May 7, 1929. D. A. QUARLES 1,711,653

LOADING SYSTEM

Filed Aug. 14, 1924

Fig. 1

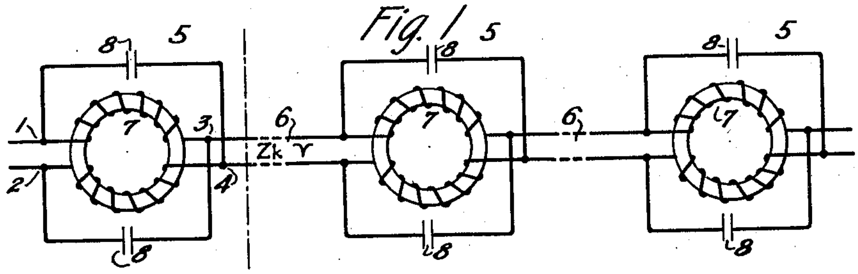


Fig. 2

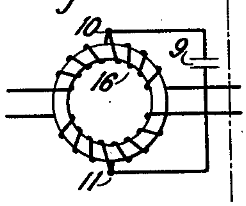


Fig. 3

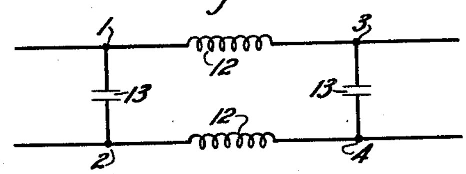


Fig. 4

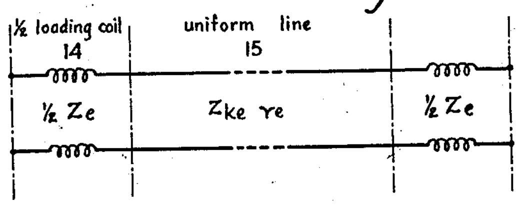


Fig. 7

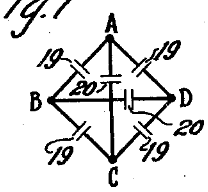


Fig. 5

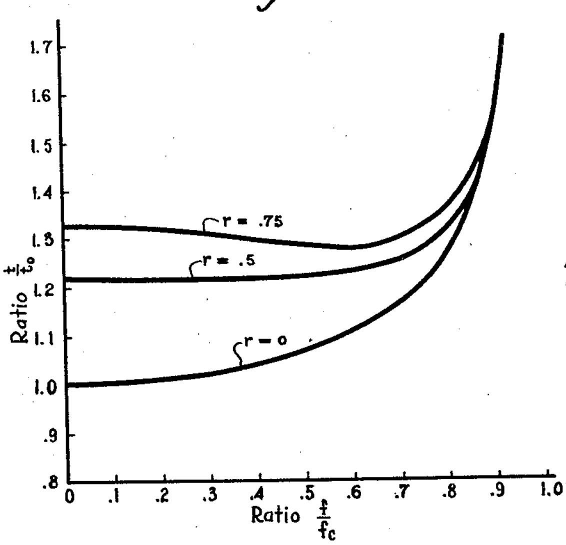
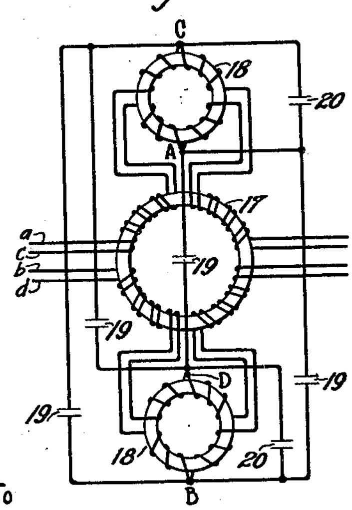


Fig. 6



Inventor:
Donald A. Quarles,
by E. W. Adams Atty

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UNITED STATES PATENT OFFICE.

DONALD A. QUARLES, OF ENGLEWOOD, NEW JERSEY, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

LOADING SYSTEM.

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This invention relates to loaded lines for the transmission of telephonic currents and the like. The object of the invention is to provide a system of loading applicable especially to long lines which will improve the quality of transmission.

The Pupin-Campbell system of loading, as originally conceived and hitherto practiced, has as a principal object the reduction of attenuation, thereby increasing the possible range of the telephonic transmission of speech. With the advent of the efficient telephone repeater, mere reduction of the attenuation by loading ceased to have its former fundamental importance, while at the same time the possible length of lines for telephonic communication was much increased. These considerations made it necessary to give more serious attention to the quality of transmission and the received speech because in long lines various factors combine to impair the quality. One of these factors which requires particular attention is the transient distortion, a phenomenon that is observable when all waves are not transmitted over the line with equal velocities.

The part played by the transient distortion may be illustrated by the consideration of a simple case in which a simple sinusoidal E. M. F. is suddenly impressed upon a loaded line. Although the impressed E. M. F. oscillates at but one frequency yet its sudden application corresponds to impressing upon the line a very large number of E. M. F's. of closely spaced frequencies extending throughout the frequency spectrum, the summation of which represents the rapid growth of the amplitude of the principal wave. If all of these waves arrive together at the distant end of the line, the current in the receiving apparatus will be built up with substantially the same rapidity as was the amplitude of the impressed wave, but if some of the components are delayed in transmission more than the others the building up of the received current will proceed in a quite different manner.

The rapidly varying amplitudes of speech waves produce effects of a similar character and unless the proper precautions are taken the currents received at the distant end of a line may never build up to any thing remotely resembling the form of the impressed wave in the short interval during which the latter exists. The effect produces or may produce serious impairment in the quality and intelligibility of the received speech even when the line is so designed that the steady-state attenuation of all currents within the speech range is substantially constant and the system, therefore, from the steady-state standpoint substantially distortionless.

The present invention proposes to overcome this difficulty by using instead of the inductance coils of the Pupin-Campbell system an improved loading unit, the effective inductance of which is a variable quantity depending upon the frequency of the transmitted waves and diminishing as the wave frequency increases. By virtue of its diminished inductance at the higher frequencies the propagation velocity of the line falls off less rapidly with increasing frequency than it does in an ordinary loaded line, and by properly proportioning the loading unit the velocity may be substantially equalized throughout a wide frequency range.

Fig. 1 of the accompanying drawings represents a section of a line equipped with loading units of the improved type;

Fig. 2 shows a modified type of loading unit which is equivalent to those of Fig. 1;

Fig. 3 shows in schematic form a network to which both types correspond;

Fig. 4 is a simplified schematic of a loading section of the improved type.

Fig. 5 illustrates graphically the velocity characteristics of lines loaded in accordance with the invention, and

Figs. 6 and 7 represent the application of the invention to the loading of phantom or duplex circuits.

The transmission line of Fig. 1 comprises loading units 5, between which extend equal sections, 6, of unloaded line having uniformly distributed constants. The loading units consist of inductance coils 7, the inductance of which is equally divided between the two sides of the line and two condensers 8 of equal capacity connected diagonally between the line terminals 1—4 and 2—3 respectively. The complete unit constitutes a bridge, or lattice, structure of the type, the general properties of which are described in an article on the Physical theory of the electric wave filter by G. A. Campbell published in the Bell System Technical Journal, volume 1, No. 2, November 1922.

The characteristics of wave propagation over a line of the type illustrated may be determined exactly by methods which are described in part in the above noted publication and in part in a paper on the subject of Cissoidal oscillations by G. A. Campbell printed in the Transactions of the American Institute of Electrical Engineers, volume XXX, page 857. The general method of the solution consists in resolving each complete loading section, comprising one loading unit and a section of the non-loaded line, into a T or a π network of simple impedances. These networks when joined in series constitute a network equivalent to the whole line the propagation through which may be determined by simple network formulæ. Methods and formulæ for effecting the transformation of the loading section into its equivalent forms of network are given in the above noted paper on cissoidal oscillations, these including formulæ for the transformation of a line with uniformly distributed constants to a network of three simple impendances. Formulæ for determining the wave propagation through the ladder structure equivalent to the actual line are given in the first of the references mentioned above. In the following analysis of the operation of the invention this method will be used, but, to simplify the solution, certain approximations will be made, these being of such a nature as will not materially affect the accuracy of the solution, particularly with respect to the velocity of propagation.

Transformation of the lattice structure of the loading unit 5 into its ii type equivalent network results in the network shown in Fig. 3, which comprises two shunt condensers 13 having fixed capacities and two series inductances 12, which have variable coefficients dependent upon the value of the frequency. The coefficients of the impedance elements of the equivalent network are expressed in terms of the constants of the loading unit impedances by the following equations:

$$R_e+jpL_e=\frac{R+jpL}{1+1/2p^2LC} \quad (1)$$

$$C_e=C \quad (2)$$

in which R_e, L_e and C_e represent the total resistance and inductance of the two coils 12 and the capacity of condensers 13 respectively and in which the corresponding quantities on the right hand side of the equations refer to the inductance coil 7 and the condensers 8 of the loading unit. The symbols j and p in accordance with common practice refer to the imaginary quantity $\sqrt{-1}$ and to the equivalent angular velocity 2ii× frequency, respectively. The terminals 1, 2, 3 and 4 of the equivalent circuit correspond to the similarly marked terminals of the loading unit.

That the two networks are equivalent may be readily checked by comparing their iterative impedances as measured at the terminals 1—2 and their propagation constants for the flow of current from terminals 1—2 to terminals 3—4. The first of these quantities is, in the case of a symmetrical network, equal to the geometric mean of the short circuit and the open circuit impedances of the network, the terms short circuit and open circuit referring to the condition of the terminals remote from those at which the impedance is measured. The propagation constant is, in a like case, equal to the square root of the ratio of the open circuit impedance to the short circuit impedance.

If in Fig. 1 the network of Fig. 3 be substituted for the actual loading unit it will be seen that the condensers 13 are directly in shunt to the ends of the non-loaded section of the line. To simplify the further solution of the propagation characteristics it will be assumed that these capacities may be regarded as effective merely to increase the distributed capacity of the line, that is, as though they also were uniformly distributed over the non-loaded section. The justification of this assumption lies in the fact that the series impedance of a single section of the line in practice seldom exceeds in value 10% of shunt impedance of the line capacity. The loaded line may thus be regarded as a uniform line of increased distributed capacity loaded by means of spaced inductance coils, the inductance of which decreases as the frequency increases in accordance with the variation expressed by Equation (1) above. A single section of the equivalent line is shown in Fig. 4, the section being terminated at each end in the middle of a loading unit. The half coil 14 has an impedance

$$\frac{1}{2}Z_e=\frac{1}{2}(R_e+jpL_e) \quad (3)$$

both R_e and L_e being variable as expressed by Equation (1). The uniform line section 15 is characterized by an iterative impedance Z_{ke} and a propagation constant γ_e for its full length, these quantities corresponding to the iterative impedance Z_k and the propagation constant γ of the actual line section 6 of Fig. 1, but modified by the effect of the added capacity.

To the equivalent line may be applied the equation for the propagation constant of a coil loaded line first given by G. A. Campbell in the Philosophical Magazine, volume 5, 1903, page 313 et seq., namely

$$\text{Cosh } P = \cosh\gamma_e+\frac{Z_e}{2Z_{ke}}\sinh\gamma_e \quad (4)$$

The propagation constant P is in general a complex quantity, having a real component A which represents the attenuation and an imaginary component B which represents the phase change and is related to the time of propagation. Equation (4) gives the total propagation constant for a single loading section, since the quantities γ_e and Z_e are based on the loading section as the unit length of the transmission line.

While Equation (4) is sufficient for the computation of the propagation constant it is more convenient to derive therefrom separate expressions for the attenuation and phase constants. In addition, since the ideal method of loading would consist in adding to each section of the line a uniformly distributed inductance having a total value equal to that of the loading coil, and having no added capacity, it is of interest to express the propagation constants of the actual line in terms of the corresponding constants of the ideally loaded line.

Let the total resistance of a non-loaded section of the actual line be denoted by R_o and its total capacity by C_o, the distributed inductance and leakance being assumed to be zero. The total capacity added to each section of line by the loading units is 2C, the capacity of one of the condensers 8, being added at each end. Let the ratio of this capacity to the line capacity be denoted by r. The constants Z_{ke} and γ_e of the non-loaded section of the equivalent line are expressed in terms of R and C by the following equations

$$Z_{ko}=\sqrt{\frac{R_o}{jpC_o(1+r)}} \quad (5)$$

$$\gamma_e=\sqrt{jpC_o(1+r)R_o} \quad (6)$$

The expansions of cosh γ_e and sinh γ_e in a power series and the substitution therein of the values for Z_{ke} and γ_e given by the foregoing equations gives the following equation for cosh P, only those terms involving the frequency in the second degree and lower being retained

$$\text{Cosh } P+1-\frac{p^2L_cC_o(1+r)}{2}+j\frac{pC_o(1+r)(R_o+R_e)}{2} \quad (7)$$

To relate the propagation constant to the attenuation and phase constants of the ideally loaded line having the same total inductance these quantities must first be expressed in terms of the line constants. For a length of the uniformly loaded line equal to that of one section of the coal loaded line the attenuation and phase constants have the following values respectively

$$\alpha=\frac{R_o}{2}\sqrt{\frac{C_o}{L}} \quad (8)$$

$$\beta=p\sqrt{LC_o} \quad (9)$$

It is assumed that in the ideal system no resistance is added by the addition of the inductance. By means of Equations (8) and (9) Equation (7) may be transformed into the following:

$$\cosh P=1-\frac{\beta^2}{2}\frac{1+r}{k}+j\alpha\beta(1+r)(1+\rho) \quad (10)$$

in which k is the factor $(1+1/2p^2LC)$ of Equation (1) which relates the effective line impedance of the lattice loading unit to the impedance of the inductance coil, and ρ is the ratio of the effective resistance R_e of the loading unit to resistance R_o of the line. This equation when the components of P are written down has the form

$$A+jB=\cosh^{-1}(X+jY) \quad (11)$$

the right hand side of which may by standard mathematical processes be expanded into two terms, one real and one imaginary thereby giving expressions for A and B separately. The separation of $\cosh^{-1}(X+jY)$ into its real and imaginary components is given in the aforementioned paper in the Philosophical Magazine. For small values of Y, which by comparison with Equation (10) correspond to small values of the propagation constant, the values of A and B are respectively

$$A=\frac{Y}{\sqrt{1-x^2}}$$

$$\frac{\alpha(1+\rho)\sqrt{k(1+r)}}{\sqrt{1-\frac{\beta^2}{4}\cdot\frac{1+r}{k}}} \quad (12)$$

and

$$B=2\sin^{-1}\sqrt{\frac{1-x}{2}}=$$

$$\beta\times\frac{\sin^{-1}\frac{\beta}{2}\sqrt{\frac{1+r}{k}}}{\frac{\beta}{2}} \quad (13)$$

The critical frequency of a coil loaded line is defined as the cut-off frequency of the structure having equal inductances and capacities but having no resistance in any of its branches. For a loaded line with the lattice type of loading units the critical frequency is equal to

$$f_c=\frac{1}{\pi\sqrt{LC_o}} \quad (14)$$

which is the same as that for a line loaded in the ordinary manner with coils of the same inductance.

The time required for a wave to traverse the loading section is given by the equation

$$t=\frac{B}{p} \quad (15)$$

When the quantities B and k are expressed in terms of the critical frequency by means of Equation (14), this equation for the propagation time becomes

$$t=\frac{\sqrt{LC_o(1+r)}\cdot \sin_{-1}\frac{f}{f_c}\sqrt{\frac{1+r}{1+r\left(\frac{f}{f_c}\right)^2}}}{\frac{f}{f_c}\sqrt{1+r}} \quad (16)$$

The time of propagation over a uniformly loaded line of length equal to one loading section and having a total inductance L and capacity C_o+2C is equal to

$$t_o=\sqrt{LC_o(1+r)} \quad (17)$$

which in accordance with Equation (16) is also the time of propagation of a very low frequency wave over the lattice loading section. The factor multiplying

$$\sqrt{LC_o(1+r)}$$

in the right hand side of Equation (16), therefore expresses the ratio of the propagation time for a wave of any frequency lower than the critical frequency of the line to the limiting time t_o in lines having various proportions of added capacity.

The three curves plotted in Fig. 5 show the values of this factor for the particular cases in which the ratio r is 0, .5, and .75, respectively; it is evident that values of r between .5 and .75 result in a greatly increased uniformity of the propagation time over a substantial fraction of the range below the critical frequency of the line.

The attenuation of a line loaded in accordance with the invention is increased by the addition of the loading unit capacities, the increase as indicated by Equation (12) being substantially proportional to the square root of the increased value of the total effective capacity. In most cases this may be offset by increasing the amount of gain in the repeaters inserted in the line, and in some cases the fact that a greater portion of the transmission range of frequencies is available for high grade transmission permits a greater amount of inductance to be used thereby reducing the critical frequency to a lower value, but at the same time reducing the attenuation.

Instead of employing two equal capacities connected diagonally between the line terminals of the loading coil, the same results may be obtained by employing a single condenser of twice the capacity connected between the middle points of each line winding of the loading coil. A loading unit of this type is shown in Fig. 2. The single condenser 9, which is connected to the mid-points 10 and 11 of the line windings of the coil 16, has a capacity 2C or twice that of the condensers 8 and the coil has an inductance equal to that of the coil 7.

By the application of the methods of circuit transformation referred to in the foregoing text it may be demonstrated that the loading unit of Fig. 2 is completely equivalent to those of Fig. 1 when the two halves into which each line winding is divided by the condenser connection are perfectly coupled. With a degree of coupling of about 90% which is generally exceeded in practice the equivalence of the two circuits is substantially complete the effect of the imperfect coupling being negligible within the transmission range of the line. When the coupling is as low as 70% the effect of the leakage inductance may be substantially compensated by an increase in the capacity of the condensers that amounts only to 10%. The fact that one condenser only is required in the modified form of loading unit results in a somewhat cheaper system of loading as compared with the system of Fig. 1. The balance necessary for duplex operation is also more easily secured with the use of a single condenser. For these reasons the loading unit of Fig. 2 is the preferred type for most purposes. The lattice type of Fig. 1, however, has an advantage in that it may be applied to lines already loaded in the standard Pupin-Campbell manner without it being necessary to make any modification of the existing loading coils.

Fig. 6 shows a complete loading unit for a duplex circuit, the velocity compensating condensers being added in accordance with the system of Fig. 2. Two pairs of wires *a—c* and *b—d* each constitute the conductors of a side circuit, the phantom circuit being superimposed thereon, so that the phantom currents flow out over wires *a* and *c* in parallel and return on wires *b* and *d*. The phantom circuit loading coil 17 is wound with paired wires connected respectively to the line pairs *a—c* and *b—d* so that inductance is added only to the phantom circuit. Each phantom winding is divided at its mid-point and led to the side circuit loading coils 18, the line windings of which include tap connections at their mid-points A—C and B—D. The side circuit coils are wound to add inductance to the side circuits and since the phantom currents traverse both line windings in the same direction, the coils are non-inductive with respect to these currents. The tap connections A—C and B—D correspond to the mid winding points not only of the side circuit coils but also of the phantom circuit coil. Four condensers, 19 are necessary for the loading of the phantom circuit, these being so arranged that two condensers are connected between each wire and the two wires of the other pair, and being so proportioned that each contains one fourth of the total capacity to be added. These condensers serve also in part for the loading of the side circuits, being connected in a series-parallel system between the two line wires of each pair. The capacity that they add to the side circuit, however, will not in general be sufficient to secure the desired uniformity of velocity and condensers 20 are therefore added directly between the side circuit line windings to bring the total capacity up to the desired amount. The points A and C and also the points B and D being at equal potential with respect to the phantom currents it is evident that the additional condensers 20 are without effect upon the phantom circuit. The condenser network is shown in simplified form in Fig. 7, in which the elements correspond to the similarly designated elements of Fig. 6.

In the practical application of the invention it is not necessary that all loading units in a line be of the improved type. A substantially equivalent gain with respect to uniformity of velocity may be had if only the alternate units are of the improved type, the others being simple loading coils of the Pupin-Campbell type. In this case the capacity added in the modified units should be increased in the ratio 1.46 and the inductances should be increased in the ratio 1.37 as compared with the values for a system in which all loading units are of the modified type. Other distributions of the improved units throughout a system may also be used to secure different degrees of velocity compensation.

What is claimed is:

1. In an inductively loaded transmission line, a plurality of uniformly spaced uniform loading units each comprising an inductance coil in series with the line and a capacity in shunt to the line, said capacity being connected to the midpoint of said inductance.

2. In an inductively loaded transmission line having two line wires, a plurality of uniformly spaced uniform loading units each comprising an inductance coil having equal windings connected in series with said line wires, and a capacity connected in shunt to said line wires between the midpoints of said windings.

3. A two-wire transmission line comprising a plurality of equal sections divided by inductive loading units, said units comprising an inductance having equal windings in series with the wires of said transmission line, and a capacity effectively connected between the midpoints of said windings, said capacity having a value between .4 and .8 of the total capacity between the wires of one of said sections.

4. A wave transmission system comprising a transmission line and uniform loading units included therein at substantially uniform intervals, said units comprising combinations of series inductance elements and shunt capacity elements proportioned and arranged substantially as described to make the wave propagation velocity in the system substantially uniform for a wide range of frequencies.

5. A signaling line comprising inductive coils for periodically loading said line according to the Pupin system, and means included in said line at each loading point for compensating the variation of wave velocity with frequency due to the periodic loading.

6. A signaling line comprising inductive coils for periodically loading said line according to the Pupin system, and supplementary impedance elements included in said line at each loading point for compensating the variation of wave velocity due to the periodic loading.

7. A signaling line comprising inductive coils for periodically loading said line according to the Pupin system, and condensers included in shunt to said line at each loading point for compensating the variation of wave velocity due to the periodic loading.

8. A combination in accordance with claim 7 in which the condensers are connected to the line at the mid points of the loading coil windings.

In witness whereof, I hereunto subscribe my name this 13th day of August A. D., 1924.

DONALD A. QUARLES.