Telephone Transformers*

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Review of the Subject. In the communication art transformers are used to transfer inductively the energy of speech currents from one electric circuit to another. In addition to this primary function which must be efficiently performed without distorting the speech significance of the transmitted energy, there is a variety of secondary functions such as making possible the super-position of phantom circuits on ordinary telephone circuits, discriminating between speech and telegraph or signaling frequencies, isolating circuits carrying direct current, and preventing inductive interference between adjacent circuits.

A discussion is presented of the frequency range over which telephone transformers must operate efficiently in transferring energy between two circuits and the three most common limiting impedance combinations of these circuits, namely, both circuits resistances, one circuit a resistance and the other a positive reactance and one circuit a resistance and the other a negative reactance. The efficiency with which energy is transmitted is measured by comparison with an ideal transformer which is one which introduces no losses and has the best ratio to connect the two circuits. In studying its action the transformer is replaced by its equivalent T network which affords a ready means of analyzing its losses. The variation of the transformer losses with frequency is discussed for the three above mentioned combinations of circuit impedances and characteristic curves are shown for transformers of different mutual impedances. Characteristics are also given showing the operation of the input transformer into the vacuum tube as the mutual impedance and the transformer ratio are varied. The circuit conditions of the input transformer represent a common special case of the third combination of circuit impedances.

The mechanical construction of various transformers is shown, namely, that of the ordinary battery supply repeating coil, of the telephone induction coil, and of three more recent types of transformers used principally in various vacuum tube circuits such as telephone repeaters, carrier frequency and radio circuits. These transformers are all constructed so as to give the desired accuracy of speech transmission under their particular circuit conditions. The climatic conditions present in the widely distributed telephone plant have been carefully considered and the transformers designed to maintain their initial efficiency over a long period of years.

INTRODUCTION

THE transformers used in the telephone plant are required to transmit speech or signaling currents from one electrical circuit to another in such a way as to obtain maximum transfer of power. They differ in their required action from power transformers in two main respects. They have to transmit milliwatts efficiently instead of kilowatts and must operate efficiently under a variety of conditions of voltage, frequency, etc., instead of under single fixed conditions. These various requirements of operation make it necessary in designing a telephone transformer to proportion it differently from a power transformer.

The requirements of circuits in which telephone transformers are used make it necessary to consider their efficiency in detail over a wide range of frequency and at the same time make sure in each particular case that they have characteristics apart from this efficiency which will enable the circuits to function properly. Such other characteristics, one or more of which may be required of a transformer, are:

1. The efficient transmission of telephone currents while carrying super-posed direct current as in the cord circuit battery supply repeating coil.

2. A high degree of impedance balance between the windings in order: (1) to avoid unbalancing the circuit and rendering it subject to noise or cross-talk troubles; (2) to limit cross-talk in closely associated circuits as in the case of the phantom circuit repeating coil in which the balance required is very precise, the two phantom circuit windings being balanced to about 0.01 per cent; or (3) to prevent sustained oscillations or singing in a two-way telephone repeater as in the case of the repeater output transformer.

3. High efficiency as a low-frequency power transformer, for example, at 16⅔-cycle signaling frequency, as well as high efficiency as a telephone speech frequency transformer.

4. Low efficiency as a power transformer at the frequencies of interruption of direct current used in Morse telegraph as well as high efficiency as an audio frequency transformer. This low power efficiency is necessary in order to reduce troubles, such as, noise interference, false operation of relays and acoustic shock when the same lines are used for both telephone and telegraph.

5. Impedance transformation closely approximating that obtained with an ideal transformer as in the line transformers in circuits in which

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two-way telephone repeaters are employed. By impedance transformation is meant the modification of the line or network impedances when viewed through the transformer.

6. Impedance transformation for a pair of transformers alike over the transmitted audio frequency range for use as the line and network transformers in two-way repeater operation.

7. Stable impedance transformation even when having been subject to large magnetizing forces as in the line transformers in two-way telephone repeater circuits in order to maintain the required balance between line and network under all conditions of service.

8. Minimum production of harmonics due to the magnetization characteristics of the iron which would cause interference in the normal transmission frequency range, as in the line transformers on circuits which are used for the transmission of Morse telegraph in addition to speech.

9. To isolate conductively one portion of a circuit from another as in transformers used to connect grounded to metallic lines or to isolate subscriber sets from the telephone lines which parallel high-tension power lines and which may therefore be exposed to large inductive disturbances.

10. To maintain the usual conductive isolation and furnish a path to ground for longitudinal currents as may be obtained with a transformer with a shield between primary and secondary windings. By a longitudinal current is meant one which flows along a circuit and returns by some path exterior to that circuit.

As the primary function of the telephone transformer is to transmit telephonic speech efficiently, this paper will be limited to this part of the subject, although the complexity of the telephone plant rarely permits a transformer to be free from the necessity of meeting one or more secondary requirements such as those mentioned above. Two winding transformers only will be discussed.

FREQUENCY REQUIREMENTS

In the ordinary telephone circuit a range of frequency of about 200 to 2500 cycles is allotted to the transmission of speech, both of these limits varying somewhat with the type of circuit. In the case of long distance lines in which it is desirable to utilize the circuits to the best economic advantage, the frequency range below 3000 cycles is allotted to speech, signaling and telegraph and above that frequency to the transmission of carrier telegraph and telephone. A transformer used for the transmission of speech currents is required to operate efficiently over the entire range of frequency transmitted.

With the present intensive use of the telephone lines, transformers may be required to transmit low-frequency signaling of 16⅔ or 20 cycles, composite ringing of 135 cycles, speech from 200 to 3000 cycles and carrier from 3000 to 30,000 cycles. This carrier frequency is divided into a number of frequency channels which are used for separate telegraph or telephone circuits. A carrier range from 3000 to 10,000 is generally used for telegraph while with carrier telephone a frequency range from 6000 to 30,000 is used.[1] In certain radio telephone circuits transformers are required to operate at frequencies of the order of 50,000 to 100,000 cycles and in radio frequency amplifiers at approximately 1,000,000 cycles. Telephone transformers may be required to operate at any one of these frequencies or frequency bands or they may be required to transmit efficiently two or more of them. Illustrations of this are the ordinary phantom circuit repeating coil which transmits low-frequency (16⅔ cycles) signaling and composite ringing (135 cycles) as well as speech, and the transformers which connect the Key West-Havana cable to the shore lines and which are designed to transmit carrier telegraph up to about 6000 cycles as well as ordinary telephonic speech.

In radio transmitters used for broadcasting and in Public Address Systems[2] where it is desired to transmit music and to reproduce accurately the exact quality of the speaker's voice, it is necessary that any transformers in the circuit operate efficiently at frequencies at least as low as 50 cycles and as high as 5000 cycles.[3]

[1] Colpitts and Blackwell: "Carrier-Current Telephony and Telegraphy," TRANS. A. I. E. E., Vol. XL, page 301.

[2] Green and Maxfield: "Public Address Systems," *Electrical Communication*, Vol. I, No. 4

[3] Fletcher: "The Nature of Speech and Its Interpretation," *Electrical Communication*, Vol. I, No. 1.

Martin and Fletcher: "High Quality Reproduction of Speech and Music," *Electrical Communication*, Vol. II, No. 4.

In the following the operation of transformers over the voice range of frequencies only will be discussed but it is to be noted that the principles involved apply to transformers for carrier and radio frequencies as well.

IMPEDANCE REQUIREMENTS

Another important factor in determining the design and operation of the transformer are the impedances of the circuits which the transformer connects. The circuit impedances, which are the impedances as measured from the place where the transformer is to be located, may be but a few ohms in magnitude or may be several megohms. They may also vary appreciably in magnitude or phase angle over the frequency range.

The circuit impedances met in the telephone plant are seldom either substantially pure resistances or reactances over the entire frequency range and in considering the action of a transformer between two such circuits at any frequency the actual impedances of the circuits at that frequency must be employed. It is impossible to discuss all possible combinations of circuit impedances here. However, with a knowledge of the action of transformers between three limiting combinations of circuit impedances an indication will be given of their operation under all conditions of importance. These three limiting impedance conditions are:

1. Sending and receiving end impedances both resistances.
2. Sending end impedance a resistance, and receiving end impedance a positive reactance.
3. Sending end impedance a resistance, and receiving end impedance a negative reactance.

It is, of course, to be understood that the sending and receiving end impedances may be interchanged. There are, in addition, three other possible limiting circuit impedance conditions—the sending and receiving end impedances both positive or negative reactances and the sending end impedance a positive reactance and the receiving end impedance a negative reactance. These three impedance conditions are less usual than the first three and it is felt to be unnecessary here to discuss in detail the action of telephone transformers in circuits of this type.

TRANSFORMER EFFICIENCY

The telephone transformer is generally used for transmission in both directions and the usual definition in power work for the primary as the winding which receives the energy from the supply circuit does not hold. The terms primary and secondary are therefore used simply to distinguish between the two windings without regard to the energy flow.

It can be shown that maximum power may be delivered from one circuit to another if the impedances of the circuits are equal in magnitude and opposite in phase, that is, if the resistances are equal and if the reactances annul each other. Maximum power may be delivered from one circuit to another in which the reactances annul each other and in which the resistances are not equal provided an ideal or perfect transformer of proper ratio is used to connect the circuit resistances. In the ordinary case it is not possible to annul the reactances over the entire frequency range to be transmitted and no attempt is therefore made to modify them. Under these conditions transformers are used to connect the two circuit impedances and without annulling reactances the greatest amount of power will be delivered by connecting these impedances by means of an ideal transformer of the best ratio.

By an ideal transformer is meant one which neither dissipates nor stores energy. Such a transformer has infinite primary and secondary self-impedances, infinite mutual impedance, unity coupling factor or zero leakage impedances, and zero d-c. resistances. An ideal transformer for any given circuit condition also has the best ratio to connect the circuit impedances.

It may be stated that when the circuit reactances are not annulled by the addition of reactances of the opposite sign, it is possible to deliver more power to the load impedance at certain frequencies by the use of an actual than by an ideal transformer as the transformer impedances may tend to annul the circuit reactances.

It has long been customary in dealing mathematically with a transformer to use in its place some equivalent network such as a π or a T network.[4] The use of an equivalent T network

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[4] Campbell: "Cissoidal Oscillation" TRANS. A. I. E. E., Vol. XXX, Part 2, page 873.

changes a coupled circuit into a simple circuit in such a way as to make it easier to see the effect of changes of the transformer constants on the transmission of the circuit. The equivalent *T* network of a two-winding transformer is shown in Figure 1 in which the junction point of the three arms is considered not accessible and in which *P*, *S* and *M* are respectively, the primary, secondary and mutual impedances.

The series arms *a* and *b* of the *T* network consist respectively of the differences of the primary and mutual impedances and the secondary and mutual impedances. The equivalent *T* network of the transformer is sometimes shown having series arms $P + M$ and $S + M$ and shunt arm $-$ M. These two *T*'s may be derived from the transformer impedances depending on whether the secondary is connected to give a received current in one direction or the other. The *T* shown here is the most convenient for ordinary considerations. Considering for the present a unity ratio transformer, the arm *a* will contain the d-c. resistance of the primary and the arm *b* the d-c. resistance of the secondary. In addition, the leakage impedance will be divided between them. Whether the leakage impedance should properly be considered principally in the arm *a* or principally in the arm *b* or divided equally between them depends on the relative location of the primary and secondary windings. However, in the ordinary case the coupling factor is so near unity and the leakage impedance is so small in comparison with the primary, mutual and secondary impedances that practically no error is introduced if it is assumed to be divided equally between them.

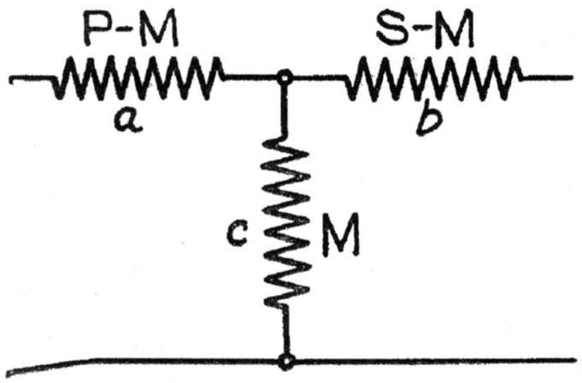

Figure 1

The shunt arm *c* of the equivalent *T* network contains the mutual impedance *M*. This mutual impedance equals $K\sqrt{P_0 S_0}$ where P_0 and S_0 are the primary and secondary impedances less their respective d-c. resistances, and where *K* is the coupling factor. The coupling factor *K* has a phase angle in actual transformers but where the coupling factor is nearly unity the angle may usually be disregarded. The mutual impedance is a complex quantity as are also the primary and secondary impedances of all usual transformers. As the mutual impedance is dependent on P_0 and S_0, any factors which enter into P_0 and S_0 will also enter into *M*. The reactance components of these impedances depend on the number and distribution of turns in the windings and the dimensions and permeability of the core. The resistance component is made up of an effective resistance due to hysteresis, eddy current and dielectric losses.

The distributed or lumped capacities of the windings are best considered in their effective values. These effective capacities may be regarded as shunted across the primary or secondary of the transformer or may be considered as located across *M* of the arm *c* of the equivalent *T* of the transformer. If this effective capacity is considered in shunt with *M* and combined in it, both the resistance and the reactance of *M* will have components due to the effect of this capacity. The effective resistance and effective reactance of *M* will then go through the usual curves for parallel resonance

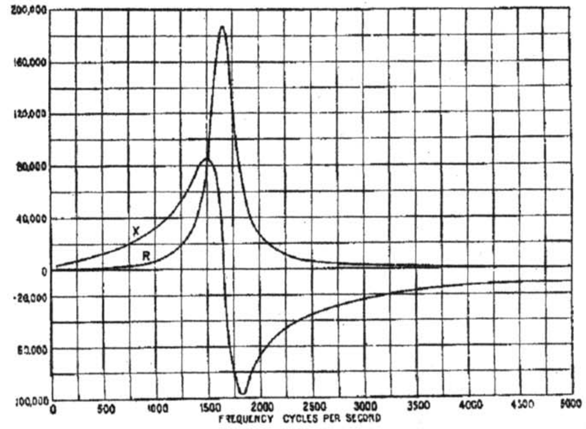

Figure 2—Mutual Impedance M of a Phantom Circuit Repeating Coil

X Effective reactance—ohms
R Effective resistance—ohms

as shown in Figure 2 for a typical phantom circuit repeating coil.

One other factor frequently enters into the determination of the effective value of M as well as P_0 and S_0. In some circuits, in order to economize on the amount of apparatus necessary, a direct current is allowed to flow through the primary or secondary windings of the transformer. This causes a uni-directional magnetizing force in the core in addition to the a-c. magnetizing force of the speech current. This d-c. magnetization causes a decrease in M from the initial value or value with no d-c. magnetization, depending upon the strength of this magnetization and the reluctance of the magnetic circuit.

The series arms of the equivalent T of the unity ratio transformer are thus impedances consisting of the d-c. resistances and the leakage impedances and are usually relatively small compared with the circuit impedances while the shunt arm is the mutual impedance which is usually large compared with the circuit impedances. The simplicity of the equivalent T network of the unity ratio transformer is very useful and convenient in studying the effect of the transformer in producing losses. With an inequality ratio transformer, however, the arms a and b which equal $P-M$ and $S-M$, respectively, do not appear as small impedances. For instance, if P is larger than S, $P-M$ will be a large positive impedance and $S-M$ will be a large negative impedance and the T network has no decided advantage, from a mathematical standpoint over the ordinary transformer network.

Figure 3 shows a transformer operating between the sending end impedance Z_1 and receiving end impedance Z_2. Z_2 may be considered less than Z_1. The actual sending and receiving circuits in telephone work are usually quite complex, each consisting of numerous series and shunt elements. According to Thévenins theorem[5] any electromotive force acting through any circuit no matter how complex will produce the same current in any receiving impedance as will some other electromotive force bearing a definite relation to the first electromotive force and acting directly in series with the impedance which would be obtained by a measurement of the circuit looking away from the terminals from which the receiving circuit has been disconnected. From this theorem it may be shown that the complex sending and receiving circuits may be replaced respectively by simple series impedances Z_1 and Z_2 which are the impedances of the complex sending and receiving circuits looking away from the place where it is desired to join them, and a transformer or any other structure studied between these impedances will act identically as if connected between the more complex actual circuits.

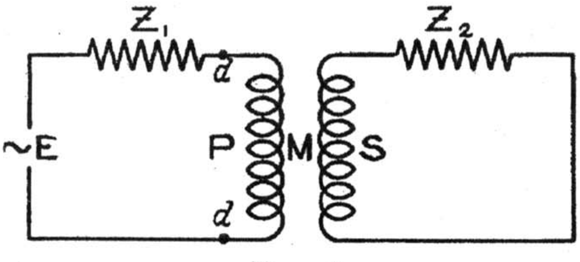

Figure 3

If the transformer shown in Figure 3 were the ideal transformer to connect the circuit impedances Z_1 and Z_2, the best impedance ratio could be found as follows: The current received through the impedance Z_2 is

$$I = \frac{E\,M}{(Z_1 + P)\,(Z_2 + S) - M^2}$$

But since in the ideal transformer P, S and M are infinite pure reactances and the coupling factor is unity and $M = \sqrt{P\,S}$

$$I = \frac{E\,M}{Z_1\,S + Z_2\,P}$$

This expression may be shown to be a maximum when the ratio P/S is equal to the absolute magnitude of $Z_1 \,/\, Z_2$.

A transformer designed for the circuit of Figure 3 should, therefore, have an impedance ratio $R = P/S = Z_1/Z_2$. With an ideal transformer of such a ratio the impedance at d, d looking toward the receiving end with the sending end open at d, d will equal Z_1. Such an impedance characteristic as measured with an actual inequality ratio transformer having an impedance ratio of 1:2.66 and a receiving end impedance Z_2 of 2000 ohms non-inductive resist-

[5] Comptes Rendus for 1883, Vol. XCVII, page 159.

ance is shown as $R+jX$ in Figure 4. The corresponding characteristic for an ideal transformer of the same ratio is shown as R^1. These characteristics show that an actual transformer in transforming or modifying the circuit impedance adds both a resistance and a reactance component to the value of the circuit impedance divided by the transformer impedance ratio except at low frequencies where the transformer has a considerable shunting effect on the circuit impedance as explained later on, and where the resistance falls below the value obtained with an ideal transformer and the reactance is increased over its value at higher frequencies.

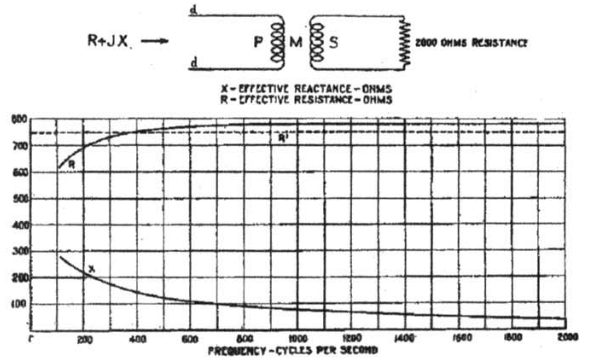

Figure 4—Impedance Measured at *d-d* Ratio of Impedances P:S = 1:2.66

It may be stated that under certain circuit conditions it is quite important that the transformer give a transformation of the circuit impedance which is nearly ideal in order to limit the impedance irregularity introduced in the line.

For analysis or design work involving inequality ratio transformers the circuit of Figure 3 may be reduced to a circuit in which the impedances Z_1 and Z_2 have the same absolute magnitude and the equivalent T network of the transformer may be reduced to an equivalent T of an equivalent unity ratio transformer. In this way the disadvantages of the equivalent T network of the inequality ratio transformer are avoided. This transformation is made by multiplying the circuit impedance Z_2 and the secondary impedance S by the impedance ratio R and multiplying the mutual impedance M of the transformer by $\sqrt{R}$ as shown in Figure 5. As $P_0 = M\sqrt{R}\,/\,K$, $P - M\sqrt{R}$ will be a small positive quantity, and as $S_0 = M/K\sqrt{R}$, $SR - M\sqrt{R}$ will be a small positive quantity. $M\sqrt{R}$ will be a large positive quantity. This treatment of the transformer presupposes that P_0 and S_0 have the same phase angle. This is not necessarily precise in the case of all transformers but will hold with sufficient accuracy for the usual type of iron core transformers.

The series arms a and b and the shunt arm c of the equivalent unity ratio T network consist respectively of the d-c. resistances of the primary and secondary plus the leakage impedance, and the mutual impedance, all reduced to terms of the sending end impedance Z_1. In this transformation a circuit such as is shown in Figure 3 is changed to an equivalent circuit as shown in Figure 5. This equivalent circuit gives a received current which is less than the received current of the circuit of Figure 3 by the factor $I\,/\sqrt{R}$ but the received power is the same in each case. This equivalent T of the equivalent unity ratio transformer consisting of relatively small impedances in series with the circuit and a relatively high impedance as a shunt across the circuit, furnishes an easy means of studying the losses produced by a transformer.

The telephone engineer as well as the power engineer is concerned with the delivery of power. In power work the efficiency of a device is usually expressed in per cent as the ratio of the power delivered to the power supplied or the watts output divided by the watts input. In telephone work it is customary to consider the losses caused by the device rather than its efficiency. These losses are determined by the change in received power caused by the insertion of the device in the circuit. They are expressed in terms of the attenuation of a length (in miles) of standard cable (*M. S. C.*). This unit is such that if two currents I_1 and I_2 flow through the same impedance (load) delivering powers W_1 and W_2 respectively, the number of miles corresponding to the current or power ratios is given by the relation $MSC = 21.12 \log_{10} I_1\,/\,I_2 = 10.56 \log_{10} W_1\,/\,W_2$. It can be shown from the above that for small losses a change in current ratio of 1 per cent corresponds approximately to 0.1 mile of standard cable.

In inserting an ideal transformer of best ratio between two circuits of different impedance an increased current is obtained through the receiving end impedance and a transmission gain is effected. If an actual transformer were used in place of the ideal transformer a somewhat lesser gain would usually be obtained due to the losses of the transformer. The transformer loss is determined by the ratio of the received current with the transformer in circuit to the received current with the ideal transformer in circuit.

It is to be noted that the above mentioned ratio of received currents which is used as the basis of the transmission loss of the telephone transformer takes no account of the phase angle of the load impedance and bears no direct relation to the ratio of the power output to the power input. There is, therefore, no very simple relation between the miles loss and the power efficiency. For example, a telephone transformer might have equally low losses when operating into a pure reactance as when operating into a resistance, whereas, the power efficiency approaches zero when the phase angle of the load approaches 90 deg. When operating into a resistance load the current ratio of the telephone transformer approaches the square root of the power efficiency for very efficient transformers.

TRANSFORMER OPERATING BETWEEN RESISTANCES

From the circuit of Figure 5, it can easily be seen that provided the circuit impedances approximate resistances, the smaller $P - M\sqrt{R}$ and $SR - M\sqrt{R}$ are and the larger $M\sqrt{R}$ is, the smaller will be the loss caused by the transformer. The speech current used in most telephone circuits is so minute that the permeability of the transformer cores remains at approximately its initial value regardless of what winding is placed on the transformer. An increase in the mutual impedance will lower the shunt losses, but will also cause an increase in the series losses, as there will be an increase in the d-c. resistance and the leakage impedance in practically the same ratio as the increase in the mutual impedance. If the capacity in the transformer windings is neglected, it will be noted that both the series and shunt arms of the transformer T contain components of impedances which increase with the frequency and that at zero frequency the shunt loss will be infinitely great and at infinite frequency the series loss will be infinitely great while at intermediate frequencies these losses will be finite. It is, therefore, evident that for a given transformer there will be some frequency at which the transformer operates with minimum losses, and that for operation at a given frequency there is a value of mutual impedance for any given transformer structure at which the losses are a minimum.

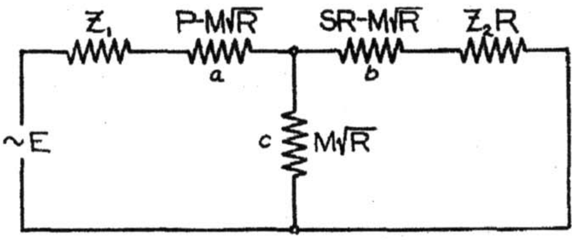

Figure 5

The transformer of Figure 5 when operating between non-inductive resistance impedances will produce a loss-frequency characteristic, as shown in Figure 6, in which the various curves are for a fixed circuit condition and for several different windings or values of mutual impedance. In these characteristics the d-c. resistance of the winding produces a loss which is practically independent of frequency. There is an increase in loss at the lower part of the frequency range due to the increased shunting effect of $M\sqrt{R}$ at the lower frequencies. This loss decreases as the frequency increases. Although in any actual case the departure of the angle of $M\sqrt{R}$

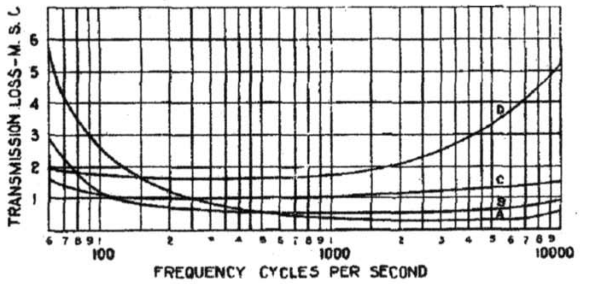

Figure 6—Transformer Operating Between Resistances

Sending end resistance 6000 ohms
Receiving end resistance 2000 ohms

Transformer	$\frac{M\sqrt{R}}{Z_1}$ at 1000 cycles
A	5
B	10
C	20
D	40

from 90 deg. may cause an appreciable part of the shunting loss it is usually possible to obtain greater reduction in loss by increasing the absolute magnitude of this impedance than by increasing the phase angle. If the transformer has sufficient capacity in and between the windings to affect appreciably this impedance, it may also affect the loss due to it. In some transformers, the effective capacity may be large enough to cause resonance within the frequency range which is transmitted efficiently. This would cause $M\sqrt{R}$ to have a maximum value at the resonance frequency, and the loss due to the shunt arm would go through a minimum value at this frequency. If the capacity is large enough to produce this resonance near the lower end of the transmitted frequency range, its effect at the higher frequencies in decreasing the magnitude of $M\sqrt{R}$ might be sufficient to cause an appreciable loss at these frequencies.

The magnitude of the leakage impedances, which, together with the d-c. resistance, make up the series arms of the *T*, also tends to increase the loss at the upper frequencies, as this impedance increases with the frequency. In cases where both the leakage and the capacity are high, the effect of one may to some extent tend to lessen the loss produced by the other at some frequencies.

It is to be noted that as the leakage impedance generally consists of a larger reactance than effective resistance, this impedance has far less effect in determining the value of received current through Z_2 when the circuit impedances are resistances than does the d-c. resistance.

In the design of telephone transformers to operate with little distortion between resistance impedances, it follows that the transformer impedance ratio is determined as the ratio of the circuit impedances between which the transformer operates, the loss at the lower frequencies is determined principally by the impedance of the shunt arm of the *T* network, $M\sqrt{R}$, and the loss at the higher frequencies is determined principally by the leakage impedance and the effective capacity. The d-c. resistance adds a loss which is practically constant over the frequency range.

The determination of the windings of such a transformer would be made as follows, assuming for the present that the transformer construction has already been decided upon. The impedance ratio of the transformer is calculated as the ratio of the circuit impedances. Using this ratio, the winding is calculated, choosing such sizes of wire as will make the ratio of d-c. resistance of primary and secondary the same as the impedance ratio, and will completely fill the winding space with an allowance for commercial variations in the winding space, dimensions, wire diameter, winding and insulation. As the transformer dimensions and core permeability (initial or low magnetic density value) are known, the inductance for a given number of turns may be calculated as proportional to the square of the turns or from a trial winding the relation between impedance and number of turns may be obtained. The coupling factor and effective capacity are best obtained by a trial design using the arrangement of winding which is expected to be used in the final design. All the information for determining equivalent *T* networks is thus available.

The loss curves for different values of mutual impedance may be predetermined from these equivalent networks and the desired winding chosen from these characteristics. Such a series of curves for a transformer operating between resistance impedances is shown in Figure 6. In the table in this figure is shown the ratio of the shunt arm, $M\sqrt{R}$, of the equivalent *T* network of the equivalent unity ratio transformer at 1000 cycles, to the sending end impedance Z_1.

Figure 7 shows the transmission loss characteristic of a phantom circuit repeating coil operating between non-inductive resistance lines of 1830 ohms. The mutual impedance-frequency characteristic of this repeating coil was shown in Figure 2 from which it may be noted that the

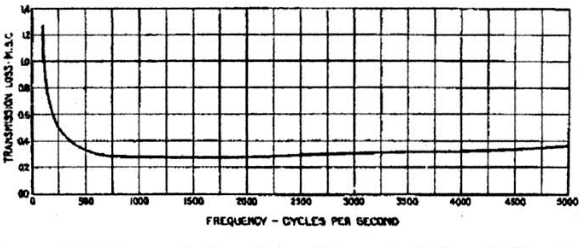

Figure 7—Transmission Loss Characteristic of Phantom Circuit Repeating Coil Operating Between 1830-ohm Resistance Lines

reactance component of this impedance is negative above a frequency of 1700 cycles per second. Although above this frequency the mutual impedance decreases, its magnitude is so great as compared with that of the line impedance that the loss due to it is practically negligible at a frequency of 5000 cycles per second.

TRANSFORMER OPERATING BETWEEN A RESISTANCE AND A POSITIVE REACTANCE

The case of a transformer operating into a pure positive reactance is, of course, hypothetical and no energy would be delivered unless the reactance had a resistance associated with it. In any actual case, there is always a resistance component to this impedance, but for this discussion it is assumed that the resistance component is practically zero.

In this circuit condition we have one impedance which is independent of the frequency and another which is directly proportional to the frequency. By properly choosing the transformer ratio it is possible to match the circuit impedances at any particular frequency and deliver maximum energy at this frequency. At other frequencies there would be a transmission loss due to this failure to match impedances, and it follows that even with an ideal transformer, it is not possible to obtain uniform efficiency over a range of frequency, and that by selecting the proper ratio, maximum efficiency may be obtained at any desired frequency.

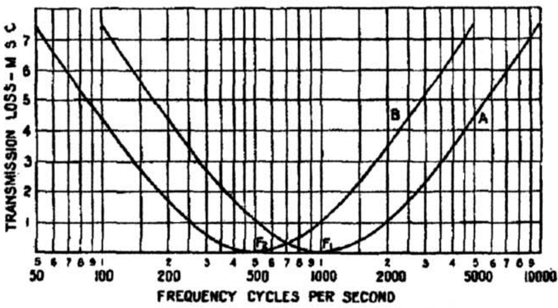

Figure 8—Transformer Connecting a Resistance to a Positive Resistance

"A" and "B" ideal transformers of Impedance ratio R/X at frequency "F_1" and "F_2" respectively.

Figure 8, curve A, shows the transmission loss, in miles due to the introduction of an ideal transformer of fixed ratio between the sending end resistance Z_1 and the receiving end reactance Z_2. This transformer serves to match these impedances at the frequency F_1 and the curve shows the loss above what would be obtained if the impedances were matched at any other frequency. Curve B is a similar characteristic for an ideal transformer, matching impedances at frequency F_2.

Figure 5 may be considered to represent the equivalent unity ratio circuit (Z_2 being less than Z_1) with the T network of the equivalent unity ratio transformer in the circuit. If, for the present the effect of capacity in the mutual impedance is neglected, the losses produced by the components of the series arms of the transformer operating under these circuit conditions, that is the d-c. resistance and the leakage reactance, are approximately of equal importance.

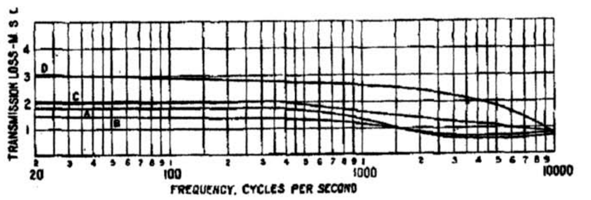

Figure 9—Transformers Operating Between a Resistance and a Positive Reactance

Transmission loss above that of an ideal transformer of the same ratio. Sending end impedance $Z_1 = 6000$ ohms.

Receiving end impedance $Z_2 = (R + jL)\,\omega$ ohms $= 20 + j\,2000$ ohms at 1000 cycles.

Transformer impedance ratio = 3:1

Transformer	$\dfrac{M\sqrt{R}}{Z_1}$ at 1000 cycles
A	5
B	10
C	20
D	40

The d-c. resistance causes a loss which is finite at low frequencies and decreases to zero at infinite frequency while the leakage reactance causes a loss which is finite at infinite frequency and reduces to zero at zero frequency. The mutual impedance produces a loss which is infinite at zero frequency and decreases to a relatively small finite value at infinite frequency.

If the mutual impedance contains a capacity component, a reduction of loss may be produced at certain frequencies due to resonance of the capacity reactance with the mutual, leakage and receiving end reactances. This may even give a gain over the characteristic of the ideal transformer for a limited frequency range, but above the resonant frequency an increased loss is produced which approaches infinity.

Characteristics A, B, C and D of Figure 9 show measurements of actual transformers having different values of mutual impedance and the proper ratio to match impedances at 1000 cycles. The transmission losses shown are the losses of the actual transformers compared with the corresponding ideal transformer of the same ratio. The ideal transformer, itself, has a loss characteristic causing distortion which varies with the frequency as shown in Figure 8. The ratio of $M\sqrt{R}:Z_1$ at 1000 cycles is shown in the table. These transformers are the same as those shown in Figure 6 as operating between resistances. The losses at the upper frequencies are reduced somewhat by the winding capacity. It may be noticed that of the transformers whose characteristics are shown in Figure 9, transformer *B* introduces minimum loss.

In designing a transformer to connect a resistance to a positive reactance, the impedance ratio of the transformer is determined as the ratio of the circuit impedances at the frequency at which it is desired to deliver maximum power. The choice of best mutual impedance may be made by assuming windings of different impedance and predetermining their loss characteristics as has been described under transformers working between resistances.

TRANSFORMER OPERATING BETWEEN A RESISTANCE AND A NEGATIVE REACTANCE

Where a transformer operates between a resistance and a negative reactance, a condition exists where one impedance is independent of and the other is a function of the frequency, although in this case the reactance varies inversely with the frequency. Here again in order to deliver power it is necessary to assume that the receiving end impedance has a small resistance component. The transformer ratio may be made to match these impedances at any frequency, delivering maximum energy, but causing an increasing loss above and below this frequency. The loss characteristic of such a transformer is shown in Figure 10 which gives the increase in transmission loss of the ideal transformer of fixed ratio over the ideal transformer of the actual ratio of the circuit impedances at all frequencies.

Referring to Figure 5 and considering Z_2 a negative reactance, there are two frequencies at which resonance takes place. At the first frequency parallel resonance occurs between the impedance $M\sqrt{R}$ and $Z_2 R$ and at the second, series resonance occurs between the leakage reactance components of $P - M\sqrt{R}$ and $S R - M\sqrt{R}$ and the receiving circuit impedance $Z_2 R$. The d-c. resistance causes a loss which, in general, is finite at zero frequency and becomes zero at infinite frequency. The leakage reactance produces a loss which, in general, increases from zero at zero frequency to infinity at infinite frequency going through a minimum, however, and in some cases causing a gain over the ideal transformer at the second resonance frequency. The mutual impedance, in general, produces a loss which decreases from infinity at zero frequency to a finite value at infinite frequency going through a minimum, however, at the first resonance frequency and possibly even causing a gain over the ideal transformer at this frequency.

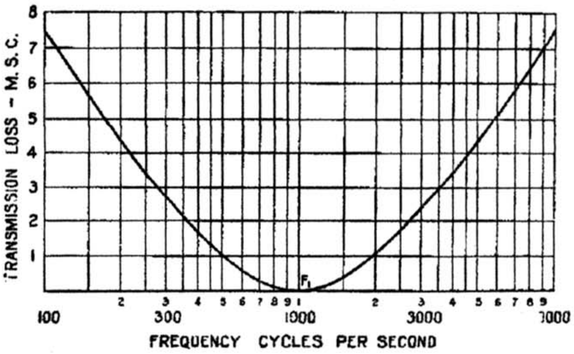

Figure 10—Transformer Connecting a Resistance to a Negative Reactance

Ideal transformer of impedance ratio R/X at frequency "F_1" = 1000 cycles

INPUT TRANSFORMER

The usual case of a transformer operating under these circuit conditions is the input transformer of the vacuum tube amplifier, the vacuum tube approximating a condenser in its grid-filament impedance.

With the receiving end impedance an ordinary capacity of constant phase angle, it is necessary in order to deliver uniform power over a range of frequency to match impedances at all frequencies or supply a voltage which decreases inversely as the square root of the frequency. In a vacuum tube amplifier, when the output or plate-filament current is proportional to the input or grid-filament voltage, uniform output power will be delivered at varying frequency provided the input voltage is kept constant. When operating into a vacuum tube, therefore, it is not required to match the circuit impedances at all frequencies to limit distortion. An ideal input transformer of fixed ratio will tend to cause the vacuum tube to deliver uniform power over a range of frequency but only throughout that part of the frequency range in which it can maintain constant voltage across the grid-filament impedance.

The receiving end circuit impedance Z_2 is usually larger than Z_1. The equivalent unity ratio circuit and the equivalent T network of the equivalent unity ratio transformer are, therefore, obtained by dividing S and Z_2 by R and M by $\sqrt{R}$ instead of multiplying as in Figure 5. Such an equivalent unity ratio circuit is shown in Figure 11.

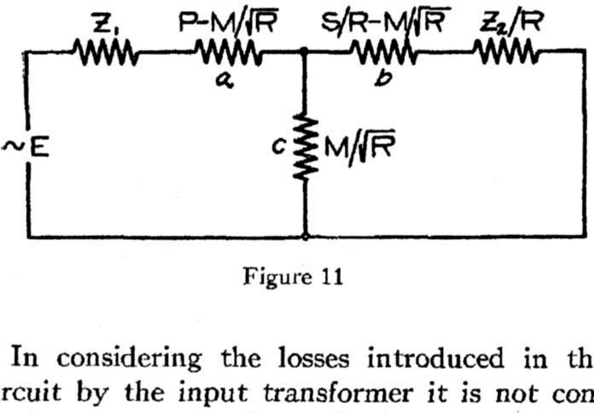

Figure 11

In considering the losses introduced in the circuit by the input transformer it is not convenient to compare the received current through the actual transformer with that of the ideal transformer of either variable or fixed ratio as neither ideal transformer delivers uniform input voltage to the vacuum tube at all frequencies or causes the amplifier to deliver uniform power. A more satisfactory basis of comparison, particularly for input transformers of different ratios which are intended for the same circuit conditions, is obtained by comparing the ratio of the potential produced across the grid-filament impedance Z_2 (see Figure 3) to the potential E impressed on the circuit. This ratio gives the amount of effective amplification produced in the amplifier by the input transformer.

The losses of the input transformer have the same general frequency variations as the losses of the transformer operating into an ordinary negative reactance except that at the first resonance frequency the losses produced by the mutual impedance $M / \sqrt{R}$ of the input transformer may be zero but never negative. It is to be noted that the d-c. resistance of the secondary produces zero loss at zero frequency while the loss due to the d-c. resistance of the primary is finite.

Input transformers designed for audio frequencies operate into the high negative reactance of the vacuum tube and therefore the secondary and mutual impedances are necessarily of large magnitude. The capacity of the transformer windings under these conditions becomes of considerable importance and even when limited by careful design usually causes parallel resonance in the arm c of the transformer network in the transmitted frequency range. The same is the case with input transformers designed for carrier frequency operation although the impedances involved are usually not so large. Above this resonant frequency both the arm c and the impedance Z_2/R are negative reactances and their impedances tend to be annulled by the leakage reactance of the arms a and b. The combined effect of the leakage reactances of these arms produces resonance with the transformer and tube capacities which may increase the transformer amplification characteristic even above the value given by the ratio of secondary to primary turns.

Amplification characteristics produced by transformers of different ratio operating from a sending end impedance of 20,000 ohms into a 216-A vacuum tube are shown in Figure 12. It will be noted that as the impedance ratio of the transformer is lowered, the amplification characteristic flattens out and the frequency distortion is reduced. In the characteristics of some of the lower ratio transformers, a gain in amplification above the ratio of turns of the transformer may be noted at the higher frequencies.

It is to be noted that in the circuit of Figure 11, a and b are positive reactances while at the high frequencies c and Z_2 / R are negative reactances and the circuit approximates a low pass filter. As a filter, it has a cut-off frequency above which it tends to limit transmission and the amplification characteristic falls off quite rapidly.

The d-c. resistance of the primary is of more importance than the d-c. resistance of the secondary. In the well-proportioned input transformer, the value of the arm *c* particularly at the resonance frequency becomes very large as compared with the sum of the impedance Z_1 and the impedance of the arm *a* and at these frequencies the transformer gives practically the amplification represented by the ratio of secondary to primary turns. However, at the lower frequency range, where the impedance of the arm *c* becomes more nearly equal to the sum of the impedances of Z_1 and the arm *a*, the d-c. resistance of the primary produces a loss in amplification. The d-c. resistance of the primary is, therefore, a factor in the distortion at the lower frequencies.

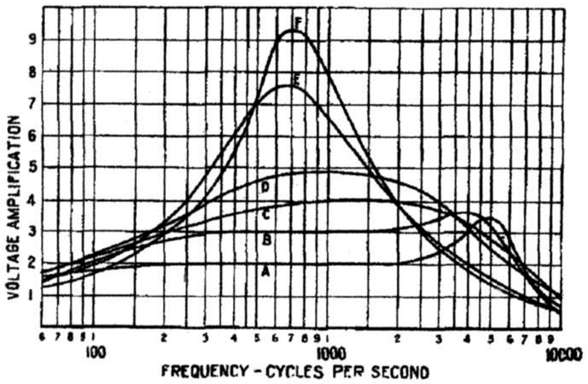

Figure 12—Voltage Amplification Characteristics of Input Transformers of Various Turns Ratios Operating from 20,000 Ohms Resistance into a 216-A Vacuum Tube

Coils	Turns Ratio
A	1:2
B	1:3
C	1:4
D	1:5
E	1:8
F	1:10

For the rapid analysis of an input transformer, it is customary to consider the d-c. resistance of *P* as added directly to Z_1 to form Z_0; to consider the total leakage reactance, $+jX_L$, located entirely in the arm *a*; to neglect the d-c. resistance of *S*; to combine the capacity of the vacuum tube and effective capacity of the transformer as determined as located across *S* to form the reactance $-jX_c$ and to consider the mutual impedance *M* as the impedance due to the transformer windings exclusive of capacity. Such a circuit as shown in Figure 13, approximates the actual circuit conditions quite closely in the ordinary case and is useful in design work.

For an audio-frequency input transformer of a given ratio, the losses or the departure from full amplification depend at low frequencies, principally on the value of the mutual impedance, while at high frequencies the effective capacity of the tube plus that of the transformer has a considerable influence. As the mutual impedance is a function of the number of turns, while the capacity is practically independent of the number of turns, it follows that, in general, for an input transformer operating over a wide band of frequencies, the higher the mutual impedance, the wider will be the transmitted frequency band.

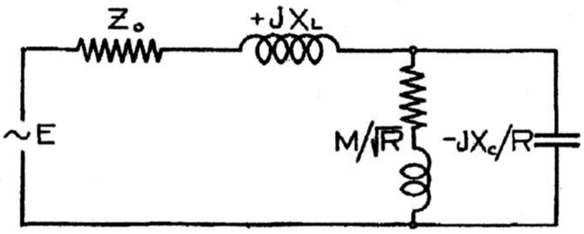

Figure 13

Figure 14 shows the variation in amplification obtained with input transformers of the same ratio but of different mutual impedances operating between a resistance of 15,000 ohms and a 216-A vacuum tube. It will be noted that as the mutual impedance is increased the width of the transmitted frequency band is increased and the mid-band frequency is lowered. The upper slope of the frequency characteristic is determined principally by the leakage reactance of the transformer and the transformer and vacuum tube capacities. In transformer *C* the leakage reactance is so proportioned that resonance with

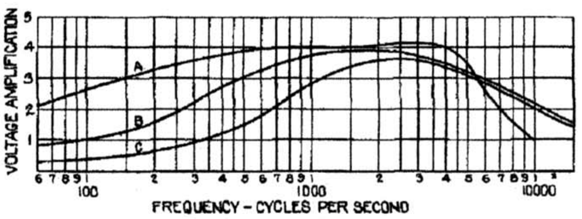

Figure 14—Voltage Amplification of Input Transformers of Different Mutual Impedances

Impedance ratio of 1:16 and operating from 15,000 ohms resistance into a 216-A vacuum tube

Transformer	Ratio $\frac{M\sqrt{R}}{15,000}$ at 1000 cycles
A	1:1
B	1:4
C	1:10

this capacity extends the flat portion of the amplification characteristic upward in the frequency range. The lower slope of the characteristic is determined principally by the mutual impedance of the transformer.

This advantage of high mutual impedance explains the use of No. 40 and No. 44 A. w. g. enameled wire for the secondaries in most audio frequency input transformers, as giving the highest impedance secondary windings that can be commercially applied with different methods of winding. With the gage of wire and the secondary impedance thus determined, the possible amplification characteristic will depend on the transformer ratio. With a number of predetermined characteristics of different ratio transformers prepared as shown in Figure 12, the required windings for the input transformer may be determined to give a desirable compromise between the amplification and the transmission distortion permissible.

From the standpoint of minimum distortion, it should be mentioned that it is desirable to use vacuum tubes of low plate-filament impedance in the amplifier, particularly if this can be done without sacrificing the tube amplification factor. The effect on the input transformer characteristic of operating it from tubes of different plate circuit impedance is shown in Figure 15.

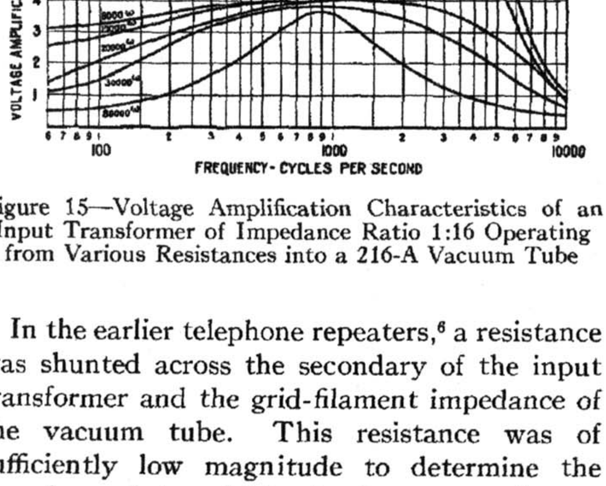

Figure 15—Voltage Amplification Characteristics of an Input Transformer of Impedance Ratio 1:16 Operating from Various Resistances into a 216-A Vacuum Tube

In the earlier telephone repeaters,[6] a resistance was shunted across the secondary of the input transformer and the grid-filament impedance of the vacuum tube. This resistance was of sufficiently low magnitude to determine the impedance into which the input transformer operated and the transformer was given the proper impedance ratio to match this impedance with the impedance from which the transformer was operated. This resistance served to aid in obtaining a flat amplification characteristic and to fix the impedance measured on the primary of the transformer with the secondary connected in circuit. An impedance characteristic was produced as shown in Figure 4 instead of the characteristic of the type shown in Figure 2, which represents simply a transformer with appreciable effective capacity in the windings. Later on an improvement was made by shunting the primary of the input transformer with a resistance of a value equal to the resistance formerly used across the secondary divided by the transformer impedance ratio. It will be noted that in the first case, the transformer operates into a circuit which is principally a resistance while in the second case, it operates into a capacity. Measured amplification characteristics of an input transformer operating under both circuit conditions are shown in Figure 16 which gives, in addition, the characteristic of an input transformer of the same size and construction designed to give the same value of amplification as in the first two cases but without the shunting resistance. The superiority of the latter type of circuit in giving a uniform amplification characteristic is easily seen. This last circuit connection does not have an input impedance characteristic which is practically independent of frequency and it is, therefore, more limited in its uses.

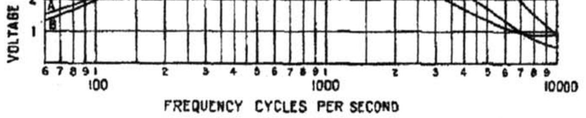

Figure 16—Voltage Amplification of Input Transformers Under Different Circuit Conditions

Curve	Transformer Impedance Ratio	Resistance Across Low Side	Resistance Across High Side
A	1:64	∞	64 × 15,000
B	1:64	15,000	∞
C	1:16	∞	∞

TRANSFORMER CONSTRUCTION

The type of transformer most used in the telephone plant is a toroidal core transformer

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[6] Gherardi and Jewett: "Telephone Repeaters," TRANS. A. I. E. E., Vol. XXXVIII, part 2, page 1287.

usually called a repeating coil. This type of transformer has a ring-shaped core of soft magnetic iron wire or silicon steel laminations completely covered with the primary winding over which is applied the secondary winding. Such a transformer, when the dimensions are properly proportioned and the winding is applied so as practically to fill the central hole in the core, is a very efficient structure. The symmetrical distribution of winding limits the stray field, thus preventing cross-talk trouble in neighboring circuits. The cost of winding has been reduced to a low value by the development of a winding machine in which a circular shuttle threading through the center of the core is used to hold the wire which is wound on the core by a motor-driven annular part of the machine. The windings are accessible and permit of easy adjustment. This type of transformer is used in telephone installations where the impedances of the circuits in which the transformer is operated are less than 20,000 ohms and where the frequency is relatively low. The usual type of mounting of two repeating coils on a common base is shown in Figure 17. The case has been removed from the front coil to show the construction.

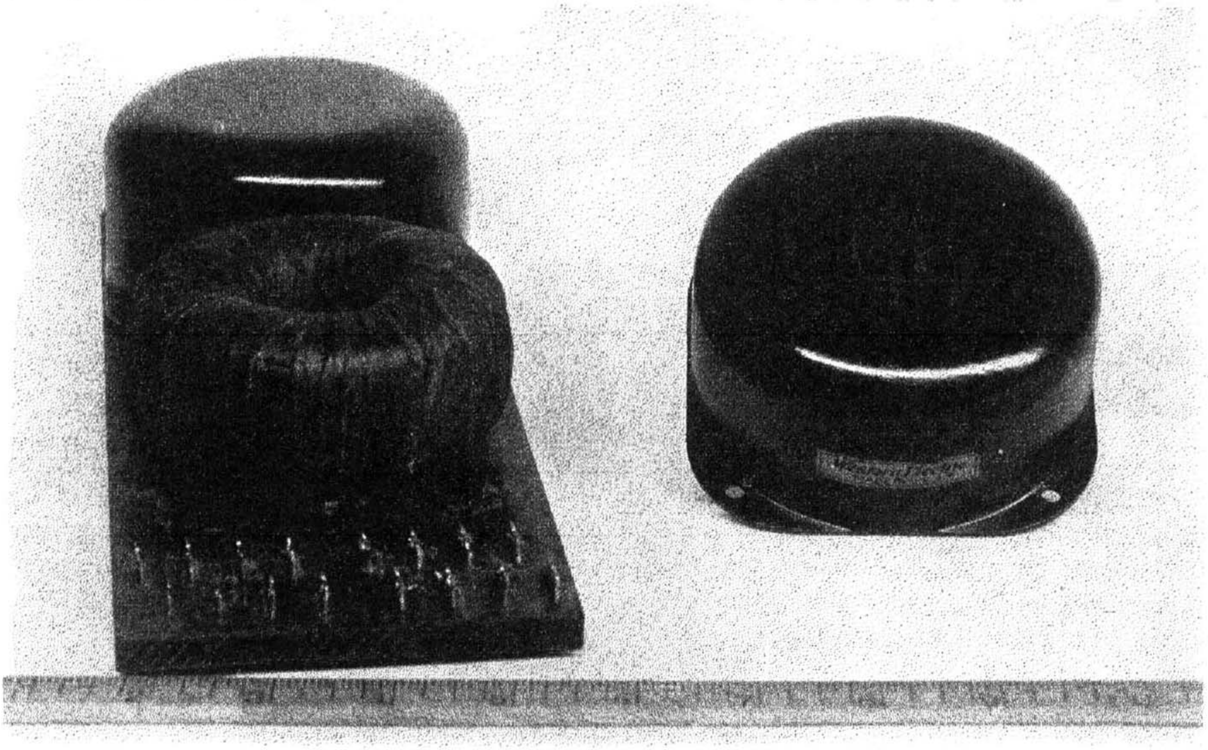

Figure 17—Toroidal Repeating Coil

The telephone induction coil used in all subscribers sets is an open magnetic circuit core type transformer. The impedance and frequency requirements of the circuit in which this form of transformer is used are not severe and the value of the transmission is relatively low due to the fact that any one transformer is used a relatively small part of the time and only for conversations from a single station. This, together with the fact that the transformer must be designed to operate with direct current through the windings and stray magnetic field is of no particular disadvantage permits the use of this relatively inefficient type of transformer shown in Figure 18. It is to be noted that in this transformer the winding is located about the center portion of the core only as in this location the highest ratio of inductance to d-c. resistance is obtained giving maximum efficiency.

For portable test sets, considerably lighter and smaller types of transformer than are generally used in the telephone plant are required. Transformer *A* of Figure 19 shows the type of transformer used in sets such as the S. C. R. 72 amplifier developed for the Signal Corps of the United States Army. This amplifier set was intended to operate on 1000-cycle telegraph signals transmitted through the ground. The transformers used in this set were required to operate efficiently only in the neighborhood of 1000 cycles and transmission at other frequencies was sacrificed to obtain maximum amplification at this frequency. An amplification characteristic of the input transformer of this set is given in Figure 20. This type of transformer was widely used in both Signal Corps and Navy radio transmitting and receiving sets throughout the war and weighed about two pounds.

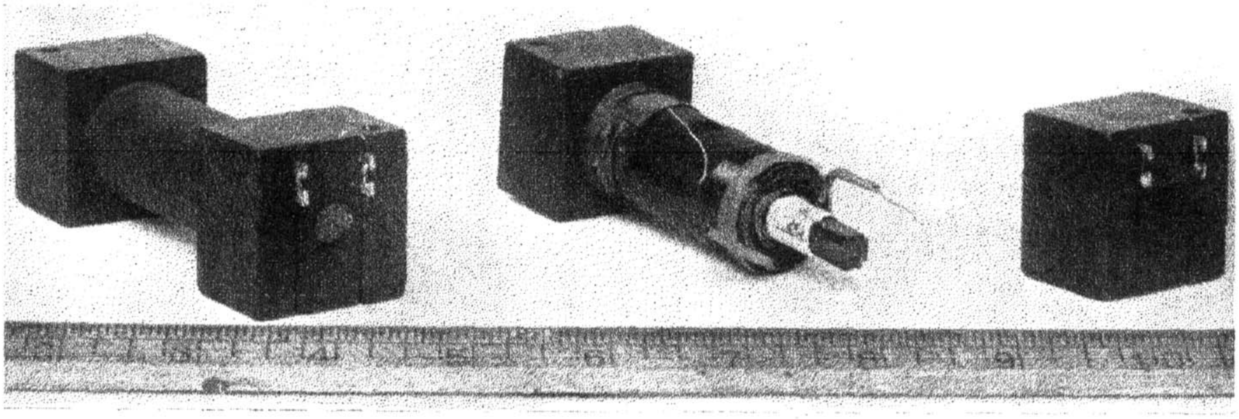

Figure 18—Telephone Induction Coil

The type of transformer shown as *B* in Figure 19 is also of shell type construction and is used in portable telephone field test sets and weighs 12 ounces.

One of the latest designs of shell type transformer and the one which was used for most of the experimental characteristics given herein is shown in Figure 21. The construction of this input transformer, the No. 224 type, is such that winding and assembly can be readily accomplished and repair easily effected if necessary. The winding space and the core have been proportioned to obtain minimum cost of manufacture. The core consists of *I* and *E* shape laminations riveted together to form an *I* and *E* part which butt together forming the core.

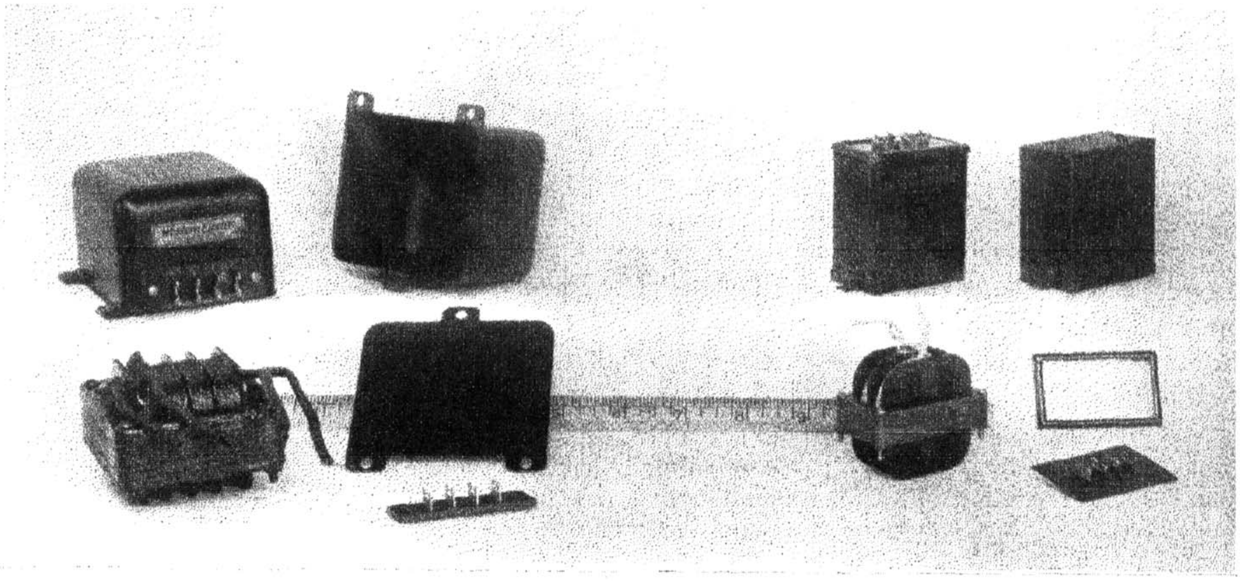

Figure 19—Shell Type Transformers

The winding is placed on a spool which fits over the central limb of the *E*. The two core parts are held together by means of two brackets which are held in place by four machine screws. The terminals are arranged on insulated mounting plates held under the screws of the mounting bracket and serving as mechanical protection to the lead wires.

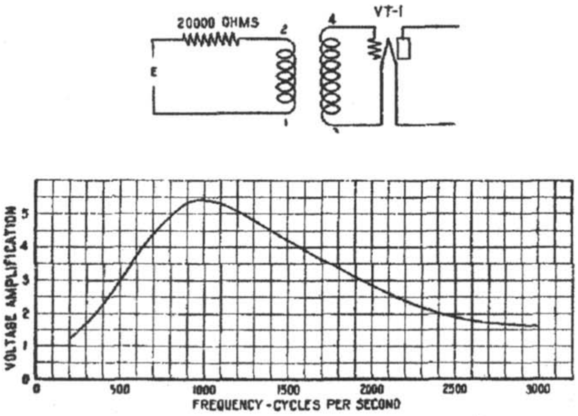

Figure 20—Amplification Characteristic, 201-A Input Transformer

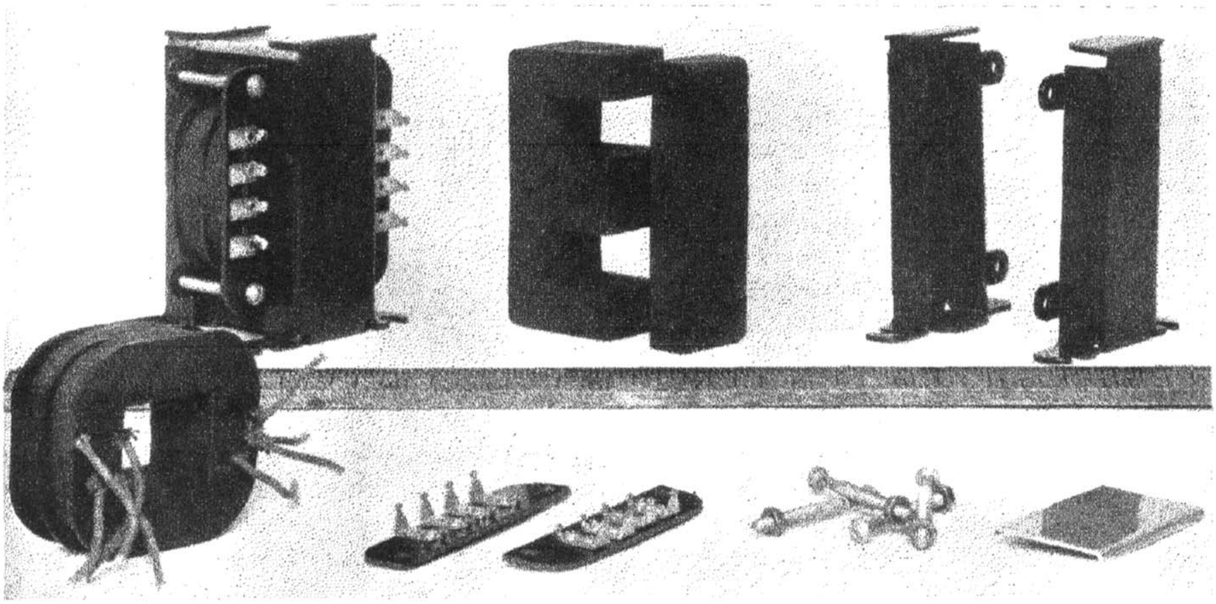

Figure 21—224-Type Input Transformer

It may be noted that whereas the form of toroidal repeating coils is core type, that of the transformers employing spool windings is shell type. The core type is used for the toroidal repeating coils as it permits ready adjustment of the windings and the shell type is used in the transformer having spool windings as it permits the use of a winding of small effective capacity.

The size of the transformer is governed by three factors, the amount of space available, the cost permissible and the ratio of inductance d-c. resistance which is required to give the desired freedom from transmission loss.

In the windings of telephone transformers, cotton or cotton and enamel is used for the insulation of the heavier gages of wire while for the smaller gages, enamel or enamel and silk is used. The gage sizes used range from No. 18 A. w. g. or heavier to No. 44. In input transformers, the d-c. resistance of the secondary winding usually causes an inappreciable loss and it is, therefore, desirable to have it take up as little space as possible and the smallest size of wire which can be used with the different commercial methods of winding is employed. The quality of the enamel insulation generally used for this winding is a determining factor in the minimum size of winding which can be used. With the best enamel, it is possible to wind No. 40 A. w. g. wire with little or no interleaving paper and with little special machinery, and have the resulting windings reasonably free from short circuits. However, with inferior enamel, it is necessary to use a covering of silk in addition to the enamel, or to use interleaving paper between each two layers of the winding. This extra insulation, needless to say, causes a considerable increase in the space taken up by the winding, which is undesirable.

In transformers in which the effective capacity is an important factor, it is frequently necessary to apply the winding in such a way as to reduce the capacity to a minimum. The effective capacity depends on the size of the transformer winding, more care being required to reduce it to a reasonable value in a large than in a small transformer. The capacity of the winding may be conveniently considered as composed of four parts, part one being the sum of the capacities between each two adjacent turns all connected in series from one terminal of the winding to the other, part two the sum of the capacities between adjacent layers in series, part three the capacities between adjacent winding sections in series and part four due to the capacities between the winding and any other metal or other windings in the neighborhood. These capacities may be considered in effective values as connected across the winding terminals. Of these component capacities, the first may usually be neglected entirely, as it consists of a large number of small capacities in series, this number being only slightly less than the total number of turns. The fourth part is usually the most important as it seldom consists of more than two capacities in series. The second and third parts of the effective capacity are of importance depending on the number of sections and layers and the capacity between adjacent ones. In high ratio transformers, it is usually sufficiently accurate to consider the lower impedance winding as an equi-potential plate and to consider the capacities with regard to the high impedance winding only.

The effect of inter-winding capacities in affecting transmission is given in Figure 22. This figure shows how sometimes these capacities may be connected between approximately equal potential points in the circuit and thus lessen the effective capacity of the winding. The transformer on which these characteristics were taken is the same as that shown in Figures 19 and 20. Characteristic *A* represents the normal connection of windings with the interwinding capacity *C* located between the parts of the circuit *a* and *e* in which it is effectively across one half the impedance of the primary, 1-2. Characteristic *B* shows the amplification obtained with the secondary winding, 3-4, reversed, terminal 3 being connected to the grid of the vacuum tube instead of the filament. In this case the capacity *C* is across the entire secondary impedance in addition to one-half the primary impedance, the combined impedance being approximately 200 times the impedance under the circuit connection *A*. The effect of this inter-winding capacity being connected across points of widely different potential in the circuit in lowering the frequency of the amplification peak is clearly shown.

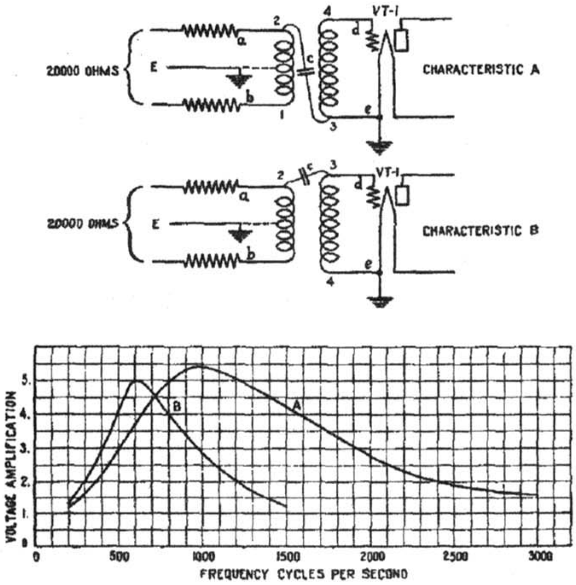

Figure 22—Transformer Amplification Characteristics with Different Winding Connections

Transformers are subjected in service to conditions of temperature and humidity which vary greatly. Conditions in exchanges in the tropics and in certain sets for outdoor use are particularly severe while in some other locations there is but little chance of trouble. Under conditions of humidity electrolytic corrosion will take place provided salts which might form an electrolyte on the addition of moisture are present in the completed windings. Corrosion will be accelerated in circuits in which there is a direct-current potential between some point in the winding and another neighboring metallic part. It frequently causes the windings of the transformer to open-circuit particularly when they are wound with the smaller gages of wire. It is rather difficult to obtain materials which are free from slight amounts of salts and to keep the transformer winding free from them during the operations incident to manufacture. Perspiration from the operator's hands or the use of soldering salts are common causes of corrosion. To reduce this trouble the windings are imbedded in a moisture resisting compound of oils or waxes which is in itself chemically inert. The moisture-proofing process is usually effected under vacuum after a baking period. The advantages of a carefully worked out moisture-proofing treatment in prolonging the useful life of transformers is so great that it has been universally adopted in all carefully designed transformers. In the foregoing, the transformer has been treated from the standpoint of the transmission of telephone currents and those features have been presented which appeared to the writer to be of special interest and usefulness to those interested in its application to this problem. In conclusion, the writer wishes to acknowledge his indebtedness to Mr. Thomas Shaw of the American Telephone and Telegraph Company and to Mr. K. S. Johnson of the Western Electric Company, Inc., with whom he has been associated for a number of years on the general problem of telephone transmission and in the application of the principles described herein.