May 11, 1926. **1,583,827**

E. I. GREEN

LOADING TRANSMISSION LINES

Filed Sept. 18, 1925 2 Sheets-Sheet 1

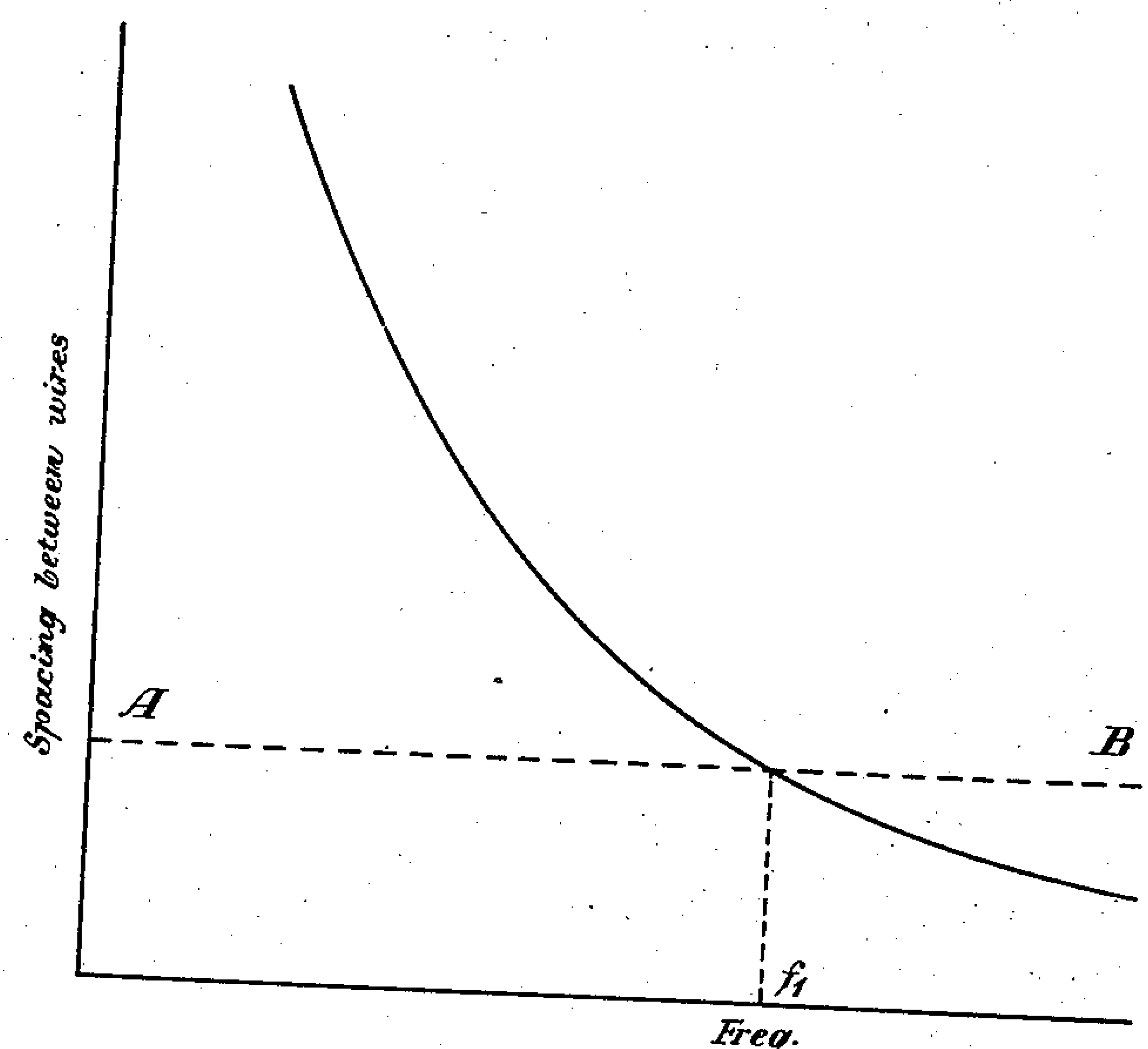

Fig. 1

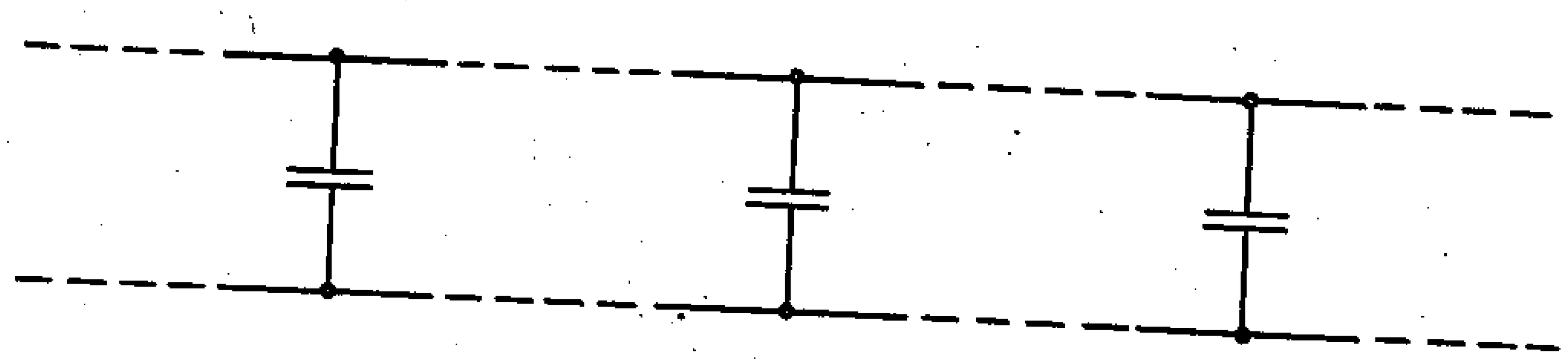

Fig. 2

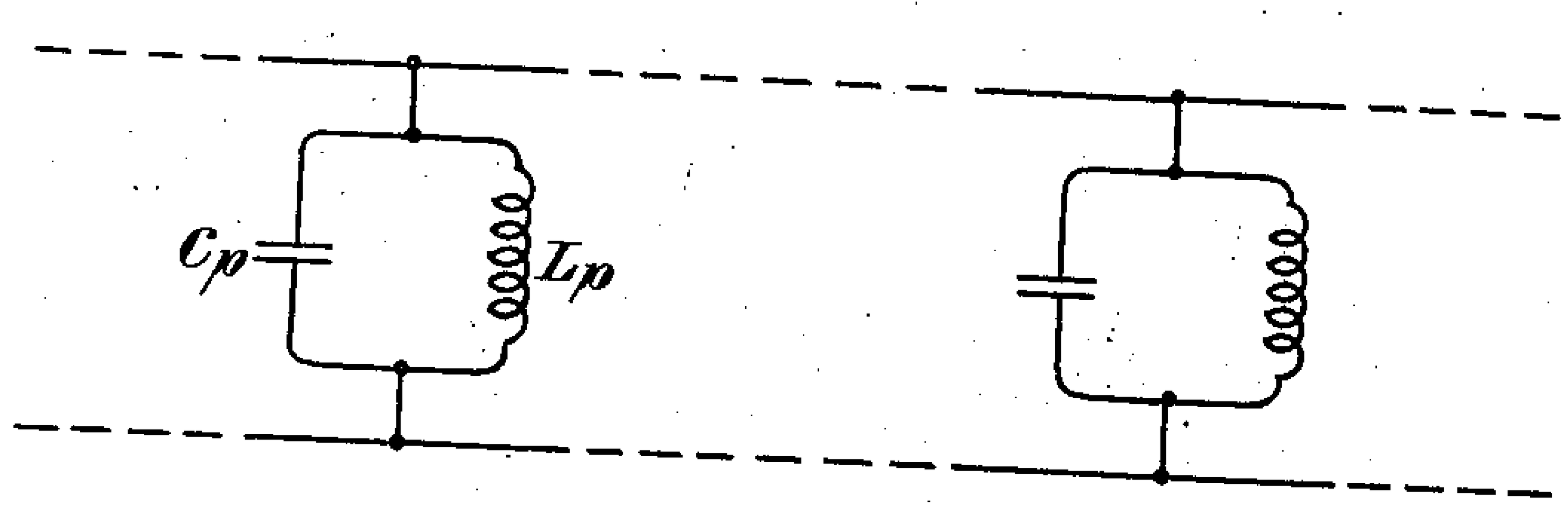

Fig. 3

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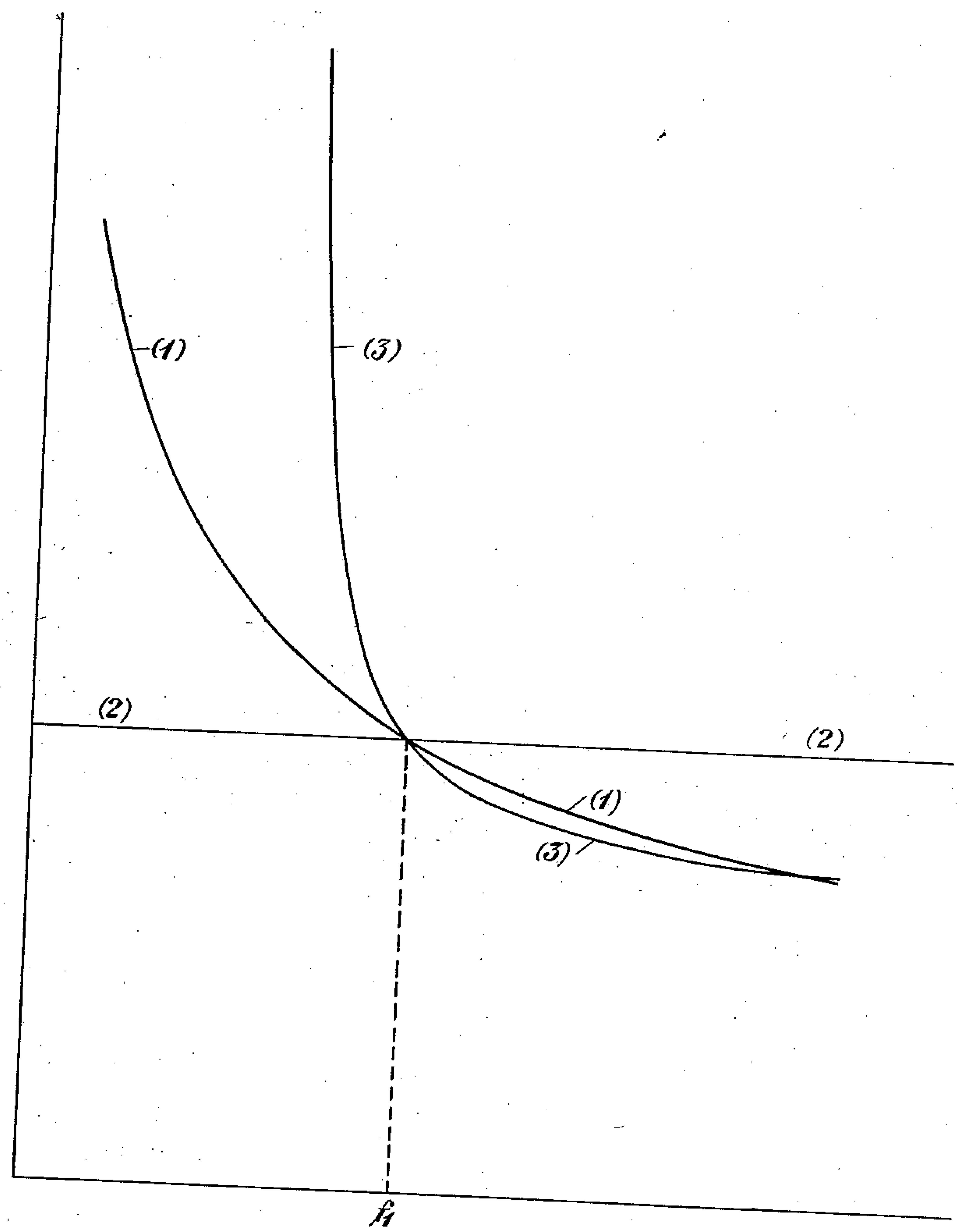

Fig. 4

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UNITED STATES PATENT OFFICE.

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LOADING TRANSMISSION LINES.

Application filed September 18, 1925. Serial No. 57,193.

This invention relates to the reduction of attenuation in transmission lines and cables, and more particularly to the reduction of attenuation by loading circuits with condensers or with networks including condensers and inductances.

It has long been known that, in the lower ranges of frequencies such, for example, as the ordinary telephone range, it is possible to reduce the attenuation of a transmission line by increasing the inductance, the increase in inductance being obtained either by inductance coils spaced at suitable intervals or by inductances uniformly added to the circuit along its length. It has also been proposed to reduce attenuation by increasing the leakage conductance, although the latter method has never been practical.

In these prior methods of attacking the problem of attenuation reduction, the capacity of the line has always been considered a detriment, and the fact was not recognized that in some other range of transmission the conditions might be such that an increase in inductance might be harmful, whereas an increase in the capacity of the line might be beneficial. The present invention involves the discovery that in the range above a certain frequency, which frequency depends upon the character of the particular line concerned, the attenuation may be reduced by increasing the capacity of the line. The invention further involves the discovery that for a given frequency the attenuation may be made a minimum by proper spacing between the line conductors.

The principles of the invention are carried out by the use of capacity loading, by means of which the line attenuation is made a minimum for a single frequency, while the attenuation for a range of frequencies above a certain critical frequency is reduced. In one form of the invention it is proposed to use a system of loading involving anti-resonant circuits so designed as to make the attenuation a minimum for a range of frequencies.

The invention may now be more fully understood from the following detailed description when read in connection with the accompanying drawing, Figure 1 of which is a curve showing the relation between the spacing of the wires and the attenuation, Fig. 2 is a simplified diagram showing how capacity loading may be applied, Fig. 3 is a similar diagram showing how the anti-resonant loading method may be employed, and Fig. 4 is a curve showing how the anti-resonant loading improves the transmission over a range of frequencies.

The usefulness of capacity loading will be apparent from a consideration of the approximate formula for the attenuation constant, which is quite accurate for the higher frequencies.

$$\alpha \doteq \frac{R}{2}\sqrt{\frac{C}{L}}+\frac{G}{2}\sqrt{\frac{L}{C}} \quad (1)$$

where

R=effective resistance in ohms per unit length.

L=effective inductance in henries per unit length.

C=effective capacity in forads per unit length.

G=effective leakage conductance in mhos per unit length and the sign ($\doteq$) denotes approximate equality. It is clear that in this equation we are not concerned with the absolute values of L and C but only with their ratio, which may be called K. The equation then becomes

$$\alpha=\frac{R}{2}\sqrt{\frac{1}{K}}+\frac{G}{2}\sqrt{K} \quad (2)$$

Differentiating this expression with respect to K will give us the value of K, which makes α a minimum. This value of K is equal to $\frac{R}{G}$, and the corresponding minimum value of α is

$$\alpha \text{ min}=\sqrt{RG} \quad (3)$$

It is evident that for any value of K other than $\frac{R}{G}$, the value of α will be greater than that given by equation (3).

The condition for minimum attenuation, then, may be expressed by the equation

$$K=\frac{L}{C}=\frac{R}{G} \quad (4)$$

Theoretically, in the case of an open wire line as ordinarily constructed, it would be beneficial to increase the value of K by increasing the inductance for transmission of all frequecies up to about 30,000 cycles, and in the case of an ordinary cable the limiting frequency would be even higher. Practically, however, in the range above 5,000 cycles, in the case of an ordinary open wire line, the improvement resulting by increasing the inductance is relatively small, and as the increase in inductance results in increasing the resistance, it has been found impractical to try to improve the range above 5,000 cycles by increasing the inductance. In the range referred to, that is, the range below about 30,000 cycles in the case of an ordinary open wire line, for example, the values of R and G are such that it is desirable to increase the value of K or, in other words, to increase the inductance of the line, as a means of approaching the condition of minimum attenuation. As the frequency is increased, however, the value of the ratio $\frac{R}{G}$ undergoes a very marked change due to the fact that G increases in more or less direct proportion to the frequency, whereas R increases at some fractional power of the frequency. Consequently, at these higher frequencies the optimum value of K may be obtained by increasing the capacity.

The physical significance of the foregoing, particularly as applied to open wire lines, may be better understood by reference to the curve of Fig. 1 of the drawing. Here, the spacing between wires that will give minimum attenuation is plotted as a function of frequency. For convenience a logarithmic scale has been used for the spacing. Since the resistance R of the line is fixed by the nature of the conductors employed and the leakage G is mostly due to the nature of the insulators employed, the values of the inductance and capacity of the circuit may be varied by varying the spacing of the conductors and in this manner, for a given circuit, a spacing between the wires may be found which will give the relation of formula (4) for any particular frequency. The curve of Fig. 1 is plotted by calculating the spacing that gives the desired relation

$$\frac{L}{C}=\frac{R}{G},$$

using the standard formulas for determining the inductance and capacity. For example, the inductance in henrys per loop mile may be determined from the following formula:

$$L=0.64374\left[2.3026 \log_{10}\frac{2D}{d}+\mu\delta\right] \quad (5)$$

where d is the diameter of each wire, D is the distance between wires, δ is the internal inductance factor, and μ is the permeability. Now, the permeability in the case of copper is 1 and δ varies from .25 for direct current to 0 where the frequency is infinite. Consequently, the term $\mu\ \delta$ in the above equation may be neglected. Similarly, the capacity in farads per loop mile may be expressed

$$C=\frac{0.019415}{\log_{10}\frac{2D}{d}}\times 10^{-6} \quad (6)$$

From equation (5) as simplified and equation (6), we obtain the following:

$$\frac{R}{G}=\frac{L}{C}=\frac{0.64374\times 2.3026\times\left(\log_{10}\frac{2D}{d}\right)^2}{0.019415\times 10^{-6}} \quad (7)$$

It is apparent from equation (7) that if we determine the ratio $\frac{R}{G}$ at a particular frequency the distance between the wires which will produce the same ratio of L to C may be at once obtained.

The curve of Fig. 1 may be plotted from values of D calculated in accordance with formula (7). In the case of an ordinary open wire line the spacing is fixed for all frequencies and hence in Fig. 1 the horizontal line A and B represents the spacing employed in an ordinary open wire line. It will be seen that this line crosses the curve representing the ideal spacing for all frequencies at the point corresponding to the frequency f_1. The significance of this is that the spacing ordinarily employed would correspond to the condition of minimum attenuation at the frequency f_1. It will be clear, then, from the curve, that at frequencies below f_1 an increase in spacing, giving larger inductance and smaller capacity, is desirable, while at frequencies above f_1 a decrease in spacing is desirable. While it is possible to reduce the attenuation to a minimum for any particular frequency by a proper spacing of the wires, in general it is impractical to use the wire spacing that electrical considerations make desirable, since the minimum is limited by the necessity for clearance between insulators and the possibility of crossing, while the maximum is limited by reasons of economy, crosstalk considerations, etc. Further, it is manifestly impossible to set a spacing that will be correct for all frequencies. By applying the methods of loading now about to be described, however, an electrical approximation of the correct spacing can be obtained at a particular frequency or over a range of frequencies.

As has already been pointed out, in any circuit it is desirable to increase the inductance in order to reduce the attenuation in the range below a certain frequency, while for the range above the said frequency the desired reduction in attenuation may be obtained by increasing the capacity. The frequency which separates these two ranges, hereinafter referred to as the critical frequency, is the frequency corresponding to the frequency f_1 of Fig. 1 or, in other words, is the frequency for which the spacing is ideal for the given circuit in accordance with equation (7).

The increase in capacity which is desirable at frequencies above the critical frequency may be very readily accomplished by connecting condensers across the wires at intervals, as illustrated in Fig. 2. Here, the added capacity is lumped at intervals along the line. Such an arrangement has the advantage over the method which involves inductance loading that the increase in the capacity does not result in any material increase in the resistance of the circuit, so that the full amount of the theoretically possible reduction in attenuation may be closely approximated in practice.

For example, suppose that it is desired to load a given open wire line for a frequency f, and that the optimum value for the ratio of inductance to capacity for this frequency is obtained by increasing the normal capacity C of the circuit to a value C_1 per unit length. The condition for minimum attenuation of this circuit may be expressed

$$\frac{L}{C_1}=\frac{R}{G} \quad (8)$$

Then the desired value for the capacity may be obtained from the equation

$$C_1=\frac{GL}{R} \quad (9)$$

As G, L and R are known, the ideal value for the capacity C_1 can readily be calculated. The capacity to be added per unit length is evidently equal to C_1-C. It remains to determine the distribution of the added capacity along the line. Let n equal the number of load points per unit length. Then the normal line capacity and line inductance per loading section are $\frac{C}{n}$ and $\frac{L}{n}$. If we load the circuit by lumped shunt capacity the line becomes analogous to a low pass filter and will have an upper cut-off point. Let f_0 be the cut-off frequency. This cut-off frequency may then be expressed approximately as follows:

$$f_0=\frac{1}{\pi\sqrt{\frac{L}{n}\cdot\frac{C_1}{n}}}=\frac{n}{\pi\sqrt{LC_1}} \quad (10)$$

Due to the fact that the cut-off of a filter is not absolutely sharp and that there is a general rounding off of the attenuation curve at the cut-off point, it is desirable to make the cut-off frequency f_0 somewhat higher than the working frequency f. The relation between these two frequencies may be, for example,

$$f_0=1.25f. \quad (11)$$

Substituting the value of equation (11) in equation (10) we may express the minimum number of loading points as follows:

$$n=1.25f\pi\sqrt{LC_1} \text{ load points per unit length} \quad (12)$$

The loading condensers to be used would generally be of approximately the same capacity, although it might be desirable to compensate for line irregularities or differences in the length of loading sections by making suitable allowances in the values of the condensers applied at the different points, as is the practice in the use of loading coils. By increasing the capacity at each pole, practically uniformly distributed loading can be secured. This might be accomplished by using a separate condenser at each pole or by increasing the capacity of the insulators. Such loading, being virtually continuous, would have an extremely high cut-off frequency.

The effect of loading with shunt condensers would be to lower the velocity of propagation for the circuit, just as is the case for series inductance loading. This type of loading would lower the characteristic impedance, however, whereas the series inductance loading raises the characteristic impedance.

For the 165-mil open wire lines commonly used, this method of capacity loading would be useful for frequencies above about 30,000 cycles, as already explained. The advantage to be obtained by adding capacity to the circuit obviously increases with the frequency. In loading a particular circuit for a particular frequency, while the attenuation is reduced to a minimum at that frequency, some reduction in attenuation is effected for all other frequencies between the critical frequency of the circuit and the cut-off frequency of the loaded circuit acting as a filter. In applying this method of loading to an open wire line on which high frequency channels are superposed on the ordinary voice channel, the improvement at high frequencies is, of course, obtained at the expense of a detriment to the lower frequency transmission channels falling below the critical frequency of the circuit. The method might therefore be most advantageously used in lines carrying high frequencies only, such as long radio antennas etc. It should be pointed out, however, that the increase in attenuation at the lower frequencies is in no case sufficient to make the total attenuation at these frequencies as large as the minimum which has been obtained at the higher frequency.

For power lines, which have smaller wire resistance and a large value of $\frac{L}{C}$ due to wide spacing, and for telephone lines specially constructed along power line principles, the method would be useful at much lower frequencies than in the case of an open wire circuit. For cables the usefulness of the method would be restricted to extremely high frequencies because of the small value of $\frac{L}{C}$. In the case of ordinary power line construction used for carrier frequencies, the limitation imposed by the increase in attenuation at frequencies below the critical frequency does not apply, as line attenuation does not figure appreciably in 60 cycle power transmission and the carrier frequency channels would all be above the critical frequency of the circuit. In fact, the capacity added to obtain the desired loading effect would be beneficial in compensating for poor power factor. This particular application of the invention has the disadvantage, however, that the cost of condensers capable of withstanding high voltages is very great. This disadvantage might be overcome, however, by so designing the power insulators as to increase the capacity the desired amount.

It has already been pointed out that the condenser method of loading gives the optimum value of $\frac{L}{C}$ for but a single frequency. This difficulty may be to some extent overcome by employing a loading system such as illustrated in Fig. 3, in which anti-resonant units comprising an inductance in parallel with a capacity are shunted across the line conductors.

It is a well known fact that at frequencies above the resonant point an anti-resonant circuit resembles a capacity which increases with increasing frequency, approaching a constant value; at the resonant point it presents an infinite reactance (or zero capacity), while below the resonant point it resembles an inductance which decreases with decreasing frequency likewise approaching a constant value. By using anti-resonant circuits shunted across the line conductors to load the transmission line, the effect is therefore to increase the effective capacity of the line at frequencies above the resonant point of the loading element and to decrease the effective capacity of the line for a range of frequencies below the resonant point of the loading element. The resonant point of the loading element may be so chosen as to coincide with the critical frequency of the circuit in its unloaded condition, that is, the frequency at which the actual spacing of the conductors corresponds with the optimum spacing (see curves of Fig. 1). If an anti-resonant circuit is used for shunt loading a close approach to the optimum value of $\frac{L}{C}$ can be obtained for a considerable range of frequencies. This is illustrated by the curves shown in Fig. 4, in which curve 1 is a plot of the ratio $\frac{R}{G}$ for the actual line. Curve 2 is a plot of the ratio $\frac{L}{C}$ for the line before it is loaded, and curve 3 is a plot of the equivalent ratio $\frac{L}{C}$ for the same line with the anti-resonant loading applied. It will be observed by comparing curves 1 and 2 that these curves coincide for a critical frequency f_1 and that at that particular frequency the line as it is normally constructed has a minimum attenuation, for at that particular frequency the relation

$$\frac{L}{C}=\frac{R}{G}$$

holds. After loading the line in the manner stated the ratio of the equivalent inductance of the circuit to the equivalent capacity thereof, which is represented by the curve 3, practically coincides with the ideal curve 1 for a considerable range above the critical frequency f_1. By properly choosing the values of the inductance and capacity of the anti-resonant circuits, this range may be made of considerable width. The anti-resonant circuit loading which produces curve 3 evidently may have advantages over loading with shunt condensers or series inductances, which would merely move curve 2 a certain distance down or up without changing its slope.

In the design of a loading system of this type, however, account should be taken of the fact that the line thus loaded is in the nature of a band filter having an upper and lower cut-off, and the loading should be so designed that the upper cut-off point falls well above the upper limit of the range of frequencies to be transmitted, while the lower cut-off point falls well below the lower limit of said range. It is clear that some decrease in attenuation over the non-loaded condition would be obtained by this method of loading at all frequencies above the critical frequency and below the upper cut-off frequency of the circuit acting as a filter. This is for the reason that capacity would be added at all frequencies in this range.

It will be obvious that the general principles herein disclosed may be embodied in many other organizations widely different from those illustrated without departing from the spirit of the invention as defined in the appended claims.

What is claimed is:

1. The method of loading a circuit for minimum attenuation at a given frequency which consists in increasing the capacity until the ratio of inductance to capacity of the circuit is substantially equal to the ratio of resistance to leakage conductance of the circuit at that frequency.

2. A loading system comprising line conductors and loading units shunted across said conductors, each loading unit including a capacity, the loading units being so proportioned as to bring the effective capacity of the circuit for a given desired frequency to a value such that the ratio of inductance to capacity will be substantially equal to the ratio of resistance to leakage conductance.

3. In a circuit whose ratio of inductance to capacity is substantially equal to its ratio of resistance to leakage conductance at a critical frequency, the method of reducing the attenuation of the circuit at frequencies above said critical frequency which consists in increasing the capacity of the circuit.

4. In a circuit having a ratio of inductance to capacity substantially equal to the ratio of resistance to leakage conductance at a critical frequency, the method of reducing the attenuation at frequencies above said critical frequency which consists in adding capacity to the circuit until the condition that the ratio of inductance to capacity equals the ratio of resistance to leakage conductance holds true at a higher frequency than the normal critical frequency.

5. A loading system comprising a pair of conductors and loading units bridged across said conductors at intervals, said loading units including inductance and capacity so related to each other as to be anti-resonant at the frequency at which the ratio of inductance to capacity of the conductors themselves is equal to the ratio of the resistance of the conductors to the leakage conductance thereof.

6. A loading system comprising line conductors having such electrical characteristics that the ratio of inductance to capacity is substantially equal to the ratio of resistance to leakage conductance at a critical frequency and loading units bridged across said conductors at intervals, each loading unit comprising inductance and capacity so related as to make the ratio of effective inductance to effective capacity equal to the ratio of resistance to leakage conductance over a range of frequencies.

7. A loading system comprising a pair of conductors having electrical characteristics such that for a critical frequency the ratio of inductance to capacity is equal to the ratio of resistance to leakage conductance and loading units bridged across said circuit at intervals, said loading units comprising inductance and capacity of such values as to be anti-resonant at the critical frequency of the line and so designed as to make the ratio of effective inductance to effective capacity equal to the ratio of resistance to leakage conductance over a range of frequencies.

8. The method of making the attenuation of a circuit a minimum for a range of frequencies by making the ratio of effective inductance to effective capacity equal to the ratio of resistance to leakage conductance for the said range of frequencies.

In testimony whereof, I have signed my name to this specification this 17th day of September, 1925.

ESTILL I. GREEN.