The Limitation of the Gain of Two-Way Telephone Repeaters by Impedance Irregularities

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Introduction

BECAUSE of the fact that it is a difficult and expensive matter to build and maintain the high grade circuits that are required for modern long distance telephone transmission with repeaters, many workers in this field have attempted to devise some form of two-way repeater which would be able to give as large a gain as desired without singing or poor quality due to irregularities existing in the lines. They have thought that if such a repeater could be constructed it would permit the use of lines less carefully built and, therefore, cheaper than are at present required, and that fewer repeaters would be required because larger gains could be obtained at each repeater.

As a matter of fact the irregularities in the lines have a very important effect and control, to a great extent, the repeater gains which can be used whenever a telephone circuit is arranged so as to be capable of transmitting in both directions over a single pair of wires with constant efficiency.

It is the object of this paper to explain, in a very simple way, why this is true. To do this the phenomenon of electrical reflection is first made clear. Then a two-way repeater system is introduced and the effects of reflection upon this system are explained. After mentioning several of the types of repeaters which have been used successfully, the paper concludes with an explanation of the fallacies underlying a number of schemes which have been proposed from time to time by various inventors.

Reflection in Telephone Lines

Whenever discontinuities or irregularities exist in telephone circuits, reflection of a certain part of the speech wave takes place at each irregularity. In order to appreciate why it is that irregularities in two-wire telephone circuits affect very greatly the amount of repeater gain which can be secured whenever two-way operation is desired, it is first necessary to obtain a clear picture of why it is that reflections take place at irregularities.

Fig. 1 represents an infinite ideal telephone line without repeaters. If such a line is non-loaded or continuously loaded each part of it is exactly like every other part having the same length. If the line is loaded with coils then each loading section is exactly like every other loading section.

When a telephone transmitter or other signaling device *A* acts upon such a line it causes a wave to travel over the line away from

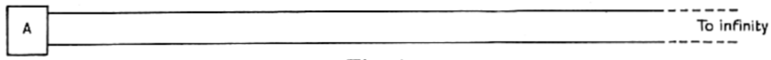

Fig. 1

the source. If the line includes resistance or other losses this wave gradually becomes smaller until it is too weak to be detected but no portion of the wave returns to the source after once leaving it.

If some portion of the line differs in its electrical makeup from other portions of the line it constitutes an irregularity and interferes with the passage of the wave.

Fig. 2 shows a line exactly like that of Fig. 1 except that an irregularity *B* has been introduced. This irregularity has been shown

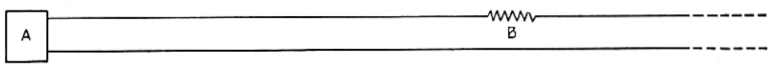

Fig. 2

as a series resistance though any other departure from the regular electrical structure of the line would produce similar effects.

When a wave encounters such an irregularity, it splits into two parts one of which continues in the original direction of propagation along the line while the other is propagated in the opposite direction toward the source.

In order to understand this phenomenon, which is called reflection, imagine that a wave is traversing the line from left to right. As it passes the point *B* a current flows through the series impedance which constitutes the irregularity and this causes a drop of potential through the impedance. Obviously, this changes the state of affairs as there is now a sudden alteration in the voltage across the line as the wave passes the irregularity whereas there is no such alteration without the irregularity.

Suppose that for the impedance element we substitute the output terminals of a generator which has a negligible impedance and arrange the generator so that it is excited by the wave traveling over the line but that the excitation is not affected by the voltage set up by the generator itself. Such an arrangement is shown in Fig. 3. The arrangement for exciting the generator is supposed not to require an appreciable amount of power or to constitute an irregularity. This generator then resembles the series impedance of Fig. 2 in that it produces no disturbance in the line when no waves are passing but as soon as a wave arrives the generator becomes active and produces a

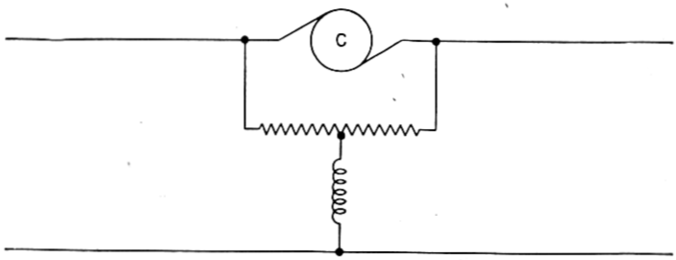

Fig. 3

voltage in series with the line. By proper adjustment of the exciting mechanism of the generator the voltage across its output terminals can be made just equal to the disturbance produced by the impedance element at *B* in Fig. 2 and so exactly reproduce the effects of the irregularity. In order to do this the generator might have to absorb energy from the wave passing over the line instead of giving it out, but it would establish the desired voltage relations.

Now as the generator has no appreciable impedance the wave passes through it without interference but the e.m.f. which it sets up obviously sends out waves in each direction from the generator.

On the right of the irregularity will be found one wave made up of the original undisturbed wave combined with that from the generator and traveling onward in the original direction. The combined wave will usually be smaller than the original wave though it might under some circumstances be larger and its shape might or might not be altered depending upon the nature of the irregularity and the character of the line.

On the left of the irregularity will be found the original wave traveling from left to right and the reflected wave traveling from right to left.

By a similar process of reasoning the reflection caused by bridging an impedance across the line at the point *B* can be illustrated. In this case the output terminals of the generator should be bridged across the line and made of very high impedance.

Any departure from the regular structure of the line such as occurs at the junction of two lines of different types or where loading coils have the wrong inductance or are wrongly spaced causes reflections in the manner described above.

Ideal Repeater on an Ideal Line

Fig. 4 shows an ideal telephone circuit consisting of two sections of line L_1 and L_2 which are free from irregularities and are joined by a repeater R. The remote ends of the line sections are connected to terminal apparatus A_1 and A_2 which have impedances which

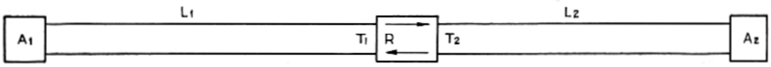

Fig. 4

smoothly terminate the lines, that is, if either line had originally extended to an infinite distance from the repeater and had been cut to connect it to the terminal apparatus, this apparatus would have the same impedance as the part of the infinite line which was cut off. The construction of the repeater R is limited only by the requirement that if an electric wave arrives at the repeater terminals T_1 or T_2 over either line a similar but larger wave is transmitted from the repeater over the other line. The gain of the repeater determines the relative sizes of the waves arriving at and departing from the repeater.

If now a wave is started at one end of the circuit, for example A_1, it traverses the line L_1 and is absorbed or dissipated in the portion of the repeater connected to the terminal T_1. This wave acts upon the internal mechanism of the repeater in such a way as to send out a larger wave which traverses the line L_2 and is completely dissipated in the terminal apparatus A_2.

Ideal Repeater on a Line Containing Irregularities

Fig. 5 illustrates a line exactly like that of Fig. 4, except that an irregularity B_1 (or B_2) has been introduced into each section. If a

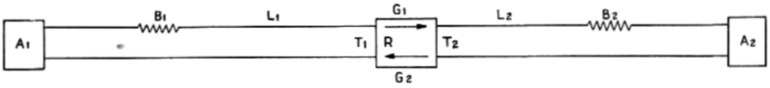

Fig. 5

wave leaves one terminal such as A_1, it traverses the line L_1 eventually arriving at the terminal T_1 of the repeater R with a certain strength. This wave is amplified and transmitted into the line L_2 which it follows until it encounters the irregularity B_2. At B_2 it is partially reflected, one portion returning to the repeater and the other traveling to the terminal A_2 where it is absorbed. The reflected wave passes through the repeater, is amplified and transverses the line L_1 until it encounters the irregularity B_1 where it is again reflected, one part being propagated to the terminal A_1 where it is dissipated, while the other part returns to the repeater and repeats the cycle of amplification and reflection. This action continues indefinitely the wave being reflected alternately from the irregularities B_1 and B_2.

If the total gain in the round trip path is greater than the total loss the wave will be stronger on each arrival at any point in the circuit than on the preceding trip and will continually increase in power until the power limits of the repeater or some other cause prevents a further increase and a steady sing is established. If the gain is less than the loss, the wave will become weaker with each trip from B_1 and B_2 and back until it falls below the strength which can be detected.

Evidently, if the repeater gain is made so great that a steady sing is established, satisfactory telephoning over the circuit will be impossible. Serious quality impairment may occur, however, when the gain is not so great as this. Consequently, when irregularities are present in a line containing repeaters, the repeater gains are necessarily limited.

In the above illustration, it was assumed that two irregularities were present. Serious effects, however, due to the production of echo effects which may be heard by the talker, may be produced by reflection from a single irregularity. Consequently, a single irregularity in the circuit will set a limitation on the repeater gain even though it could not cause singing if a 22-type repeater were used.

From the foregoing explanation, it is evident that the effect of the reflections at the irregularities, which limits the repeater gains, is not dependent upon any special properties of the telephone repeaters. These limitations will necessarily exist with any types of repeater whatsoever which have the property of producing amplification in both directions at the same time.

Effect of Using the Wrong Line Impedance

The discussion will now be extended to show that not only must the lines with which a repeater is to work be smooth, if limitation of the gains is to be avoided, but also the repeaters must be designed to fit lines of one particular type. It has just been shown that reflection takes place if a series or a bridged impedance is inserted in a line. This reflection will take place whether the impedance is inserted at some intermediate point in a line or adjacent to a repeater. Inserting such an impedance adjacent to a repeater would, on account of this reflection, seriously limit the gain which could be produced by the repeater. Now inserting an irregularity adjacent to a repeater amounts to the same thing as substituting a line having a different impedance for the line with which the repeater is designed to function. Since any change in the impedance of a line connected to a repeater away from the impedance with which the repeater is designed to work is equivalent to inserting an irregularity adjacent to the repeater, it is evident that *it is impossible to construct a repeater system whose amplification will be constant in both directions and whose gain will not be limited by irregularities in the lines and by any departure of the line impedance from that for which the repeater is designed.*

Successful Types of Repeaters

Two forms of repeater circuit, the well known 21 and 22 type circuits, have been developed to the point where they have become highly important and successful parts of the telephone plant. These have been so completely described in a paper entitled, "Telephone Repeaters" by Messrs. Gherardi and Jewett,[1] that no further description will be attempted here. It is sufficient to point out that in the case of the 22 type repeater the necessary impedance requirements are met by providing networks which imitate closely the characteristic impedances of the two associated lines. Any departure of the line impedance from the value for which the network was designed or any irregularities in the line or terminal equipment impose limits on the obtainable gain in the manner described above. In the case of the 21 type circuit the impedance requirements are met by putting the repeater between two similar lines whose impedances balance each other.

Another type of repeater circuit, called the booster circuit, was mentioned in the paper just referred to. This circuit does not depend upon impedance balance in the same way as the 21 and 22 type circuits and it is capable of giving two-way amplification but its performance is even more seriously affected by impedance deviations in the lines than the latter circuits. The booster form of repeater circuit has not yet proved useful in a commercial way.

[1] Proceedings of the American Institute of Electrical Engineers, 1919, page 1255.

Devices Employing Voice Controlled Relays

Many different devices aiming to secure the practical equivalent of two-way repeater operation by means of relays (mechanical or thermionic) controlled by the voice currents themselves have been suggested. In these devices the action of the relays is such that when transmission is passing in one direction through a repeater, the transmission in the opposite direction is either wholly or partially blocked. Evidently the gain of such a repeater as this is not limited by impedance irregularities in the lines, since it is really a one-way device during the passage of speech currents.

Repeaters controlled by voice operated devices will not be discussed here further in view of the fact that the principal object of this paper is to treat repeater systems which are truly two-way in their operation.

Other Types of Repeater That Have Been Proposed

Several of the arrangements that have been proposed by inventors who sought unsuccessfully to produce two-way repeaters not subject to limitation by line irregularities will now be described.

1. *Repeaters Involving Balance.* A great many circuits have been devised which involve the principle of balance. These always involve the same fundamental principle as the hybrid coil used in the repeaters now in commercial service though often the arrangement appears quite different. This principle is that the output energy of the amplifier working in one direction, for example, the east bound amplifier, is divided into two parts, one of which is sent into the line east and the other into the corresponding network. The input terminals of the west bound amplifier are so connected that the effect on them of the current entering the line east is opposed by the effect of the current entering the network and consequently the impedances of the line and network must accurately balance each other to keep the output energy of one amplifier out of the input circuit of the other. Sometimes the balance is effected by connecting the line and network into a common electrical circuit and connecting the input terminals of the amplifier to two points of equal potential in this circuit. In other arrangements two fluxes which depend upon the currents entering the line and network are balanced against each other in the core of a special transformer so that a winding connected to the input of the amplifier is not affected.

Usually the impedance of the network equals that of the line, but arrangements are possible and even have certain advantages in which the energy is not equally divided between the line and network and the impedance of the network is either greater than or less than that of the line in a certain ratio.

Through unfamiliarity with the principles involved the inventors sometimes assume that an approximate balance such as might be obtained by using a simple resistance is sufficient to meet all requirements. None of these arrangements, however, can avoid the effects of departures of the line impedance from the values for which the networks are designed nor can they better the performance of the present repeaters in respect to the effects of impedance departures. Usually such circuits are inferior in some important respect to the arrangements now in use.

2. *Circuits using Rectifiers.* In one type of circuit the inventors propose to use rectifiers to prevent the output energy of one amplifier

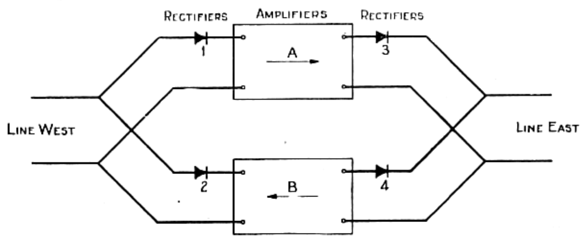

Fig. 6

acting upon the input circuit of the other. A simple diagram illustrating the operation of this scheme is given in Fig. 6. Rectifiers are placed in series with the input and output circuits of both amplifiers and poled in the directions indicated by the arrow heads which point in the direction the rectifier is supposed to permit current to pass. It is argued that the rectifier in the output circuit of each amplifier permits only currents of one polarity to enter the line and that the rectifier in the input circuit of the opposite amplifier is so poled that these output currents cannot pass it into the input circuit and, therefore, singing cannot occur.

If a wave arrives, for example over the line west, the positive half waves pass through the rectifiers 1 and 2 into the input of the east bound and the output of the west bound amplifier respectively. The negative half waves are suppressed by the rectifiers. This is illustrated by Fig. 7 which shows the wave arriving over the line and Fig. 8 which shows the part of the wave which enters the amplifiers.

That portion which reaches the output of the west bound amplifier is lost while the portion which reaches the input of the east bound amplifier, is amplified, and passed on through the rectifier 3 to the line east. If the amplifier were completely distortionless and, therefore, capable of amplifying direct currents and the rectifiers perfect, that is, offering zero resistance to currents in one direction and infinite resist-

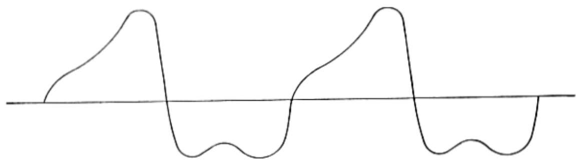

Fig. 7

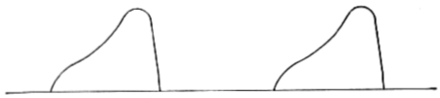

Fig. 8

ance to currents in the opposite direction, the currents transmitted to the line east would have the wave shapes shown in Fig. 8.

As it would be impracticable to make the amplifier amplify the direct-current component of the wave shown in Fig. 8 the amplifier would tend to send out a wave somewhat like that shown in Fig. 9,

Fig. 9

which is the wave of Fig. 8 with the direct component removed. The rectifier 3 then suppresses the negative half waves, finally permitting the wave shown in Fig. 10 to pass to the line east. On account

Fig. 10

of the great distortion involved the quality of speech would be greatly impaired if, indeed, the speech would not be rendered unintelligible.

Assuming, however, that intelligible speech is possible in spite of this distortion, the rectifiers would not prevent singing. Suppose the repeater shown in Fig. 6 to be cut into the line shown in Fig. 5 at R and that waves are arriving from the line west. There are certain line conditions which are practically certain to exist and which would send back reflected waves that would reverse the potential across the line east at the terminals of the repeater, causing impulses to reach the input of the west bound amplifier. These impulses will be amplified and returned to the line west where, if similar conditions exist, they will once more enter the east bound amplifier. If the gains are great enough to offset the losses caused by the rectifiers, the system will sing.

It is, therefore, evident that rectifiers offer no chance for improving on the action of the present types of repeaters because they cause

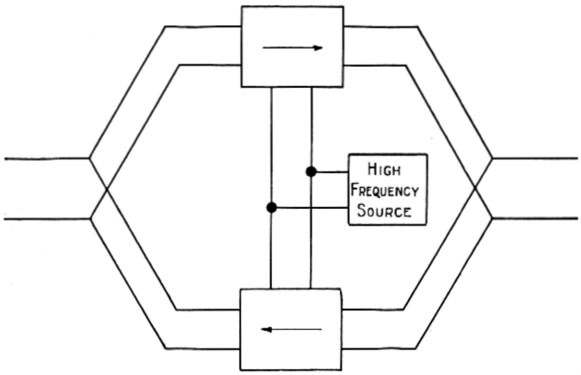

Fig. 11

serious distortion and do not prevent singing except under certain special conditions not likely to be found under practical conditions.

3. *Circuits using High-Frequency Switching.* Another device which is frequently proposed in one form or another is illustrated in Fig. 11. In this case an amplifier is provided for each direction of transmission. These amplifiers are so designed that their amplifying power can be destroyed and restored periodically at high frequency by currents from a suitable source, the amplifier in one direction being active when the other is inactive. The frequency of the controlling currents is above the audible range. In a variation of this scheme a single amplifier is used which is pointed first in one direction and then in the other at a frequency above the audible range. It is argued that since there is amplification in only one direction at any given instant the system cannot sing.

Imagine such a repeater to be inserted in the line at R in Fig. 5, and that voice waves are arriving over the line from A_1. Owing to the nature of the repeater these waves will be cut up into a series of pulses having a frequency equal to that of the controlling current and varying in magnitude according to the shape of the voice wave being transmitted. These pulses will be partially reflected at the irregularity B_2 and part of their energy will return to the repeater. Due to the fact that a finite time is required for the pulses to pass from R to B_2 and back, they are likely to arrive at the right moment to find the amplifier set for amplification in the opposite direction, in which case they will pass through towards A. For a single irregularity, it would be possible to select a frequency such that the pulse would return when the repeater is set against it, but this would require a different frequency for each irregularity which is obviously impossible.

In case the line cannot transmit the high frequency pulses, their energy would be stored in the inductance or capacity of the first elements of the line L_2 and returned to the amplifier when it is in condition to transmit from L_2 to L_1. To avoid the latter objection it has been proposed to employ low pass filters on the output side of each one-way amplifier to convert the high frequency pulses back into ordinary voice waves before passing them into the line, but this obviously defeats the object sought in using the high frequency control of the amplification because each amplifier now receives ordinary voice waves and gives out enlarged copies of them which are subject to the same reflections as if plain one-way amplifiers without the high frequency control had been used.

From these considerations it will readily be seen that repeater systems depending upon high frequency variation of the gain to avoid singing and the necessity for impedance balances, are inherently unworkable.