P.O.E.E.J Vol.48 p208 Jan.1956

Some Principles of Anti-Side-Tone Telephone Circuits

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U.D.C. 621.395.61:621.395.661

A simplified explanation is given of the basic anti-side-tone circuit employed in British Post Office telephones, and some of the factors influencing the design of telephones are discussed. Thus, this article serves as an introduction to a future article which will deal with the new 700-Type Telephone.

INTRODUCTION

G. A. CAMPBELL, in 1920, enumerated over half a million different anti-side-tone induction-coil circuits. For practical and economic reasons the number of these circuits suitable for use in British Post Office telephones is very limited and both the present standard transmission circuit, as used in Telephones No. 332, and a new transmission circuit used in the 700-type telephone, to be described in a future article, are based upon one particular Campbell circuit. This article summarises the important properties of the Campbell circuits and gives a simplified explanation of the way the circuit which forms the basis of British Post Office telephones works, assuming idealised conditions throughout. Some of the factors influencing the design of telephones based on this basic circuit are discussed and the relationship of the Telephone No. 332 circuit to it is shown. The fundamental equations for the idealised basic circuit are given in an Appendix.

FUNDAMENTAL PRINCIPLES OF CAMPBELL INDUCTION-COIL CIRCUITS

Campbell showed[1] that it was only possible for the transmitter, receiver and line of a telephone circuit to be interconnected so that each was matched to the remainder of the circuit, so ensuring maximum transfers of power, when an additional power-consuming impedance was included in the circuit. He showed that when these four impedances were interconnected so that each was matched to the remainder of the network, the power output of one of them, A, was shared between only two of the other impedances, B and C, with no power input to the fourth impedance D, while if the impedance D, to which there had been no input from A, had an output this would be shared between B and C with no input to A. He also showed that a similar conjugate relationship existed between B and C. In anti-side-tone telephone circuits the important facts are that when the transmitter, receiver, line and balance are interconnected by means of an induction coil so that each is matched to the remainder of the circuit, then

(*a*) the transmitter output is shared between the line and the balance with no input to the receiver, the desired no-side-tone condition, and

(*b*) the output from the line to the telephone is shared between the transmitter and the receiver with no input to the balance.

The lack of output from the receiver to the transmitter, and from the balance to the line, which also follow, are unimportant to the working of the telephone as these impedances do not normally have outputs. K. S. Johnson has shown[2] that although anti-side-tone circuits contain an additional power-consuming impedance they have the same theoretical efficiency as side-tone circuits, which do not include this additional impedance, because in the latter it is impossible to match all three impedances for maximum power output from, or input to, each.

THE BASIC CIRCUIT OF BRITISH POST OFFICE TELEPHONES

The basic circuit discussed is shown in Fig. 1, in which T, R and B represent the impedances of the transmitter receiver and balance circuit of a telephone and L represents the impedance of the line to which it is connected. These are interconnected by means of a three-winding induction coil of which the turns of windings 1, 2 and 3 are in the ratio $1 : n : r$. The directions of the windings are such that if a changing flux in the core of the coil induces an E.M.F. in one winding in the direction of the arrow associated with it, then the E.M.F.s in the other windings will be in the directions of the arrows associated with them.

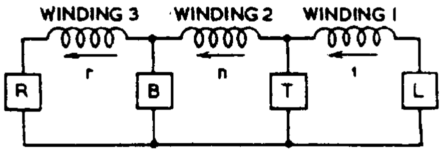

FIG. 1.—BASIC ANTI-SIDE-TONE TELEPHONE CIRCUIT.

Throughout the explanation of how the basic circuit works it is assumed that:

(*a*) The induction coil is an ideal transformer, its windings having negligible resistance and leakage reactance and infinite self-impedance.

(*b*) The circuit is working in the condition that an E.M.F. in the transmitter causes no current to flow in the receiver, the no-side-tone condition.

(*c*) Where impedances are matched for maximum power transfers their reactive components are equal and of opposite sign.

The design of a telephone circuit is influenced by the following factors:—

(i) The types of exchange used by the British Post Office, and many other administrations, require that the signalling resistance of a telephone should be low, which means that the resistance of the transmitter must be much lower than the line impedance. Circuits based on the circuit of Fig. 1 are used in telephones in preference to others because they do enable a low-resistance transmitter to be used efficiently.

(ii) Telephone circuits have to be designed to work efficiently in an existing line network, and when connected by it to older telephones.

The Basic Circuit Sending to Line.

The transmitter may be considered as an alternating E.M.F. in series with its impedance, which is almost pure resistance. This E.M.F. causes instantaneous currents i_1 and i_2 to flow in the circuit, as shown in Fig. 2. Current i_2 flowing in winding 2 has the greater ampere-turns product

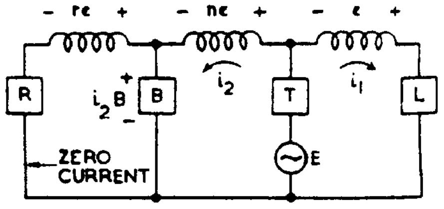

FIG. 2.—THE BASIC CIRCUIT SENDING TO LINE.

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[1] Campbell, G. A. and Foster, R. M. Maximum Output Networks for Telephone Substation and Repeater Circuits. *Transactions of the A.I.E.E.*, Vol. XXXIX, 1920.

[2] Johnson, K. S. Transmission Circuits for Telephonic Communication (The Library Press, Ltd., 1924). p. 120.

and determines the direction of the flux in the induction-coil core, hence the E.M.F.s e, ne and re induced in the windings are in the directions shown. Current i_2 flowing in B causes a back E.M.F. i_2B to appear across it and the value of r is chosen so that, with the values of B and n determined as described later:

$$re = i_2B$$

The E.M.F. applied to the receiver is the sum of re and i_2B and as they are equal and are opposed no current flows in the receiver, the no-side-tone condition.

Examination of the equation for the impedance to which the transmitter is connected, assuming side-tone balance, shows that the circuit is effectively that shown in Fig. **3.** For maximum transmitter output the impedance of this circuit should match the impedance of the transmitter and it can be made to do so by variations of n and B. Variations of n and B also vary the ratio in which the output of the transmitter is used in the line and wasted in the balance. This ratio is sometimes termed the Y ratio of the circuit and the greater it is, the greater is the sending efficiency, but the lower is the receiving efficiency, as explained later. The values of n and B are chosen therefore to simultaneously match the transmitter to its load and to give the required Y ratio.

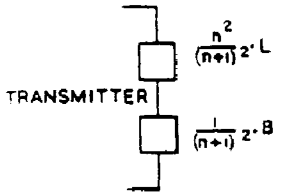


FIG. **3.**—IMPEDANCE TO WHICH TRANSMITTER IS CONNECTED.

The Basic Circuit Receiving from Line.

The input from the line can be considered as caused by an alternating E.M.F. in series with its impedance and this causes instantaneous currents i_3 and i_4 to flow in the circuit, as shown in Fig. **4.** Current i_3 flowing in winding 1 has the greater ampere-turns product and determines the direction of the flux in the induction-coil core, and the E.M.F.s e, ne and re induced in the windings are in the directions shown. Current i_4 flowing in R causes a back E.M.F. to appear across it and the value of R is chosen so that (with the values of B, n and r chosen to give no side-tone, to match the transmitter to its load, and to give the required Y ratio),

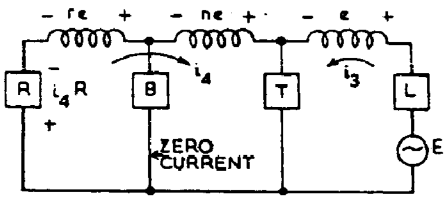


FIG. **4.**—THE BASIC CIRCUIT RECEIVING FROM LINE.

$$i_4R = re$$

(The impedance of any physical design of receiver may be varied in magnitude, but not in angle, to suit circuit requirements by varying the gauge of wire and the number of turns of its winding.) The E.M.F. applied to B is equal to the sum of i_4R and re, and as they are in opposite directions and are equal, no current flows in the balance as a result of the E.M.F. in the line.

The equation for the impedance of the telephone circuit viewed from the line terminals shows, when the value of R has been chosen to give no current in B when receiving, that the circuit is effectively that shown in Fig. **5.** It is a property of the basic circuit that when n, r and R have been chosen in the ways described the impedance of the telephone circuit for receiving matches the line, so ensuring the maximum transfer of power from the line to the telephone.

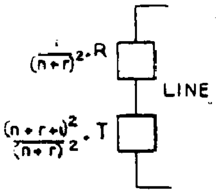


FIG. **5.**—IMPEDANCE OF TELEPHONE CIRCUIT, AS SEEN FROM THE LINE.

It will be seen from Fig. **5** that the power received by the telephone from the line is shared between the receiver, used power, and the transmitter, wasted power. It is another property of this circuit that in the no-side-tone condition, and with no received power dissipated in the balance, the ratio:

$$\frac{\text{Received power wasted in the transmitter}}{\text{Received power used in the receiver}}$$

is the same as the ratio:

$$\frac{\text{Transmitter power sent to line}}{\text{Transmitter power wasted in the balance}}$$

previously referred to as the Y ratio.

The Balancing of Sending and Receiving Efficiences.

From the foregoing, it will be seen that values of Y greater than 1 increase the sending efficiency of a telephone circuit at the expense of the receiving efficiency, while values of Y less than 1 do the reverse. The relationships between the Y ratio and the sending and receiving efficiencies of a perfect telephone are shown in Fig. **6**, and Fig. **7** shows how the sum of the sending and receiving efficiencies, the overall efficiency of the telephone, varies with Y. Fig. **7** shows that the maximum overall efficiency is obtained when $Y = 1$, and if a telephone was designed for use only with telephones of its own type this ratio would be used.

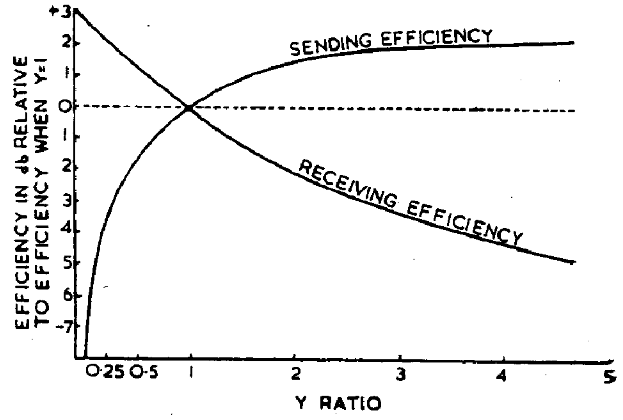


FIG. **6.**—SENDING AND RECEIVING EFFICIENCIES OF A PERFECT TELEPHONE.

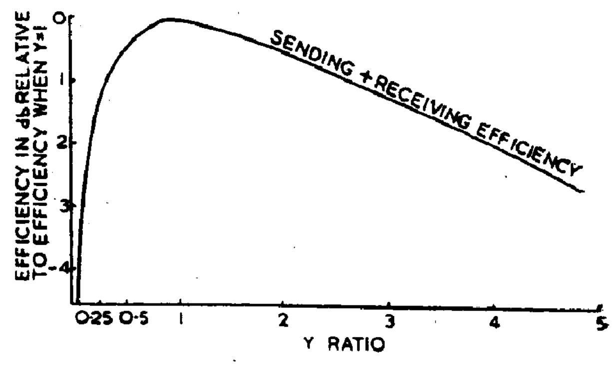


FIG. 7.—OVERALL EFFICIENCY OF A PERFECT TELEPHONE.

A new telephone can, however, only be introduced into a system gradually and for many years it has to work with older telephones. To enable economic advantages to be obtained from any improved performance it is necessary for the new telephone to be used on longer lines. To do this when working to older telephones when, as in the British Post Office system, transmission limits are determined by the direction of worst transmission, it is necessary for the new telephone to have both transmitting and receiving performances superior to the older telephones. If the improved performance of the new telephone springs from either a transmitter with greater output or a more sensitive receiver, but not both, transmission in only one direction will be improved. In these circumstances the *Y* ratio can be changed so that the improved transmitter or receiver results in a balanced increase of sending and receiving efficiencies. From Figs. **6** and **7** it will be seen that values of *Y* departing far from 1, while improving one efficiency give a disproportionate decrease in the other. For example, if the *Y* ratio is increased from 1 to 5, sending efficiency increases by approximately 2·2 db while receiving efficiency decreases by 4·8 db. For this reason the values of *Y* used are usually near 1.

The Addition of a D.C. Blocking Capacitor.

For practical telephones an essential modification to the circuit of Fig. **1** is the provision of a capacitor in the position shown in Fig. **8**. The main purpose of this capacitor is to force all the line D.C. current to flow through the transmitter. This is essential when high sending efficiency is required because the A.C. output of a carbon-granule transmitter increases with the increase of D.C. current flowing in it. A subsidiary function which the capacitor performs is to prevent polarising D.C. currents from flowing through the receiver, as these would aid or oppose, depending upon their direction, the flux in the receiver due to its permanent magnet. Increased or decreased flux are equally undesirable because the magnet flux is adjusted during manufacture to the optimum value and any departure from this reduces the receiver sensitivity. In British Post Office telephones the same capacitor also performs two auxiliary signalling functions. When the telephone is not in use on a call the capacitor is connected in series with the bell across the line, blocking the exchange D.C. signalling E.M.F. but allowing an A.C. calling current to ring the bell. During dialling the capacitor forms part of the spark quench for the dial pulsing contacts. The impedance of the capacitor, the value of which is usually about 2μF, is low at speech frequencies and its presence may be ignored at all but the lowest. The use of larger values of capacitance, although desirable, is ruled out because of size and cost.

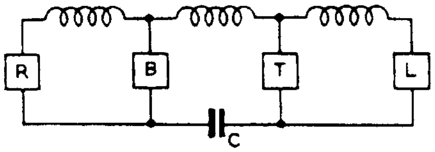
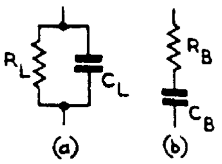


Fig. 8.—Addition of a D.C. Blocking Capacitor.

Departures of Practical Telephone Circuits from the Ideal

The conditions which, in order to simplify the explanation of how the circuit works, were earlier assumed to be met are of course unattainable in practice. In particular the balanced no-side-tone condition is achieved but rarely. For no side-tone it is necessary for the impedances of the balance circuit and the line to have a fixed relationship, depending upon the turns ratio of the induction coil, and this relationship must hold at all speech frequencies. It would be possible to design a balance circuit which would achieve this for a particular line with a particular terminating condition but practical telephones are not made to suit individual lines and the terminating conditions of the lines they are used on vary from call to call. The maintenance of good side-tone suppression at the lower speech frequencies is particularly difficult. The impedance of a line is of the type shown in Fig. **9**(*a*), the resistance path being completed in the exchange apparatus via the central battery and the capacity being the wire-to-wire capacity. The impedance of the balance of a telephone using a D.C. blocking capacitor is, if the frequency is too low for the impedance of the capacitor to be ignored, of the type shown in Fig. **9**(*b*). As the frequency falls the impedance of the circuit of Fig. **9**(*a*) approaches R_L while the impedance of Fig. **9**(*b*) approaches infinity. The two impedances will thus diverge widely, the frequency at which the divergence becomes important depending on the value of C_B.



(*a*) Line Impedance.
(*b*) Balance Impedance.

Fig. 9.—Type of Line and Balance Impedances.

The problem in the design of a practical telephone circuit becomes therefore not a question of achieving side-tone balance at a particular frequency for a rigid set of line conditions, but of keeping the side-tone low over the important part of the frequency band for the range of line conditions which will be met in service.

The Present Standard British Post Office Telephone Circuit.

The present standard British Post Office telephone circuit is typified by Telephone No. 332, the circuit of which is shown in Fig. **10**. To show the relationship between this circuit and the basic circuit which has been discussed it is necessary to rearrange it. If, in a circuit, elements are in series their order may be interchanged without in any way affecting the working of the circuit. Making use of this fact the part of the circuit of Fig. **10** enclosed by dotted lines may be interchanged with winding 2 of the induction coil, with which it is in series, to give the circuit of Fig. **11**. Similarly the order of winding 3 and the receiver may be reversed and, if this is done, the circuit may be re-drawn as shown in Fig. **12**, in which irrelevant signalling contacts have been omitted. The circuit of Fig. **12** is exactly equivalent to that of Fig. **10** for transmission purposes, the arrangement of Fig. **10** being adopted for the practical telephone because it allows the use of a 3-way handset cord in place of the 4-way cord needed by the circuit of Fig. **12**.

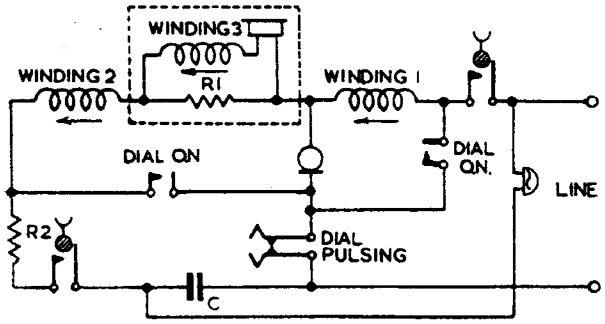


Fig. 10.—Circuit of Telephone No. 332.

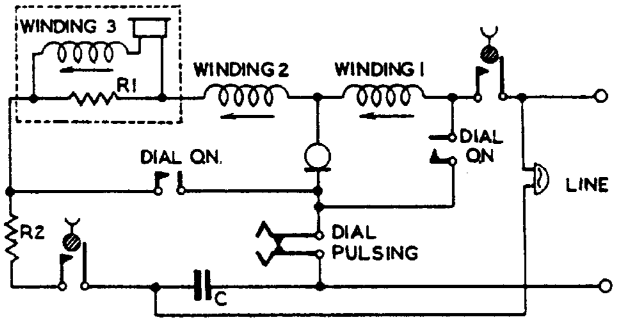


Fig. 11.—Rearranged Circuit of Telephone No. 332.

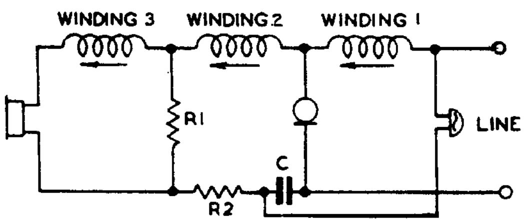


Fig. 12.—Basic Transmission Circuit of Telephone No. 332.

Comparison of Fig. **1**, the basic circuit, and Fig. **12**, the Telephone No. 332 circuit, reveals their similarity. The circuits differ due to the inclusion in the 332 circuit of a D.C. blocking capacitor, the need for and effect of which have already been discussed, a bell and the resistor R2. The impedance of the bell to speech frequencies is so high that its presence may be ignored. The resistor R2, which is included as a separate component to form part of the dial spark quench, does not fundamentally affect the method of working described for the basic circuit but it does require different proportioning of the circuit constants and results in a slight loss of receiving efficiency.

When the 332 circuit is sending to line the no-side-tone condition is achieved by choosing the ratio r so that the E.M.F. induced in winding 3 is equal to and opposes the back E.M.F. in R1 in the receiver circuit. With no current flowing in the receiver due to the transmitter E.M.F., the effective part of the circuit to be considered during sending is that shown in full lines in Fig. **13.** In this, it is resistors R1 and R2 in series which correspond to the balance of the basic circuit and it is their combined value which, in conjunction with the ratio n of the induction coil, determines the ratio of transmitter power sent to line to power lost in the balance, the Y ratio. With R1 and R2 chosen so that their sum, together with the value of n, gives the required Y ratio and matches the transmitter to its load, the presence of R2 does not involve any loss of sending efficiency compared with the basic circuit.

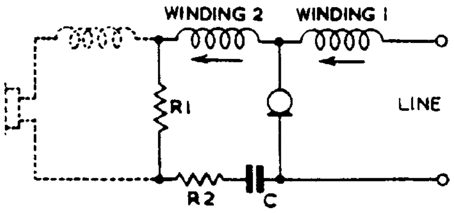


Fig. **13**.—Sending Circuit of Telephone No. 332.

When the Telephone No. 332 circuit is receiving from line, with the circuit balanced for no side-tone when sending, no current flows in the balance (R1). This is because the E.M.F. induced in winding 3 and the back E.M.F. in the receiver are equal and are applied to R1 in opposition. The effective part of the circuit, if no current flows in R1, is that shown by full lines in Fig. **14.** The resistor R2 is in series with the receiver and as a result the power received from the line, which in the basic circuit is shared between the transmitter and the receiver in the Y ratio, in this circuit is split between the transmitter and the combination of the receiver and R2. The power which, in the basic circuit, went to the receiver only is therefore further sub-divided between the receiver and R2 and the circuit is less efficient than the basic circuit for this reason, but as the ratio of R2 to the receiver impedance is low the loss of receiving efficiency is very small.

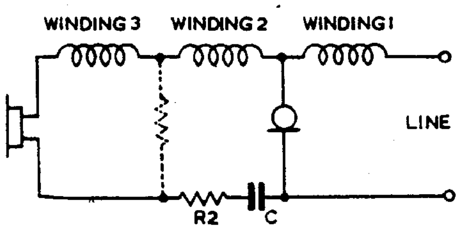


Fig. **14**.—Receiving Circuit of Telephone No. 332.

All practical versions of the basic circuit have, in the inevitable resistance of winding 2, a resistance equivalent to R2, but as it is not present as a separate component it is apt to be lost sight of. By interchange of series components, R2 in the Telephone No. 332 circuit could be made to appear adjacent to winding 2 and could be "hidden" in it, although it could then no longer perform its spark quench function. It does however represent an increase over the unavoidable resistance of winding 2 and means that the transmission performance of the circuit is slightly degraded to enable the one capacitor to be used for transmission purposes and as a spark quench, with resulting economy.

APPENDIX

The Fundamental Equations for the Basic Anti-Side-Tone Circuit Used by the British Post Office.

The symbols T, R, L and B are used throughout (in place of Z_r, etc., for the sake of clarity) to represent the impedance of the transmitter, receiver, line and balance respectively:—

1. For maximum output from the transmitter:

$$T = \frac{n^2L + B}{(n + 1)^2}$$

2. For maximum output from the line:

$$L = \frac{R + T\,(n + r + 1)^2}{(n + r)^2}$$

3. For no side-tone:

$$B = \frac{n\,r}{n + r + 1} \cdot L$$

4. For a required power ratio Y:

$$Y = \frac{n^2L}{B}$$

The values of T, L and Y are fixed by considerations outside the control of the circuit designer, thus the above four equations are sufficient to fix the variables n, r, B and R.

5. For no power loss in the balance when receiving:

$$R = T \cdot \frac{r}{n}\,(n + r + 1)$$

This is not an independent equation and it may be derived from the first four equations.