THEORY OF RETURN LOSSES

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1. GENERAL

1.01 The design and maintenance of telephone circuits are on the basis of providing low enough net losses to permit the circuits to give satisfactory service to the customers, and must therefore take into account all factors that act to limit the reduction of the net loss. Prominent among these on circuits or connections involving amplifiers are echo and singing. Just as voice sound waves are echoed or reflected by a wall, a cliff, or other obstacle in the path of the waves, so will analogous obstacles in a telephone circuit reflect the electrical voice waves and give rise to the same sensation of echo. If the delay of the echo is sufficient, a distinct repetition of the talker's voice may be produced; if the delay is small the echo tends to merge with the sidetone or the direct transmission. Talker echo is echo heard by the talker due to his own speech and its effect is principally to annoy and disturb the talker and perhaps delay the conversation. Listener echo is echo heard by the listener due to the far-end subscriber's speech; this may reduce the intelligibility of conversation and may also be the source of considerable annoyance, but is usually less objectionable than the "talker" echo. If the echo is very pronounced a circulating current may be started around a repeater and the repeater in effect converted into an oscillator. The oscillating current will be heard by listeners on the circuit and give them the effect of a howl or "singing" on the circuit, through which it may be impossible to talk, or which may otherwise react unfavorably on transmission. Singing is of especial concern in two-wire circuits and is the subject to be treated in this section.

1.02 Any change in the fundamental constants of a circuit may constitute an impedance irregularity, at which voice power is partially reflected or echoed back towards its source. In traveling back, this reflected power may, in conjunction with other reflections, be of sufficient magnitude to lead to an oscillating or singing condition in a repeater on the circuit, the possibility of which depends among other things on the amount of the reflected power and the gain in the repeater. Since the net loss of a circuit depends to a large extent on repeater gains, the reflected power may be and frequently is one of the factors that determine the lowest net loss at which a given circuit may be satisfactorily operated.

1.03 Reflections at irregularities, giving rise to "returned" or "unbalance" currents and reacting on the operation of repeaters, are, therefore, at the bottom of singing phenomena. The theory of such reflections is first taken up in this section following which are given the effects of the returned currents, a discussion of methods of measuring these currents in such terms as return loss and singing point, and a discussion of how these currents come into theoretical and practical considerations of the design and maintenance of circuits.

2. THEORY OF RETURN LOSSES

Reflection at Irregularities - Reflection Coefficient

2.01 An electrical wave impressed on a uniform circuit travels along the circuit, undergoing uniform attenuation and phase change. No reflections take place and hence no unbalance currents arise. The ratio ($\frac{E}{I}$) of the voltage and current at any point in the circuit is the characteristic impedance, Z_0, of the circuit. If a circuit infinitely long or smoothly terminated is broken at any point, F, the impedance looking either to right or left from F is Z_0, and by Pollard's (Thevenin's) theorem the voltage impressed, say, at the left can be represented by a voltage in series with Z_0, as shown by Fig. 1a. If an irregularity is inserted at F, the impedance looking through this irregularity to the right becomes Z_t or the impedance that in effect terminates the uniform line to the left, as pictured in Fig. 1b.

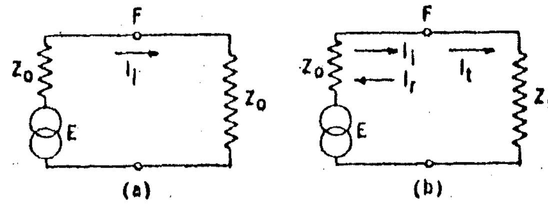

Fig. 1.

2.02 The current I_1 at F when there is no irregularity (Fig. 1a) is $\frac{E}{2Z_0}$ and is sometimes called the incident current. With the irregularity inserted the current at F becomes I_t which equals $\frac{E}{Z_0 + Z_t}$ (Fig. 1b). The insertion of the irregularity in effect sets up a reflected current I_r (See Fig. 1b) which combines vectorially with I_1 to produce I_t, i.e., $I_1 + I_r = I_t$ or $I_r = I_t - I_1$. The directions of the current arrows shown in Fig. 1 are arbitrary since each of the currents is a vector quantity. The relation of interest is how much of the current that would exist with no irregularity is reflected by the irregularity, i.e., $\frac{I_r}{I_1}$, which, from the above, is:

$$\frac{I_r}{I_1} = \frac{I_t - I_1}{I_1} = \frac{\frac{E}{Z_0 + Z_t} - \frac{E}{2Z_0}}{\frac{E}{2Z_0}}$$

This expression simplified becomes:

$$\frac{I_r}{I_1} = \frac{Z_0 - Z_t}{Z_0 + Z_t} \qquad (1)$$

2.03 The ratio $\frac{Z_0 - Z_t}{Z_0 + Z_t}$ of formula 1, called the "reflection coefficient," multiplied by the incident current, I_1, gives the value of the reflected current. It applies only for non-loaded or continuously loaded circuits and for coil loaded circuits having irregularities at mid-section or mid-coil, for only in these cases is the characteristic impedance the same looking to right or left as was assumed in the derivation of the ratio.

Computation of Insertion Return Loss

2.04 Where the inserted facility does not present its characteristic impedance, account must be taken of the reflection at both junctions with the circuit under study and of the attenuation and phase shift in the inserted facility. One way of handling this situation is to compute the impedance looking through the inserted facility (a method of doing this is given in Section AB42.026 of Basic Transmission Data) and then determining from formula (2) or curves the return loss between this impedance and the characteristic impedance of the circuit under consideration. In case the impedance so computed terminates a coil-loaded line at other than half-coil or half-section, the return loss is computed as discussed in Appendix A, which requires a consideration of the iterative impedance of the loaded circuit looking from the junction toward the sending end and also of the impedance required at the junction to terminate the loaded circuit smoothly. This latter may be called the complementary iterative impedance. The return loss, however, may be computed by formula (2), or read from the curves, with only small error in the usual case, by assuming Z_0 to be the complementary iterative impedance, i.e., if the junction occurs 0.2 of a section from a loading coil, Z_0 is the iterative impedance of the circuit as seen 0.8 of a section from the loading coil.

2.05 A somewhat different method of computing insertion loss in case of uniform circuits and coil-loaded circuits with insertions at half-coil or half-section is developed in Appendix B. This method consists essentially of determining the junction return loss between the inserted facility and that under study and then correcting this value by amounts depending on the length and type of the inserted facility. The effect of the insertion and the trend of the correction with increasing lengths of inserted facility is thus directly seen. The corrections become zero when the inserted facility is long enough to present its characteristic impedance, leaving the junction return loss as the effect of the insertion. This method is presented in the drawings on pages 103-105 to facilitate practical computations, and a sample application of these drawings is given in Appendix B. It may be noted that from these drawings curves could be prepared showing directly the insertion return loss of varying lengths of given types of inserted facility.

2.06 The insertion return loss as computed or as read from appropriate curves exists at the junction nearer the sending end. It must usually be referred to the repeater or other point of reference as discussed in paragraphs 2.10 and 2.11.

2.07 For the computation of insertion return loss at a particular frequency, data at that frequency must be available for:

- (a) Characteristic or iterative impedances of the circuit under study.
- (b) Characteristic impedance of the inserted facility.
- (c) Attenuation constant of the inserted facility.
- (d) Phase shift constant of the inserted facility.

3. COMPONENT RETURN LOSSES AFFECTING THE REPEATER SECTION RESULTANT

3.01 Taking as a unit part of a circuit the portion between two adjacent repeaters, or a repeater section, there are several sources of returned currents in the section, the effects of which must be combined to arrive at the resultant repeater section return loss. These component return losses are discussed in the following.

Structural Return Loss

3.02 Structural return loss is a measure of the departure, due to random irregularities, of the impedance of a circuit from its theoretical characteristic impedance. In a loaded circuit for example it is impractical to avoid small variations of the loading coil inductance from the normal value, to place the loading coils precisely at the theoretical locations, or to so manufacture a cable that each pair in each loading section will have the same capacitance. These small variations, or structural irregularities, while singly not usually large enough to affect the return loss very much, do give a cumulative effect of appreciable magnitude. Although structural return loss theoretically is a function of the ratio of reflected current to the current that would flow in a perfect circuit, practically, as regards its measurement and the way it influences repeater operation, it is a measure of the accuracy with which the network impedance and the sending-end impedance of the line agree. With modern precision type networks, with circuits having constants close to those assumed in the network design, and with careful building out to simulate such cable end section as may be involved there is but little difference between the practical and theoretical concepts except at extremely high or low frequencies in the transmitted band.

3.03 The theory of structural return loss is developed in Reference I (see Part 16) and the return loss S in db is represented by the formula:

$$S = S_H + S_W + S_F - S_A \qquad (5)$$

where: S_H = irregularity function

S_W = frequency function

S_F = distribution function

S_A = attenuation function

3.04 The irregularity function S_H depends on the structural irregularity, which for a loaded cable line is the combination of:

(a) Small deviations in loading coil inductance.

(b) Small deviations in capacitance of pairs or phantoms per unit length from the normal value, due to random deviations in the cable as manufactured.

(c) Loading section capacitance deviations due to placing loading coils at other than their precise theoretical locations.

The larger of any of these variations, the smaller S_H, and hence the smaller S. The value S_H is independent of frequency.

3.05 The frequency function S_W depends only on the ratio of the frequency to the cutoff frequency of the facility under consideration $(W = \frac{f}{f_c})$. Its value decreases with frequency, and for a given frequency, will vary with the weight and spacing of the loading involved.

3.06 S_A depends on the attenuation of the circuit, which in turn is dependent both on frequency and on the type of circuit. It is a kind of summation factor that sums up the returned currents from the individual loading sections represented by S_H, hence the minus sign preceding it in the formula. The greater the loading section attenuation, the smaller S_A; and, due to the minus sign of the formula, the greater S.

3.07 The function S_F takes account of the facts that the structural irregularities are not all the same magnitude and sign and that the returned currents from these irregularities arrive at the repeater at different phases. The loading coil inductance may for example be either larger or smaller than the correct value, and may be larger or smaller by various amounts. One cannot say that the variations for a particular circuit will be of a certain magnitude, but can say, from a knowledge of the distribution of the magnitude and signs of variations observed in the manufacture of a large number of loading coils and cable lengths, etc., that in a certain percentage of cases the variations due to the several causes will be equal to or in excess of a certain value. In other words a definite value of structural return loss at a given frequency cannot be forecast for a particular circuit but rather a distribution of the return losses between different circuits. A value can only be established which, based on probability, it is expected will be met or exceeded by the structural return losses of a certain percentage of circuits. The larger the percentage of circuits whose structural return losses must equal or exceed a certain value, the smaller that value must be. As may be seen from Reference I, the value of S_F is dependent only on the percentage assumed and is zero for a 63 per cent. distribution. If a certain value of S were computed such that 63 per cent. of the circuits would have structural return losses equal to or exceeding it ($S_F = 0$), the value of S for a 96 per cent. distribution would be about 5 db less ($S_F = -5$), regardless of the type of circuit concerned.

3.08 This idea of distribution, which means working with values that will be exceeded in a certain percentage of cases rather than with definite and fixed values, will also be encountered in singing points and will be a consideration in both complete circuits and parts of circuits. The laws of probability then enter into singing considerations, and judgment will of necessity have to be applied in many practical problems.

3.09 For a given distribution and a given type of circuit the structural return loss due to the combined effect of the several factors becomes less with increasing frequency, so that in general the upper frequencies will be limiting in singing phenomena. Fig. 3 for example shows for 19 gauge H and B-88-50 circuits the distribution of the return loss values for different frequencies which will be equalled or exceeded by those on 63 per cent. of such circuits, assuming certain load coil and capacitance variations.

3.10 Structural return loss as discussed above applies especially to loaded cable circuits. In the case of open-wire circuits minor variations of constants occur due to differences in sag, differences in the number of wires on the lead, etc. These are not so pronounced as the variations in cable circuits and in general the value of structural return loss used for open-wire is regarded as a fixed value with frequency and without regard to distributions, especially as the structural value is usually modified by intermediate irregularities. A repeater section of open-wire is seldom a smooth open-wire circuit throughout, whereas cables are usually of the same type of facility throughout.

<u>Return Loss Due to Terminating Irregularity</u>

3.11 Under actual operating conditions, a repeater section or a circuit is never terminated smoothly. For example, a cable circuit ending at an office with 0.8 section from the last loading coil would, to be terminated smoothly, have to be connected to an impedance equal to that of an infinitely long circuit of the same type as

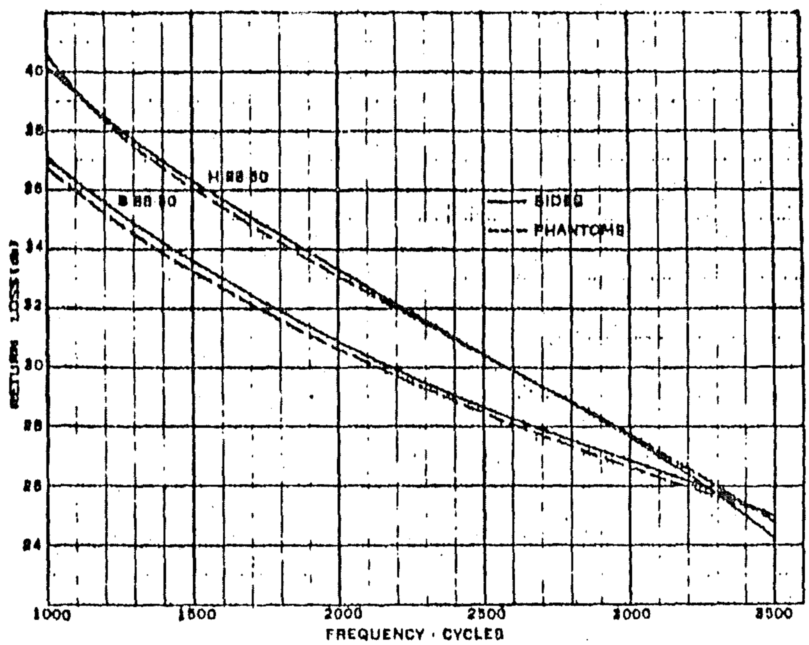

Fig. 3.

seen 0.2 of a section from a loading coil, that is, to its complementary impedance. It is necessary therefore to take into account the effect of the terminal irregularity.

3.12 In the case of a multi-repeatered circuit, the operating termination for each section, except for the end paths or the end sections where terminal repeaters are not used (see paragraph 3.20), is the adjacent repeater. In such cases the terminating impedance is the impedance seen looking into the repeater from the line side of the line equipment. Cable circuits usually end at half-section or half-coil, so that this terminating impedance compared with the half-section or half-coil impedance, in accordance with formula (2) or the junction return loss curves, gives the terminating return loss. Where the cable ends at other than half-section or half-coil the return loss may be obtained with sufficient accuracy by comparing the terminating impedance with the impedance required to smoothly terminate the circuit. The reaction of this terminating return loss on the adjacent repeater is obtained by adding to it twice the repeater section attenuation. For this reason the terminating irregularity unless unusually large, or the repeater section short, generally has but small effect on the overall resultant return loss.

<u>Return Loss Caused by Intermediate Irregularity</u>

3.13 In general, the introduction of any equipment or change in type of facility at an intermediate point in a repeater section causes a reduction in the repeater section return loss. Examples of such irregularities are repeating coils or composite sets at an intermediate office, omitted or defective loading coils, deviations in loading spacing in excess of those involved in a consideration of structural return loss, section of non-loaded cable, or the junction between dissimilar circuits with or without the use of the proper inequality ratio repeating coils. As already noted the return loss of the irregularity may be determined if the impedance looking through the irregularity is known. In some cases this will be the characteristic impedance of the connected circuit, in others the insertion return loss curves may be applied, and in others the impedance may be arrived at by combining the impedance of the irregularity with that of the circuit beyond. Suppose for example that the irregularity is excess or deficient loading section capacitance as illustrated in Fig. 4.

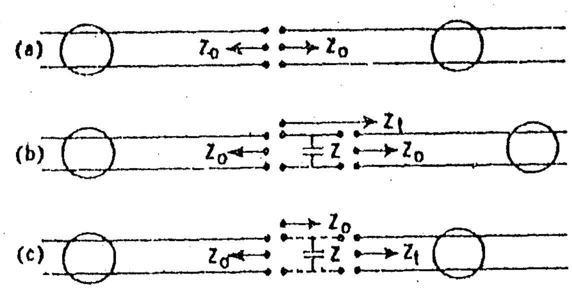

Fig. 4.

3.14 The irregularity may be assumed to be concentrated at the center of the loading section at which point the characteristic impedance is Z_0 (see Fig. 4a).

Excess capacitance is represented by impedance Z of this capacitance inserted ahead of the half loading section to the right (Fig. 4b), and the terminating impedance, Z_t, is merely Z and Z_o in parallel or

$$Z_t = \frac{Z\ Z_o}{Z + Z_o}$$

For deficient capacitance, represented by the dotted portion in Fig. 4c, Z_o is equal to Z and Z_t in parallel, i.e.,

$$Z_o = \frac{Z\ Z_t}{Z + Z_t}$$

From this, Z_t, which connects with Z_o to the left, becomes:

$$Z_t = \frac{Z_o\ Z}{Z - Z_o}$$

3.15 Other types of irregularity may be similarly handled. The effect of repeating coils for example may be treated through the use of T-networks simulating the repeating coils' electrical characteristics.

Office Cabling and Equipment Return Losses

3.16 Another component of the overall return loss depends on the degree of precision with which it is economical and practicable to make balancing equipment at a repeater simulate such line equipment as repeating coils, composite sets, carrier filters, etc.

3.17 The return loss between the balancing equipment with its interconnecting cable and the associated line equipment depends on the precision of manufacturing processes and on the precision which may be used in pairing items of line and balancing equipment, and also on the care taken in balancing the office cabling. Although this return loss is usually fairly high it must generally be taken into consideration, particularly if high structural return losses are involved.

3.18 One item of office equipment may be omitted from the above as follows. The network for a lump-loaded line is usually made to simulate the line impedance as seen at approximately 0.2 of a loading section from the last loading coil.

If, therefore, a circuit begins at more than 0.2 section, the excess length must be balanced with a building-out unit connected to the network. The balance between the network plus the building-out unit and the line is generally regarded practically as the structural return loss so that the building-out unit does not enter into the equipment balance proper. On the other hand where an open-wire line enters an office through an appreciable stretch of non-loaded cable the balance between the cable and the T-network (generally assembled locally) simulating the cable in the balancing circuit may or may not be negligible depending on the care and accuracy with which the T-network is assembled.

Internal Repeater Balance

3.19 If the windings of the hybrid coil are not identical a circulating current is set up within the repeater even though the impedances connected to the line and network terminals of the hybrid coil match each other perfectly. The return loss corresponding to this internal balance, particularly in later types of repeaters, is usually high enough to be neglected. If this is not the case it should be considered along with the foregoing component return losses in arriving at the combined value for the section.

Terminal Return Loss

3.20 The termination (end-path) at the distant end or terminal of a circuit under operating conditions consists of a toll switching trunk or tributary circuit (if required) and a subscriber loop and subscriber set. The return loss between the impedance of this termination and the impedance required to smoothly terminate the circuit is called the terminal return loss. It does not form part of the repeater section return loss but is rather a separate component, differing from the intermediate paths in that:

(a) It is usually important (or low) compared with any one intermediate return loss; and,

(b) Due to its comparative uniformity over the frequency band and to its remoteness as discussed later, it tends to combine more pessimistically (in phase) with the other return loss components.

3.21 The terminal return loss varies between offices, between different connections at the same office, and from time to time for the same connection (due to transmitter resistance variations, etc.) A recent survey at a more or less typical office indicated that the terminal return loss in the frequency range important from a singing viewpoint was in the order of 7 db or more for about 63 per cent. of connections and that it followed very much the same distribution (S_F) as structural return losses. Both the magnitude and the distribution may be found on further investigation to vary appreciably for different offices, but in the meantime the above values are considered reasonable for general design purposes. Where a fixed value of terminal return loss is needed for detailed computations or for purpose of test terminations, a value of 5 db is generally used.

4. COMBINING COMPONENT RETURN LOSSES

4.01 The component return losses to be combined must first be referred to some common point (usually a repeater) at which the overall return loss for the section is to be determined. As noted previously this is done by adding to the return loss the sum of the losses out to the point at which the return loss exists and back to the place of reference. If there were any gains in the path, these would have to be subtracted. A return loss is expressed for a certain frequency, so that the component return losses to be added must all be for the same frequency. The gains and losses used in referring the return losses to a common point must likewise be at the same frequency.

4.02 Each return loss represents a certain amount of returned current with respect to the current that would flow in a perfect circuit, and the larger the returned current, the smaller the return loss. If all the returned currents combined in phase (0° apart), a maximum amount of current would result and would give the lowest possible combined return loss. On the other hand, if say, the currents representing two return losses combined out of phase (180° apart), they would tend to cancel each other and give the highest possible combined return loss. These are the two extreme ways of combining. In general the circuit conditions are not well enough known, or else an unwarranted amount of work would be required, to determine the exact phase relations of the various currents. (An exception to this occurs in the computation of insertion return loss.) Not knowing then what the phase relations are, it is natural to assume a middle course between the two extremes 0° and 180° apart, and thus combine the currents at right angles or 90° apart, i.e., the combined current would be the square root of the sum of the squares of the component currents. Theory also says that when the phases are unknown but are substantially at random, right angle combining is about right. For the majority of component return losses, such right angle combining is shown both by computation and by measurement to give reasonably accurate results.

4.03 Letting I_a and I_b represent the returned currents from two irregularities (assuming unit current sent into a perfect circuit), the combined current would be $\sqrt{I_a^2 + I_b^2}$. The component return losses are:

$$db_a = -20 \log I_a \text{ and } db_b = -20 \log I_b$$

and the combined return loss is:

$$db_{(a+b)} = -20 \log \sqrt{I_a^2 + I_b^2}$$

$$= -10 \log (I_a^2 + I_b^2)$$

4.04 The last formula is the usual formula giving transmission loss corresponding to power ratios, represented by the squares of the current ratios, I_a^2 and I_b^2. In other words, to combine two (or more) return losses, all that is required is to add up the power ratios corresponding to the component return losses and to find from a table of power ratios the db value corresponding to this sum. The following illustrates this method of combining the component return losses 31, 31, 28 and 20 db.

Individual Return Losses	Power Attenuation Ratio
31	0.000794
31	0.000794
28	0.00158
20	0.01000
Sum of Power Ratios	0.013168
Combined Return Loss	18.8 db

4.05 An exception to this method of combining is noted in the case of large distant irregularities. With a long stretch of loaded circuit between the reference point and the distant irregularity, only a very small change in frequency is required to make a large change in the phase shift, i.e., a slight change in frequency will be sufficient to bring the returned currents in phase without appreciably altering their magnitude. This condition is met in practice particularly in the so-called end-path, or the return loss corresponding to the distant terminal irregularity, which irregularity, in operating conditions may be quite large. Two currents, I_a and I_b, combining in phase, give a resultant current $I_a + I_b$. The component return losses are:

$$db_a = -20 \log I_a \text{ and } db_b = -20 \log I_b$$

The combined return loss is:

$$db_{(a+b)} = -20 \log (I_a + I_b)$$

This formula is simply the db corresponding to the sum of the current ratios I_a and I_b, so that to combine two (or more) return losses "in phase" or on the current ratio basis, the current ratios corresponding to the component return losses are added together and the db value corresponding to the sum looked up from a table of current ratios. Taking the same example as before, but assuming the 20 db return loss to combine in phase with the resultant of the other three:

Individual Return Losses	Power Attenuation Ratio
31	0.000794
31	0.000794
28	0.00158
Sum of Power Ratios	0.003168
Combined Return Loss for These Three Components	25.0 db

This resultant 25 db is then combined with the 20 db component on a current ratio basis to obtain the overall resultant.

Individual Return Losses	Current Attenuation Ratio
25	0.0562
20	0.1000
Sum of Current Ratio	0.1562
Combined Return Loss	16.1 db

Note that the overall resultant is lower than that obtained by adding all four components at right angles.

5. PASSIVE AND ACTIVE RETURN LOSS

5.01 When energy is introduced into the path of returned currents (the return path) only by the measuring apparatus, the return loss thus measured is called a passive return loss. It should be noted that a passive repeater may be used as the termination for a passive return loss measurement; this is but one of a number of possible terminations which might be used.

5.02 Return loss may be computed or measured for a section of circuit including one or more repeaters which amplify some of the returned currents. In this case reflected currents are amplified by any repeaters that may be located between the irregularity and the sending end. The result, therefore, is partly a function of the gain supplied by the active repeaters. This return loss, for the condition where energy is introduced other than by the measuring apparatus, is termed an active return loss.

6. RETURN LOSS - FREQUENCY CHARACTERISTIC

6.01 The relative effects of the fundamental constants of a line and of terminations, etc., vary with frequency, and hence, the portion of the current returned to the source and consequently the return loss also varies. It is meaningless therefore to state a value of return loss without specifying at what frequency it applies. The return loss-frequency characteristic of a line shows the variation in return loss over the frequency range under consideration. If this characteristic is obtained by measurement it will show the true combination of all the component return losses involved, regardless of the number and nature of irregularities present in the circuit. As discussed in a later part, this characteristic is useful in determining the approximate frequency at which singing will occur if the circuit is equipped with a repeater.

6.02 It has already been noted that the return loss at an irregularity is dependent only on the scalar value of the ratio of reflected to incident current and not on the phase relation. The phase comes in only in so far as the angles of the impedances affect the scalar value of the reflection coefficient. The change in this respect with frequency is gradual so that the return loss-frequency characteristic is a smooth curve and may gradually fall or rise with frequency. It has also been noted that this return loss referred to the sending end or point of reference is affected only by the attenuation in the intervening facility so long as only one irregularity is present. Phase relations come into prominence only when two or more irregularities are involved. In this case, owing to the difference in distances to the various irregularities, the relative phase of the returned currents will constantly change with frequency; at one frequency they will tend to come in phase (large resultant current, low return loss), at another frequency they may be out of phase (small current, high return loss), and so on, producing a resultant wavy return loss-frequency characteristic similar to the familiar impedance-frequency curve, containing peaks and valleys. And as in the case of the impedance-frequency curve, the interval between return loss peaks and valleys is a function of the distance between the irregularities. Fig. 5 illustrates this discussion with return loss-frequency curves of two irregularities separately and of the two combined, all referred to the sending end.

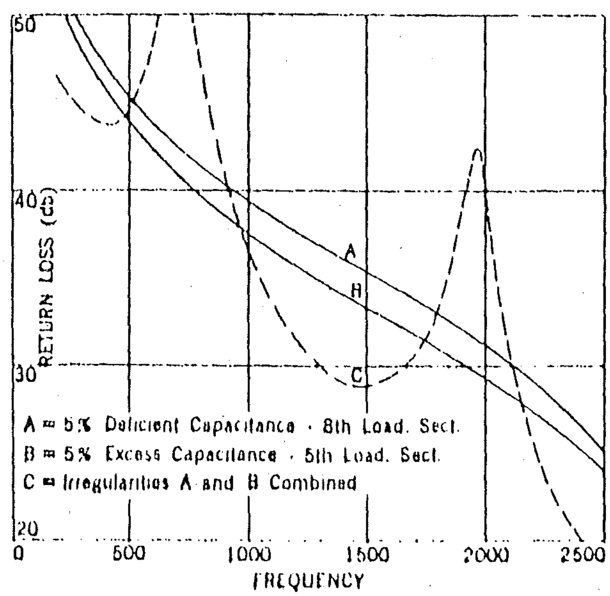

Fig. 5.