperiodic transformers, and in fact any transformer which is reasonably aperiodic over a wider band than some other part of the system.

Fig. 5 represents a system which is structurally similar to the system shown in Fig. 4, except that the lengths of lines 61 and 71 are assumed to be electrically equal and the impedances of loads 60 and 70 are assumed to be the same. The design of transformer 50 in the system of Fig. 5, however, is determined in accordance with a very different principle from the design of the transformer in Fig. 4. The terminal impedances of the transformer are matched to the surge impedances of lines 21, 61 and 71 without regard to the impedance values of the terminating loads and source. Thus the output terminals of the transformer in Fig. 5 are matched in impedance to the surge impedance of line 61 considered in parallel with the surge impedance of line 71, while the input terminals of the transformer are matched in impedance to the surge impedance of line 21. The transformer 50 when designed in this manner does not in any way compensate for the mismatch existing between loads 60 and 70 and their respective lines 61 and 71, but merely compensates for the mismatch existing at the junction of lines 61, 71 and 21. With respect to the correction of the latter mismatch, however, the system shown in Fig. 5 is completely aperiodic, so that this system is adapted to be employed where a number of different frequencies are used or where a band of frequencies is used. The usefulness of this system can best be understood by comparison with a similar system in which transformer 50 is omitted, lines 61, 71 and 21 being directly connected together. In such a transformerless system, reflected waves will be set up at the termination of lines 61 and 71 as a result of the mismatch of loads 60 and 70. The reflected waves thus produced in lines 61 and 71 have amplitudes which are a certain percentage of the amplitudes of the forwardly transmitted waves; for example we may assume that the amplitude of the reflected waves is 40% of the amplitude of the forwardly transmitted waves. Upon the assumption that the mismatch between load 60 and its line 61 is the same as the mismatch between the load 70 and its line 71, the percentage of reflected waves in each of these lines will be equal. Also, since we have assumed that lines 61 and 71 are of equal electrical length, the reflected waves will arrive at the point of junction with line 21 in the same phase. If no transformer is provided at the junction of lines 21, 61 and 71, however, these reflected waves will be propagated into line 21 with a change in amplitude, so that the percentage of reflected waves existing in line 21 will not ordinarily be the same as in lines 61 and 71. Thus if the reflected waves in lines 61 and 71 were 40% as large as the transmitted waves in these lines, it might be found that the reflected waves in line 21 were less than 8% as large in amplitude as the transmitted waves in this line 21 or, on the other hand, it might be found that the reflected waves in line 21 had an amplitude 65% as great as the amplitude of the forwardly transmitted waves in this same line 21. This change in the percentage of reflected waves when the waves propagate lines 61 and 71 into 21, depends upon the phase of the reflected waves relative to the transmitted waves at the junction point of the three lines. Therefore, if the system shown in Fig. 5 were employed without matching transformer 50 for a band of frequencies, or for a number of frequencies, the percentage of standing waves existing in lines 61 and 71 would, for certain ones of these frequencies, be greatly increased upon propagation into line 21. The importance of this increase is particularly evident when the amplitude of the reflected waves is expressed not in percentages as above, but by the so-called "standing wave ratio" which is the ratio of peak amplitudes to minimum amplitudes of the resulting standing waves produced by the superposition of the reflected and forwardly transmitted waves. The increase in this peak-to-valley ratio of the standing waves would, for unfavorable phase conditions, be as great as 2 to 1. Thus a standing wave ratio of 14:6 in lines 61 and 71 would result in a standing wave ratio of 14:3 in line 21 under the worst conditions of phase.

By employing a transformer to interconnect the three lines 61, 71 and 21, in accordance with the present invention as shown in Fig. 5, and by designing the transformer to match the surge impedances of the lines at the junction point, as previously described, all the above changes in reflected wave percentage and standing wave ratio are eliminated. Thus when a 40% reflected wave exists in lines 61 and 71, corresponding to a standing wave ratio of 14:6, this same reflected wave percentage and this same standing wave ratio will also be found in line 21. This result is of great practical utility because of the fact that the reflected wave percentages and standing wave ratios encountered in practice as a result of the mismatch of terminating loads or sources are very often sufficiently low to be tolerable. When such a reflected percentage or standing wave ratio is increased by propagation through a transformerless junction, however, it frequently occurs in practice, that the resulting reflected wave percentages and standing wave ratios become intolerably large. If line 21 is comparatively short, the primary result of the high reflected wave percentages or standing wave ratios is to usually render the coupling of source 20 to line 21 inefficient, and this inefficiency increases rapidly with an increase in the standing wave ratio. Furthermore, if the length of line 21 is considerable, which is frequently the case in practice, the actual dissipative losses in line 21 increase nearly in direct proportion to the standing wave ratio in this line. In addition to the above disadvantages of high standing wave ratios, it would be noted that when these ratios become unduly large, the increased potentials in the transmission line network begin to cause difficulties of all kinds as the result of insulator breakdowns, corona effects and arc-overs. Furthermore, the use of correcting networks for eliminating the reflected waves becomes increasingly difficult when the standing wave ratio becomes greater. For all these reasons as well as for the sake of uniformity of transmission efficiency at different frequencies, it is exceedingly desirable when mismatches are present in a system, to arrange the junction point in such a manner that the reflected wave percentages introduced by the given mismatches will not be altered by the effect of the junction. In accordance with my invention, this desirable result is obtained by merely connecting a 4-wire transformer at the junction point of the three lines as shown

in Fig. 5. When there are several junctions in tandem these effects are even worse, if no transformers are used at the junctions. Correspondingly, if transformers are used the advantages are even greater since one single matching network may serve for correcting the mismatch of four or eight antennae.

The construction of the transformer **50** in Fig. 5, is also unusually simple and convenient, especially if absolute accuracy in the design of the transformer is not required, which in practice is usually the case. Not only is it possible to eliminate the special structure **13** as used in Fig. 1, by connecting the transformer conductors directly to the lines **6***l* and **7***l* as shown in Fig. 5, but also it is possible to effect great simplification both in construction and in design, with only a slight sacrifice in accuracy. This simplification results from the peculiarly suitable relationship of spacings and terminal impedances which are encountered in practice in joining three open wire lines of similar type.

If it is assumed that in the system of Fig. 5, all of the transmission lines are of the same construction and have the same diameter of wire and spacing, then the impedance ratio theoretically desired for the transformer will be simply 2 to 1. For absolutely accurate design such a transformer would require a variation in the dimension W as well as in the dimension H, and therefore the spacing of this transformer would necessarily differ from the spacing of the transmission line to which it is connected at least at one end of the transformer. If the transformer is constructed of the same diameter wire as the three lines which it joins, it would furthermore result that the transformer spacing W would differ from the spacing of the transmission line at all three points of connection in case absolutely accurate design were required. For most purposes, however, sufficient accuracy is obtained by taking the transformer of the same diameter wire as the transmission line and with a constant spacing W equal to the spacing of each of the transmission lines. This construction then amounts merely to joining an extra conductor to each wire of line **2***l* and then diverging the double line so formed at a suitable rate before connecting this double line to the continuous wires which constitute lines **6***l* and **7***l*. The width spacing is not altered at all, but merely remains equal to the uniform line spacing of lines **2***l*, **6***l* and **7***l*.

In designing the transformer for this approximate case, as shown in Fig. 5, Formula (1) may be used just as in the case of Fig. 1, the dimension W being simply taken as constant and the dimension H being determined in accordance with the formula to define the curve of divergence of the transformer conductors of like polarity. In applying Formula (1) to a transformer of this approximate type, however, the input impedance of the transformer cannot be set equal exactly to the surge impedance of line **2***l*, nor can the output impedance of the transformer be set equal to the surge impedance of line **6***l* in parallel with the surge impedance of line **7***l*. Therefore, for this approximate type of transformer in which the dimension W is fixed by the spacing of the line, the conductances M and N are not taken as the starting point in applying Formula (1) but, on the contrary, the values of W and H at the two ends of the transformer are assumed and the corresponding values of the coefficients M and N are derived therefrom.

At the high impedance end of the transformer, W will preferably be chosen equal to the spacing of the transmission line and H equal to $2r$, since the center-to-center spacing of two wires is equal to twice the radius when the wires are in direct contact. At the low impedance end of the transformer, W is again equal to the spacing of the transmission line, while H is arbitrarily taken to be any convenient value greater than three times the value of W and preferably greater than five times W. Thus from these boundary conditions the values of M and N can readily be found. For example, if the transmission spacing is four inches and the diameter of the conductors is one-tenth of an inch, W will be $80r$. If the maximum value of H is assumed to be five times W, i. e., twenty inches, then H will be $400r$ at the low impedance end. Setting $X=0$, $W=80r$, $H=2r$, Formula (1) becomes

$$138M \log [80\sqrt{40^2+1}]=1$$

therefore $M=.00207$. Similarly by setting $X=1$, $W=80r$, $H=400r$, Formula (1) becomes

$$138N \log [80\sqrt{0.2^2+1}]=1$$

therefore $N=.00379$. Now from these values of M and N the value of H may be found for any position X upon the assumption that the value of W is always $80r$.

The above method of computing transformer dimensions from arbitrarily given end dimensions instead of from the impedance values to be matched, may be applied in whole or in part whenever all or some of the dimensions of the transformer are fixed by practical limitations. This general process of computation is useful particularly in designing the high impedance end of the transformer shown in Fig. 1, in those compromise cases where the spacing W at this high impedance end of the transformer is to be the same as the spacing of transmission line **1**—**2**, and the diameter of conductors **4**, **5**, **6** and **7** is to be the same as the diameter of conductors **1** and **2**.

Fig. 6 represents a system, part of which is similar in principle to the system shown in Fig. 5. In this figure, the transformer **50** is designed to match the surge impedances of three lines, **3***l*, **6***l* and **7***l*, for the purpose of preventing alteration of the reflected wave percentage or the standing wave ratio resulting from the mismatch of loads **60** and **70** with respect to their lines **6***l* and **7***l*. In this figure, it is again assumed that the mismatch between load **60** and line **6***l* is the same as the mismatch between load **70** and line **7***l*, the two loads and the two lines being preferably identical. It is also assumed that the electrical lengths of lines **6***l* and **7***l* are equal, which will be the case if these lines are identical in length and in construction. A source **20** is connected to transmit high frequency waves over line **2***l* and through network **30** to line **3***l*, and this line **3***l* is joined to lines **6***l* and **7***l* by means of transformer **50** designed in the manner explained in connection with Fig. 5. Network **30** is arranged to match the surge impedance of line **2***l* to the total resultant impedance of line **3***l* taken together with transformer **50**, lines **6***l* and **7***l*, and loads **60** and **70**. If a number of separate discrete frequencies are to be transmitted through the system, network **30** may be a composite network designed to perform the above described matching at each of these discrete frequencies. Because of the action of transformer **50**, the standing wave ratio existing in line **3***l* will be no more severe than that existing in lines **6***l* and **7***l*,

and for this reason network 30 can readily be designed without encountering the difficulties which result from attempting to compensate for standing waves of high ratio. By this arrangement, therefore, one single network 30 serves to match a plurality of separate loads and, therefore, performs the function of two separate networks located in lines 61 and 71. This is of importance not only because of the saving in the number of compensating networks required, but also because it avoids the difficulty of constructing a network in each of the lines 61 and 71 which are frequently inaccessible and are in many cases too short to permit the inclusion of a satisfactory network. Although it is preferred to locate network 30 as close to the transformer 50 as is conveniently possible, this network may be located at an intermediate point or even in the immediate neighborhood of source 20 without introducing serious losses, since the standing wave ratio in line 31 will not be excessive for any frequency.

The arrangement shown in Fig. 6 is particularly useful in connection with transmitting or receiving antenna arrays. For a transmitting array the loads 60 and 70 may be simply replaced by radiating antennae; for a receiving array the loads 60 and 70 may be replaced by receiving antennae and the source 20 may be replaced by suitable receiving equipment. In this latter case, because of the reversal of the direction of transmission, the discussion given in connection with Fig. 5 with respect to reflected waves and standing waves will not be literally applicable. In view of the well known reciprocity theorem whereby sources and loads may be interchanged without loss of efficiency however, the gain in efficiency which has been shown to exist in the case of Figs. 5 and 6, will still be available when the loads of these figures are replaced by sources, such as receiving antennae, and the sources are replaced by loads, such as receiving equipment. Because of the symmetry of Figs. 5 and 6, and the consequent cophasal energization of loads 60 and 70 in these figures, the arrangements shown in these figures are primarily applicable to broadside antenna arrays or other arrays in which a cophasal energization of the separate antenna elements is desirable. In the case of receiving antenna arrays the converse is true, and broadside arrays or other arrays in which the receiving antennae collect energy in a cophasal relationship are particularly suitable.

It will be understood that the arrangements illustrated in Figs. 5 and 6 are not restricted to systems in which one source feeds two loads or two sources feed one load, but are also applicable to systems in which a larger number of transmission lines are to be joined. Four loads, for example, could be coupled to one source by employing a first transformer to divide the incoming line into two principal feeder lines and then employing a separate transformer to divide each of these feeder lines into two lines which extend to the loads. In such a case, compensating networks of the type represented by 30, could be inserted in the two principal feeder lines or preferably, one single compensating network could be inserted in the single line extending from the source. Alternatively, it is also apparent that more than two lines could be joined by means of one single transformer to a single feeder line and this arrangement is especially suitable in case an odd number of lines is to be connected. In such a case the general principle of transformer design set forth in connection with Figs. 1, 2, 3, 7, 8 and 9 should be followed in order to match the impedance of the single feeder line to the combined parallel impedance of the plurality of lines to which it is to be joined. By using a six-conductor transformer for junctions where three lines are to be joined to one single line, and by using an eight-conductor transformer where four lines must join one single line, the transformer design can be simplified in case accurate matching is not essential in the same manner described in connection with Fig. 5.

While I have described certain particular embodiments of my invention for the purposes of illustration, it will be understood that various adaptations and modifications thereof occurring to one skilled in the art may be made within the spirit of the invention as set forth in the appended claims.

I claim:

1. An aperiodic high frequency transformer comprising two two-wire transmission lines extending in the same general direction substantially alongside each other and connected in shunt with each other at both ends, each of said two-wire lines comprising two circular cylindrical wires spaced from each other variably along the length of the line, and said two lines being spaced from each other variably along the length of the transformer.

2. An aperiodic high frequency transformer comprising a plurality of transmission lines each comprising a plurality of wires disposed in proximity and extending substantially along side each other in substantially the same direction, the mutual spacing of the wires of each line being such that they have substantial mutual interaction and the spacing of the complete lines with respect to one another being such that these complete lines also have substantial mutual interaction and at least one of said spacings being varied along the length of the transformer, and means at each end of the lines for connecting said lines effectively in parallel with each other.

3. An aperiodic high frequency transformer comprising at least four cylindrical wires in proximity in a dielectric and extending substantially alongside each other in substantially the same direction, at least two of said wires being so disposed that their mutual spacing varies along the length of the transformer and that their mutual interaction is substantial at at least one end of the transformer, and means at each end of the transformer for connecting said lines together in groups.

4. An aperiodic high frequency transformer comprising at least two pairs of cylindrical wires in proximity in a dielectric and extending alongside each other in substantially the same direction, the two wires of each pair being so disposed that their mutual spacing varies along the length of the transformer and that their mutual interaction is substantial at at least one end of the transformer, and means at each end of the transformer for connecting said wires together in two groups.

5. In a transmission system for transferring power from a source to a plurality of similar loads, an aperiodic transformer, a single transmission line connecting the input side of said transformer to said source, and a plurality of similar transmission lines each connecting the output side of said transformer to one of said loads, the load impedances being such that the ratio of the surge impedance of said single line

to the combined parallel connected surge impedances of said plurality of lines is markedly different from the ratio of the total effective impedance of said single line with its connected source to the total effective impedance of said plurality of lines with their connected loads, and the impedance ratio of said transformer being substantially equal to said ratio of surge impedances.

6. In a transmission system for transferring power from a source to a plurality of similar loads, an aperiodic transformer, a single transmission line connecting the input side of said transformer to said source, a plurality of similar transmission lines each connecting the output side of said transformer to one of said loads, the impedance ratio of said transformer being substantially equal to the ratio of the surge impedance of said single line to the combined parallel connected surge impedances of said plurality of lines, and matching means interposed in said single line and adapted to match the surge impedance of that portion of said single line which is intermediate the source and the matching means to the combined impedance of said loads as viewed through the plurality of lines and through the transformer and through that portion of said single line intermediate the matching means and the transformer.

7. In a transmission system for transferring power among several impedances of which at least one is a source, the combination of a transformer, a plurality of lines connecting one side of said transformer to a plurality of said impedances, a further line connecting the opposite side of said transformer to a further one of said impedances, at least one of said impedances being substantially mismatched with respect to the line to which it is connected and the impedance ratio of said transformer being substantially equal to the ratio of the surge impedance of said further line to the combined parallel-connected surge impedances of said plurality of lines.

8. In a transmission system for transferring power among several impedances of which at least one is a source, the combination of a transformer, transmission means connecting one side of said transformer to a plurality of said impedances, further transmission means connecting the opposite side of said transformer to a further one of said impedances, at least one of said impedances being substantially mismatched with respect to the transmission means to which it is connected and the impedance ratio of said transformer being substantially equal to the ratio of the surge impedance of said further transmission means to the combined parallel-connected surge impedances of said transmission means first mentioned.

9. In a transmission system for transferring power among several impedances of which at least one is a source, the combination of a transformer, a plurality of lines connecting one side of said transformer to a plurality of said impedances, a further line connecting the opposite side of said transformer to a further one of said impedances, at least one of said impedances being mismatched with respect to the line to which it is connected and the impedance ratio of said transformer being substantially equal to the ratio of the surge impedance of said further line to the combined parallel-connected surge impedances of said plurality of lines, and matching means interposed in said further line and adapted to match the surge impedance of that part of said further line remote from the transformer to the complete effective impedance of that portion of said further line toward the transformer together with all equipment connected to said portion.

10. In a transmission system for transferring power from a source arrangement to a load arrangement, one of said arrangements being a single impedance and the other of said arrangements consisting of a plurality of similar units, the combination of an aperiodic transformer, a plurality of similar two-conductor transmission lines of equivalent electrical length each connected between one side of the transformer and one of said similar units and each being substantially mismatched by approximately the same amount with respect to the unit to which it is connected, and a further two-conductor transmission line connected between the opposite side of the transformer and said one of said arrangements, said transformer having a transformation ratio suitable for matching the surge impedance of said further line to the combination of the parallel-connected surge impedances of said plurality of lines.

11. In a transmission system for transferring power from a source arrangement to a load arrangement, one of said arrangements being a single impedance and the other of said arrangements consisting of a plurality of similar units, the combination of an aperiodic transformer, a plurality of similar two-conductor transmission lines of equivalent electrical length each connected between one side of the transformer and one of said similar units and each being mismatched by the same amount with respect to the unit to which it is connected, a further two-conductor transmission line connected between the opposite side of the transformer and said one of said arrangements, said transformer having a transformation ratio suitable for matching the surge impedance of said further line to the combination of the parallel connected surge impedances of said plurality of lines, and matching means interposed in said further line and adapted to match the surge impedance of that part of said further line remote from the transformer to the complete effective impedance of that portion of said further line toward the transformer together with all equipment connected to said portion.

12. In a transmission system for transferring power from a source to a load consisting of a plurality of similar units, the combination of an aperiodic transformer, a plurality of similar two-conductor transmission lines of equivalent electrical length each connected between one side of the transformer and one of said similar units and each being substantially mismatched by approximately the same amount with respect to the unit to which it is connected, and a further two-conductor transmission line connected between the opposite side of the transformer and said source, said transformer having a transformation ratio suitable for matching the surge impedance of said further line to the combination of the parallel-connected surge impedances of said plurality of lines whereby the standing waves resulting from reflections of waves at said mismatched units have the same standing wave ratio on both sides of the transformer.

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