An Explanation of the Common Battery Anti-sidetone Subscriber Set

By C. O. GIBBON

THE telephone transmitter serves to convert sound waves into their electrical facsimile; but in performing this primary function the transmitter also acts as an amplifier. Under some conditions the electrical power output of a transmitter may be more than a thousand times as great as the acoustic power activating it. Part of this greatly augmented power is dissipated in the circuit of the telephone set; part is impressed upon the telephone line, whence it is propagated on to the distant listener; and part finds its way into the receiver of the same set, where it is reconverted into sound waves. Speech or noise, picked up by the transmitter and reproduced by the receiver of the same set, is called sidetone.

Noise picked up and amplified by the transmitter and heard as sidetone tends to obscure incoming speech, thereby impairing reception. Similarly, the sound of his own voice, heard more loudly than normal as sidetone because of transmitter amplification, impels the talker involuntarily to lower his voice; thus impairing the reception of his speech at the far end of the connection. The consequent desirability of reducing sidetone has long been recognized, and operator and subscriber sets which accomplish this have been developed.

Circuit schematics of the common battery sidetone and anti-sidetone subscriber sets at present standard in the Bell System are shown in Fig. 1. The anti-sidetone set has become increasingly common during the past few years, and because of the improvements in effective transmission which it affords, bids fair ultimately to be well nigh universally employed. It is, therefore, not surprising that numerous requests have arisen for an explanation of this anti-sidetone circuit which may be more easily followed than one based on the methods usually employed in network analysis. The present paper provides an explanation by means of diagrams with a minimum of mathematical treatment which it is believed those to whom the mathematical approach does not appeal will find helpful in picturing the behavior of this circuit.

The explanation given in this paper is, however, confined to idealized conditions. No concern is given to whether the conditions necessary to exact attainment of the balances described are actually feasible;

nor is any attempt made to discuss questions of practical design beyond pointing out something of the nature of the problems involved. Equations for this anti-sidetone circuit are given and discussed in an appendix, and a vector diagram is shown which illustrates graphically relations among the currents and voltages under the ideal condition of exact balances.

Rearrangement of Circuit Patterns

Simplified explanations of anti-sidetone sets are most frequently based upon analogues with balanced arrangements resembling the

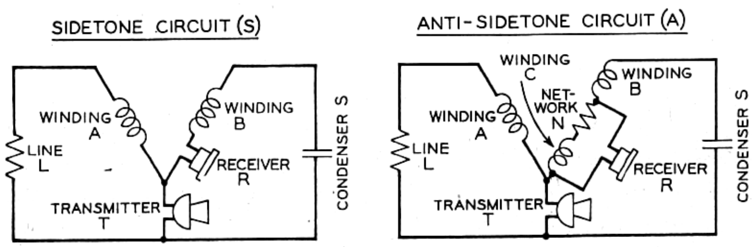


Fig. 1

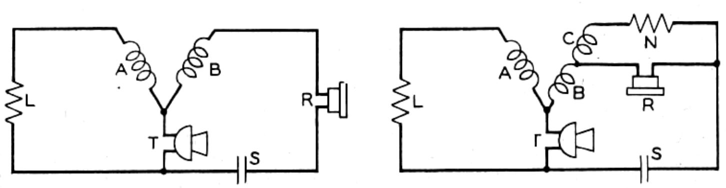


Fig. 2

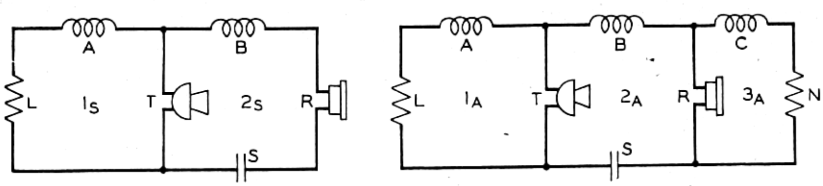


Fig. 3

Group I—Convenient schematic rearrangements

familiar circuit pattern of the Wheatstone bridge, and several such explanations have been devised for the set now to be considered. A wholly different approach will, however, be employed here. The schematics supplementing the present discussion have been arranged in groups to assist in visualizing and coordinating the steps in the explanation. The diagrams of Group I rearrange the familiar conventional schematics of the common battery sidetone and anti-sidetone circuits in Fig. 1 into the patterns most convenient for present purposes.

From the intermediate step in Fig. 2 the circuits in Fig. 3 will be seen to be the same electrically as those in Fig. 1. Inasmuch as its effects upon the features to be discussed are negligible, the ringer branch has been omitted. The circuit meshes in Fig. 3 are numbered for identification, subscripts *S* and *A* suggestively differentiating meshes of the sidetone and anti-sidetone circuits. Mesh currents and e.m.f.'s in all subsequent schematics are correspondingly identified as later described.

Complementary Sidetone Circuit

From Fig. 3 the three-mesh anti-sidetone circuit is seen to differ schematically from the two-mesh sidetone circuit only by having a balancing branch consisting of a third induction coil winding *C* and a network *N* bridged across the receiver to form the third mesh. In this theoretical discussion, *N* may be assumed to be a network of whatever form is capable of providing the impedance characteristics needed to meet the requirements later discussed; in practice, it becomes merely a resistance integrally comprised within the resistance component of the self-impedance of winding *C*. The sidetone circuit which would remain if this added branch were disconnected will be called the complementary sidetone circuit or the sidetone complement of the anti-sidetone circuit. In every reference to a sidetone circuit hereafter, the sidetone complement of the associated anti-sidetone circuit is meant.

Receiving and Transmitting Features

The theoretical features of the anti-sidetone circuit to be explained are:

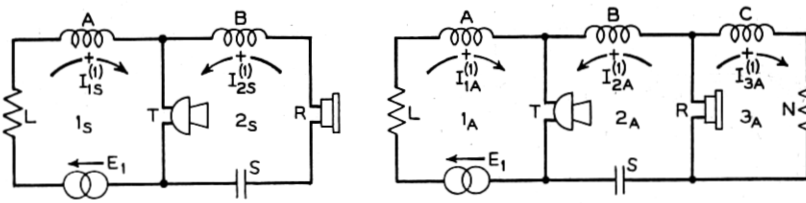
1. The receiving efficiency is the same as that of the complementary sidetone circuit.
2. The transmitting efficiency is the same as that of the complementary sidetone circuit.
3. The current through the receiver when transmitting, i.e., the sidetone, is zero.

The above efficiencies, it should be noted, are purely circuit efficiencies; they do not include electro-acoustic conversions by the instruments, and they should not be confused with questions pertaining to effective transmission performance.

Circuit Conditions When Receiving and When Transmitting

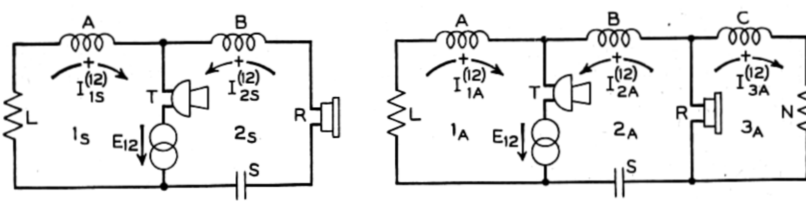
The following discussion of the diagrams in Groups II and III applies to both the sidetone and the anti-sidetone circuits.

Group II shows the e.m.f.'s impressed upon the circuits when receiving and when transmitting, and the assumed positive directions of the resulting mesh currents.[1] The schematics in Fig. 4 will be used in the later explanations of the receiving condition; but for the transmitting condition the equivalent component schematics evolved in Group III will be employed instead of Fig. 5.



Receiving

Fig. 4



Transmitting

Fig. 5

Group II—The applied E.M.F.'s and assumed * mesh currents, receiving and transmitting

By the well-known principle called Thevenin's Theorem, under the receiving condition the line and the set at its distant end may be replaced by an impedanceless generator in series with the line impedance, the e.m.f. of this generator being equal to the open-circuit voltage across the terminals of the line. Also, under receiving conditions, the transmitter will be treated as a passive impedance; and

* The curved arrows in the above and in all subsequent circuit schematics, it should be noted, do not purport to indicate the relative directions of the actual currents; but merely to denote the directions *assumed* as the positive sense of mesh currents and voltages. The selection of these directions is purely optional. As a matter of convenience, they have been so chosen that the currents through the transmitter and receiver are in every case the algebraic sum of the two contributing mesh currents.

[1] The following conventions and nomenclature are employed, see Group II:—The directions around the meshes, chosen as positive for all voltages and currents, are indicated by curved arrows. Subscripts differentiate impressed e.m.f.'s with regard to the meshes in which they are applied, and identify currents with respect to the meshes (or circuit elements—see Group IV) in which they flow. Currents are further identified with respect to the e.m.f. or e.m.f.'s to which they are due, by superscripts corresponding with the activating voltage subscripts.

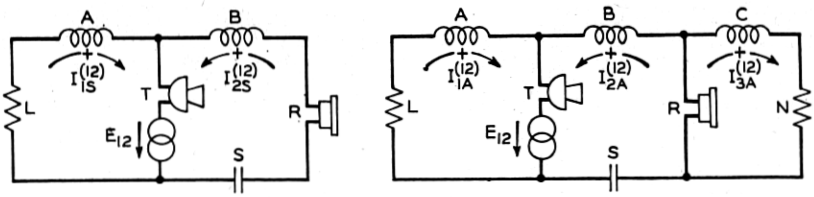


Fig. 5

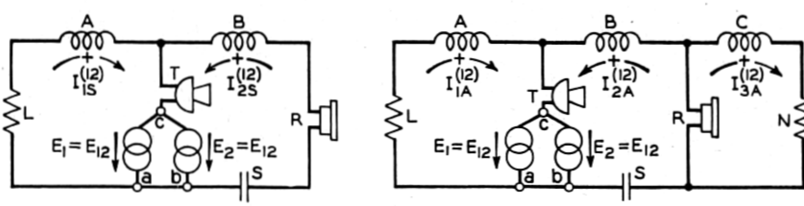


Fig. 6

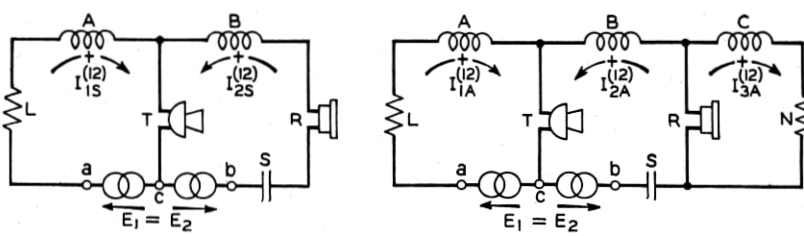


Fig. 7

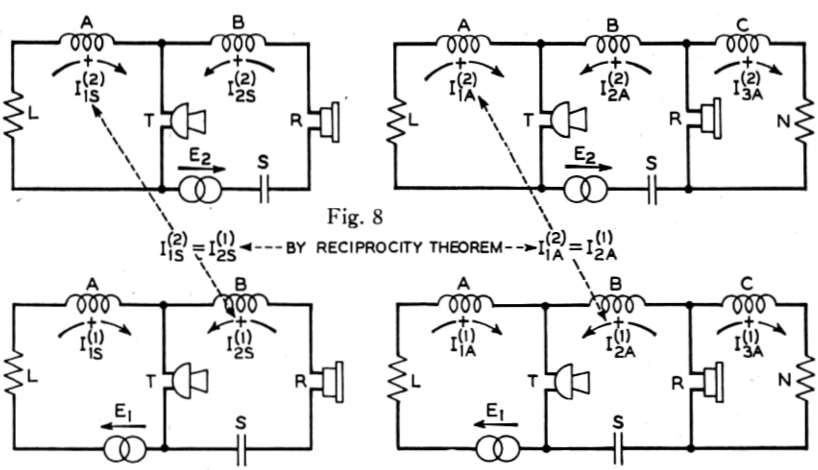


Fig. 8

Fig. 9

Group III—Components of transmitting E.M.F.'s and assumed mesh currents when transmitting (see Fig. 5 of Group III), it will be looked upon as the same passive impedance in tandem with an impedanceless generator whose e.m.f. equals the variations in voltage drop (of the battery supply current) across the transmitter due to the changes in its impedance which occur when the transmitter is agitated by sound. This e.m.f. thus replaces in the circuit the sound engendered variations in the transmitter impedance, thereby permitting this impedance to be treated as a constant. Being impedanceless, this generator may, without effect upon the circuit, be replaced by two impedanceless generators—each having the same e.m.f. as the first—connected in parallel as shown in Fig. 6. The direct connection between points *a* and *b*, however, is shunted by the impedanceless path *acb*, so that the direct connection *ab* may, without effect, be broken as in Fig. 7. Hence, the two equal e.m.f.'s in Fig. 7, acting simultaneously, are equivalent to the single e.m.f. in Fig. 5; and the mesh currents in the two figures are, therefore, identical. Hereafter, Fig. 7, rather than Fig. 5, will be considered the transmitting condition.

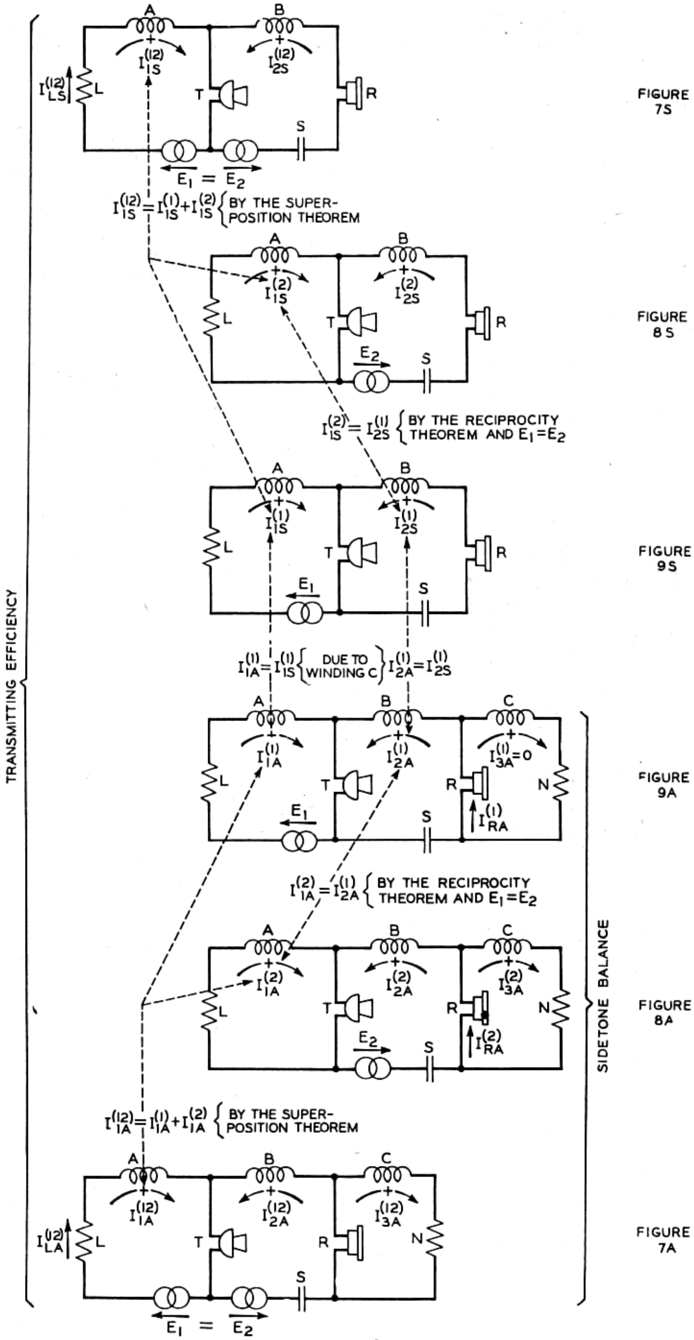
This transmitting condition may, however, be broken into two component conditions. By the fundamental principle known as the Superposition Theorem, the currents in Fig. 7 are equal to the sum of the currents which would result from each of the two e.m.f.'s acting alone. In other words, the transmitting currents in Fig. 7 are equal to the sum of the corresponding currents in Figs. 8 and 9. But by a second fundamental principle called the Reciprocity Theorem, the current at any point X in a circuit, due to an e.m.f. at any other point Y, is equal to the current which would result at Y from an equal e.m.f. at X. Applying this to Figs. 8 and 9, in which $E_1 = E_2$, the mesh currents pointed out by the arrows joining these two schematics are equal, viz.:

$$I_{1S}^{(2)} = I_{2S}^{(1)} \qquad \text{and} \qquad I_{1A}^{(2)} = I_{2A}^{(1)}. \tag{1}$$

Of the above components of the transmitting currents, those in Fig. 9 are due to an e.m.f. acting in mesh 1, i.e., in series with the line impedance. This, however, is also the condition when receiving, as will be seen by comparing Figs. 9 and 4.

Neutralizing Balance—Receiving Efficiency

Consider next the purpose of winding C. It is, of course, desirable that the transmitting and receiving efficiencies be undiminished by the anti-sidetone arrangement. If it is possible so to adjust the couplings among windings A, B and C that the current $I_{3A}^{(1)}$ in Fig. 4 or 9 is zero, the balancing branch can then be disconnected without effect



Group IV—Transmitting efficiency—sidetone balance upon the currents, and the circuit will thereby be reduced to the sidetone circuit. Hence, with this ideal adjustment of the couplings, the receiving efficiency of the anti-sidetone circuit will be the same as that of its sidetone complement.

Although equally satisfactory designs could be worked out with other polings of the coil windings, the relative inductive directions among windings A, B and C in the circuit here dealt with are such that, if a current were passed through all three in series, windings A and B would be inductively aiding; and C would be inductively opposed to both A and B. Returning to the above condition for maintaining the receiving efficiency, namely, that $I_{3A}^{(1)}$ be made zero, the windings of the coil must be so adjusted that the sum of the two voltages induced in winding C by its inductive couplings with windings A and B is equal and opposite the voltage drop across the receiver. With the windings poled as just stated, this requires that

$$(+\,I_{1A}^{(1)}Z_{AC}) + (-\,I_{2A}^{(1)}Z_{BC}) = -\,(-\,I_{2A}^{(1)}Z_R). \qquad (2)$$

This voltage balance expressed by eq. (2) will be referred to as *neutralizing balance:* its attainment requires the coil windings be adjusted to meet the relation shown by eq. (6) in the appendix.

It is important to note that neutralizing balance, and hence the efficiency relations which depend upon it, are independent of the impressed e.m.f. E_1, of the line impedance Z_L and the self-impedance of winding A, and of the network impedance Z_N and the self-impedance of winding C. This of course follows from the fact that none of these quantities is involved in eq. (2).

Transmitting Efficiency

It will now be shown that the transmitting efficiency of the anti-sidetone circuit is the same as that of its sidetone complement; and that this equality, like that of the receiving efficiencies, results from the neutralizing balance effected by winding C. This is true if, with equal transmitter e.m.f.'s in the top and bottom diagrams of Group IV, the line currents are equal, viz., if

$$I_{1A}^{(12)} = I_{1S}^{(12)}.$$

To prove this relation, refer to Fig. 7A at the bottom of Group IV and move up step by step to Fig. 9A, observing the relations between mesh currents indicated by the arrows. It will be seen that

$$I_{1A}^{(12)} = I_{1A}^{(1)} + I_{2A}^{(1)}.$$

But in Figs. 9*A* and 9*S*, due to neutralizing balance, as was shown in discussing receiving efficiencies,

$$I_{1A}^{(1)} = I_{1S}^{(1)} \quad \text{and} \quad I_{2A}^{(1)} = I_{2S}^{(1)}.$$

Finally, continuing from Fig. 9*S* upward to Fig. 7*S*, it is seen that

$$I_{1S}^{(1)} + I_{2S}^{(1)} = I_{1S}^{(12)}.$$

Hence,

$$I_{1A}^{(12)} = I_{1A}^{(1)} + I_{2A}^{(1)} = I_{1S}^{(1)} + I_{2S}^{(1)} = I_{1S}^{(12)}.$$

Primary Purposes of Winding *C* and of Neutralizing Balance

The above relations between the efficiencies of the anti-sidetone circuit and those of its sidetone complement are, however, merely incidental to the primary purposes of winding *C* and of the neutralizing balance which it provides. The major purpose of winding *C* is that, entirely apart from its neutralizing action, the voltages induced in it through its couplings make it possible to obtain sidetone balance by adjusting Z_N; i.e.—referring to Fig. 7*A* at the bottom of Group IV—given any value of Z_L, it is theoretically possible so to adjust Z_N that $I_{2A}^{(12)} = -I_{3A}^{(12)}$. The current through the receiver under the transmitting condition, i.e., sidetone, will then be zero. Neutralizing balance permits this adjustment of Z_N to be made without affecting the circuit efficiencies.

Sidetone Balance

The following discussion of sidetone balance will proceed on the assumption that the couplings of winding *C* with windings *A* and *B* have already been adjusted for neutralizing balance, since this condition is required to maintain the circuit efficiencies. This approach is merely a matter of convenience, however, for it will be indicated that the impedance of *N* required to effect sidetone balance is the same whether the neutralizing balance is taken into account or ignored. Although sidetone balance is made possible by the couplings of winding *C*, and the impedance of *N* needed to reduce sidetone to zero does depend upon the values to which the self and mutual impedances of this winding have been adjusted, neither the attainment of sidetone balance nor the value of Z_N required to provide it depends upon the existence of neutralizing balance.

If sidetone is to be zero, the voltage across the receiver under the transmitting condition, i.e., the sum of the voltages across *C* and *N*, must be made zero. Expressed in terms of the voltages in Fig. 7*A* at the bottom of Group IV, this requires that

$$I_{1A}^{(12)}Z_{AC} - I_{2A}^{(12)}Z_{BC} - I_{3A}^{(12)}(Z_C + Z_N) = 0. \qquad (3)$$

Here, at once, the dependence of sidetone balance upon the presence of the inductively coupled third winding is apparent. Without winding C the impedances Z_{AC}, Z_{BC} and Z_C in the above expression would all be zero, the terms in which they occur would drop out, and the requirement for elimination of sidetone would reduce to $Z_N = 0$, i.e., a short circuit across the receiver.

The remainder of this discussion of sidetone balance can be carried out more conveniently in terms of the mesh currents than in terms of the above voltages. As already noted, the voltage balance just examined is equivalent to requiring that $I_{2A}^{(12)}$ and $I_{3A}^{(12)}$ in Fig. 7A be made equal and opposite. But $I_{2A}^{(12)}$ is the sum of the two components, $I_{2A}^{(1)}$ in Fig. 9A and $I_{2A}^{(2)}$ in Fig. 8A; and, because of neutralizing balance, $I_{3A}^{(12)} = I_{3A}^{(2)}$ in Fig. 8A. Furthermore, by the Reciprocity Theorem, the component $I_{2A}^{(1)}$ always equals $I_{1A}^{(2)}$; and the latter, like the former, is independent of Z_N. The condition for sidetone balance may, therefore, be expressed in terms of the currents in Fig. 8A as

$$I_{1A}^{(2)} + I_{2A}^{(2)} + I_{3A}^{(2)} = 0. \tag{4}$$

The question, then, is whether N can be so adjusted that the sum of the three mesh currents in Fig. 8A is made zero; and it is fairly evident such an adjustment for any given value of Z_L is theoretically possible. Since $I_{1A}^{(2)}$ is known to be independent of Z_N, and because inspection shows the circuit to be symmetrical with respect to L and N, it appears that $I_{3A}^{(2)}$ must be independent of L—an intuitive inference which the Reciprocity Theorem confirms. The value of $I_{2A}^{(2)}$ depends, of course, upon both Z_L and Z_N. Hence, with the value of $I_{1A}^{(2)}$ remaining fixed as Z_N is varied, and with $I_{3A}^{(2)}$ independent of Z_L but under the direct control of Z_N, it may be concluded possible to meet eq. (4) by a suitable choice of Z_N for any given value of Z_L. The value of Z_N required to attain sidetone balance is shown by eq. (7) in the appendix.

With N so adjusted that sidetone is zero, it is obvious the receiver impedance may be changed in any way whatever without upsetting the sidetone balance. The same is true of any change in the impedance of the transmitter; because this, being equivalent to a compensating change in the transmitter e.m.f., would cause all mesh currents to change in the same proportion; thus leaving the balance expressed by eq. (4) undisturbed. Hence, the impedance of N required to provide sidetone balance is independent of the receiver and of the transmitter. But as has already been seen, the couplings of winding C necessary to provide the neutralizing balance in eq. (2) do depend upon the receiver and transmitter impedances. The significance of this observation is that although the value of Z_N required to provide sidetone balance does depend upon the values of the couplings of C, neither the attainment of the balance in eq. (4) nor the impedance of N required to provide it depends upon the balance in eq. (2) being met. In other words, the neutralizing balance expressed by eq. (2), and the sidetone balance expressed by eq. (4), are mutually independent; either may be attained without the other.

Practical Considerations

With the simple types of coil and network permitted by economic and space limitations, the balances upon which the above performance of the anti-sidetone circuit depends can be obtained exactly only with a given line and at a single frequency. For practical purposes, however, exact balances are needless. Sound leakage under the receiver cap and conduction through the head structure fix a limit beyond which further reduction in sidetone is not of value. Actual designs, therefore, aim at the best compromise in reducing sidetone over the voice range and the range of line impedances important in practice, as judged by the resulting effective transmission performance obtained with the instruments employed. Under typical plant conditions, designs now in service reduce the volume of sidetone with present instruments to a level averaging around 10 to 12 db below that of the complementary sidetone sets.

APPENDIX

Algebraic Solution of Circuit Equations

Referring to Fig. 10, the following circuit equations may be written:

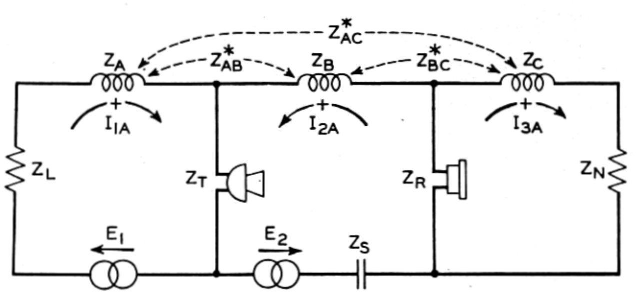
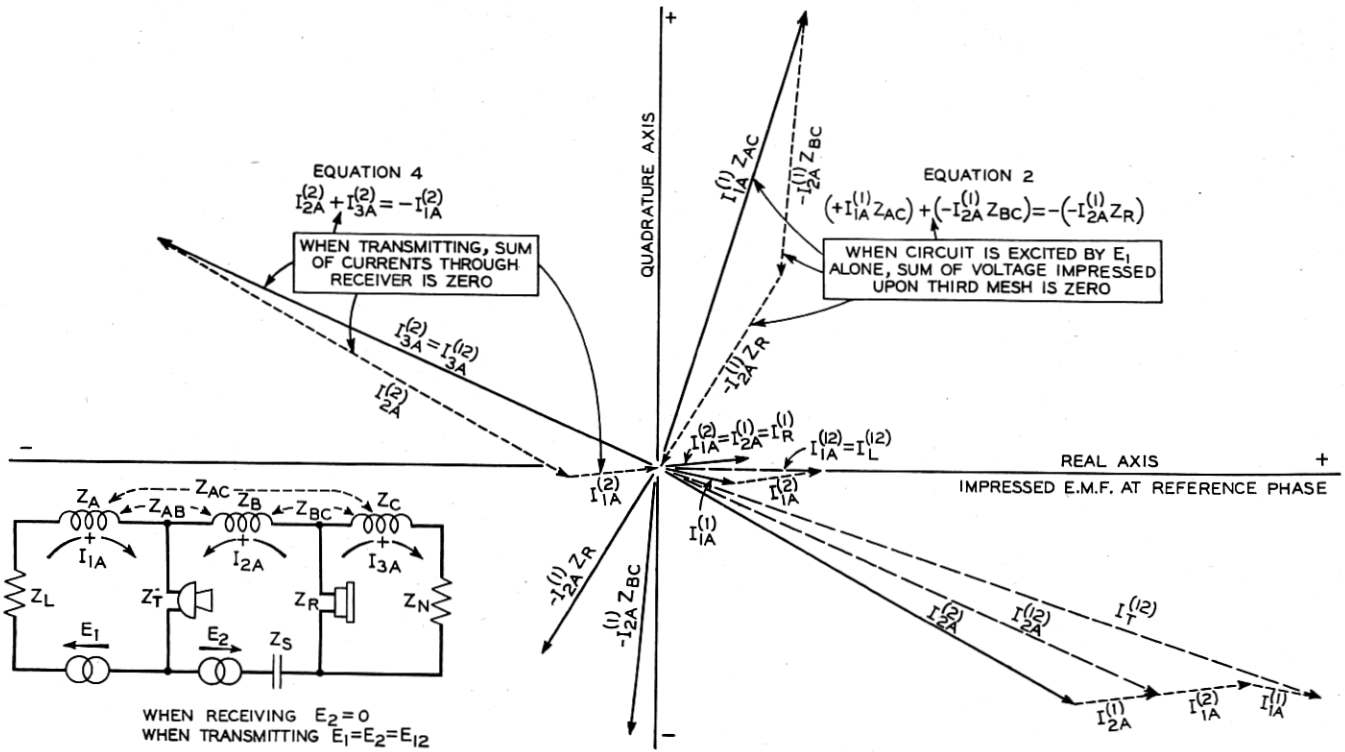


Fig. 10—* The poling of windings A and B is series aiding. Winding C is poled in series opposition to windings A and B.

$$\left.\begin{array}{rrr} (Z_L+Z_A+Z_T)I_{1A}+ & (Z_T-Z_{AB})I_{2A}- & Z_{AC}I_{3A}=E_1 \\ (Z_T-Z_{AB})I_{1A}+ & (Z_T+Z_B+Z_R+Z_S)I_{2A}+ & (Z_R+Z_{BC})I_{3A}=E_2 \\ -Z_{AC}I_{1A}+ & (Z_R+Z_{BC})I_{2A}+ & (Z_R+Z_C+Z_N)I_{3A}=0 \end{array}\right\}. \tag{5}$$



This diagram shows the following:

1. Vectors of mesh currents due to E_1 acting alone.
2. Vectors of mesh currents due to E_2 acting alone.
3. Vector additions of the foregoing components showing the following under the transmitting condition:
   A. Vectors of the mesh currents.
   B. Vectors of the currents through the transmitter and fed into the line.
   C. The sum of the currents through the receiver is zero.
4. Vectors of voltages impressed upon the third mesh when circuit is excited by E_1 alone.
5. Vector addition of foregoing voltages showing sum to be zero.

Fig. 11—Vector diagram for assumed example of anti-sidetone common battery subscriber set circuit.

These cover both transmitting and receiving conditions: when transmitting, $E_1 = E_2$; and when receiving, $E_2 = 0$.

The relation which the induction coil must meet in order to provide neutralizing balance can be determined by solving eqs. (5) under the receiving condition $E_2 = 0$, and imposing the requirement that $I_{3A}^{(1)} = 0$. This gives as the relation to be met.

$$\frac{Z_{AC}}{Z_{BC} + Z_R} = \frac{Z_{AB} - Z_T}{Z_T + Z_B + Z_R + Z_S}. \tag{6}$$

In like manner, the value of Z_N needed to provide sidetone balance can be determined by solving eqs. (5) under the transmitting condition $E_1 = E_2$, and imposing the requirement that $I_{2A}^{(12)} + I_{3A}^{(12)} = 0$. This value of Z_N, regardless of whether or not eq. (2) is imposed as a further condition in its derivation, is found to be

$$Z_N = Z_{BC} - Z_C + \frac{Z_{AC}(Z_{AC} + Z_{BC} - Z_{AB} - Z_B - Z_S)}{Z_L + Z_A + Z_{AB}}. \tag{7}$$

Note that Z_N is here independent of Z_T and Z_R, except as these may enter implicitly as factors affecting the impedances at right in designing the coil for optimum performance with specified instruments. In other words, the transmitter and receiver may be changed without disturbing the sidetone balance. Such a change would, however, upset the neutralizing balance, thereby altering the efficiencies from those of the sidetone circuit.

Vector Diagram

Relations among the component mesh currents in an anti-sidetone circuit of this type under ideal conditions of exact neutralizing and sidetone balances, are illustrated by the vector diagram in Fig. 11. As all of the current vectors indicate current per volt impressed, those for the mesh currents under the receiving condition in Fig. 4*A* are identical with those under the component of the transmitting condition in Fig. 9*A*. Vector sums of the mesh currents show the current through the receiver and that fed into the line when transmitting, and illustrate the sidetone balance. Vectors of the three voltages acting around the third mesh in Figs. 4*A* and 9*A* are also shown, together with their summation. The latter illustrates the neutralizing balance of eq. (2).