Cold Cathode Tubes for Transmission of Audio Frequency Signals

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Cold cathode gas filled tubes have been extensively applied as electronic switching elements in the telephone system. In general, these applications have been limited to control circuits. The usefulness of these tubes can be further extended by making them capable of carrying voice frequency signals. The transmission properties that are required of the tube for this use are considered. It is shown that troublesome oscillatory noise can be eliminated and that the insertion loss of the tube can be reduced to a low value. Furthermore, by a special design of cathode a stable insertion gain of a few db may be realized. Other requirements on bandwidth, power and distortion are satisfactorily met. Thus, these tubes are potentially useful in coordinate type switches in which voice frequency signals must be rapidly switched.

INTRODUCTION

Cold cathode glow discharge tubes have found increasing usefulness as two-valued switching elements in telephone and other automatic control systems. In many applications the tube functions as a simple control element which either does or does not pass current, depending on the control signals applied. The output signal is in the form of a voltage or a current which can be used to trigger other tubes or operate relays.[1]

In other types of circuits the glow discharge tube may be used as a switch in series with a transmission path for audio frequency signals. When used for this purpose, the tube not only must fulfill the switching requirements but also must meet an additional set of requirements which may be realized by controlling the dynamic properties of the discharge. This paper describes some of the characteristics of cold cathode tubes which have been developed for use as switching elements in series with voice frequency telephone transmission circuits.

TRANSMISSION REQUIREMENTS OF AN ELECTRONIC SWITCH

When an electronic switch is used as a substitute for a pair of metallic contacts, a number of requirements must be met in order that voice frequency currents be faithfully transmitted. These are as follows:

1. *Gain or Loss* — The impedance level of telephone voice frequency circuits is usually of the order of several hundred ohms. The impedance of any device inserted in this circuit should be sufficiently small compared to this value in order to restrict the insertion loss to less than 1 or 2 db. Of course, the impedance levels of the circuits may be raised to higher values. Aside from the extra cost of transformers, the problems of noise pickup and crosstalk become bothersome when this is done. Since no amplification of the signal from the telephone set is normally used in local transmission circuits, any value of loss is highly undesirable. In fact, since the use of the electronic switch may require the introduction of other circuit elements which introduce loss, it would be desirable that the electronic switch provide a small amount of gain.

The above discussion has considered the gain or loss of the switch in its "closed" condition. Between two busy circuits, there may exist paths consisting of one or more "open" switches. Each of these paths may contribute crosstalk into the circuits. Therefore, impedance required of an individual switch must be high. For a large coordinate switch, there will be a very large number of these undesired paths. This requires that the open impedance of the individual switch be of the order of hundreds of megohms.

2. *Bandwidth* — It is desirable that the electronic switch transmit faithfully frequencies of 300 to 3,500 cycles per second.

3. *Power Output and Distortion* — Since the impedance of the electronic switch may vary with the current passing through it, distortion may be introduced when the current swings are large. On the other hand, without the proper current swing, insufficient power will be delivered to the load impedance. Telephone circuits need to handle powers of the order of a few milliwatts with a harmonic distortion less than a few per cent.

4. *Noise* — The noise introduced into a telephone switching system by an electronic switch should not be noticeable to a subscriber. This means it should be below 10^{-8} or 10^{-9} watts.

5. *Stability* — The properties that have been considered above must be highly stable with time. In central office use, such devices might be used for periods of ten to forty years.

STATIC CHARACTERISTICS

A common form of glow discharge tube comprises a pair of metal electrodes in a glass envelope which is carefully evacuated and filled with a chemically inert gas to a pressure ranging from 1 to 100 mm of mercury. The negative electrode, called the cathode, is given a special processing which permits it to emit electrons readily when bombarded with positive ions of the gas. The positive electrode, the anode, serves to collect electrons emitted by the cathode as well as those produced in the gas by ionization.

A typical voltage-current characteristic is shown in Fig. 1. For discussion purposes we may divide the curve into several current ranges. In current range I a small residual current flows even at low voltages because of ionization resulting from cosmic rays or radio-active material placed in the tube. The two curves in range I are for different residual currents. At higher voltages this residual current is amplified as a result of additional ions and electrons formed in the gas but it is still extremely small. If the tube voltage is increased still more, the current increases very rapidly until in current range II, a self-sustaining discharge is established. Each electron released from the cathode gains enough energy on the way to the anode so that it produces a large number of positive ions, excited atoms, and photons in the gas. When these particles, arriving back at the cathode, on the average, release another electron, the

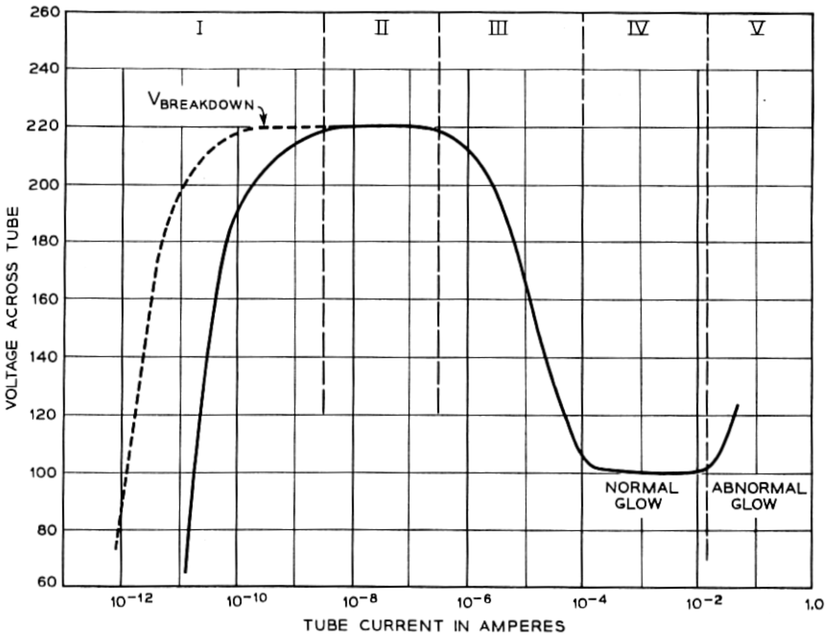

Fig. 1 — Volt-ampere characteristic of cold cathode diode.

self-sustaining condition has been achieved. The value of voltage at which the discharge becomes self-sustaining is usually referred to as the breakdown voltage. A detailed discussion of current ranges I and II has been presented by Druyvesteyn and Penning.[3]

Because the tube is a good insulator in current range I at low voltage and suddenly becomes a good conductor in range II, we often think of a gas tube as a voltage controlled device and use it as such in switching circuits. Actually, however, in current range II the tube can be controlled only by regulating the current. For this reason in the remainder of this paper, the current is considered as the independent variable.

In current range III the voltage falls rapidly with increasing current. A space charge of positive ions begins to develop close to the cathode. By the beginning of current range IV most of the voltage drop in the tube appears across this space charge layer. This region of nearly constant voltage with increasing current is called the normal glow discharge. The space charge layer immediately in front of the cathode is commonly called the cathode dark space. Electrons emitted from the cathode as a result of positive ion bombardment and other processes are accelerated through the high field of this cathode dark space and produce an adjoining layer of intense ionization and excitation called the negative glow. In tubes of the type considered here, this negative glow is the most luminous part of the tube. Beyond the negative glow toward the anode is the so-called Faraday dark space in which no new ionization or excitations are produced. Electrons from the negative glow can readily flow through this region to the anode because their space charge is almost completely cancelled by positive ions diffusing from the negative glow.

Over current range IV the cathode current density is nearly constant. This means that the cross-sectional area of the discharge increases in proportion to the current. This is evidenced by the familiar spreading of the negative glow with increasing current until it covers the entire cathode area.

In current range V the cathode is completely covered with the negative glow and the current density must increase in direct proportion to the total current. This range of currents is called the abnormal glow discharge.

The current-voltage characteristic of a cold cathode for current ranges IV and V may be modified by changing the geometry from a single plane cathode to a hollow cathode.[3] A hollow cathode is one in which there is an overlapping of the regions of cathode fall and negative glow from two portions of the cathode. This overlapping can occur on the inside of a cylindrical or spherical surface or between two plane cathodes more or less parallel to each other and closely spaced. The optimum dimensions are a function of the density and kind of filling gas used. Electrons and ions generated in the cathode fall and negative glow regions of one cathode can be more efficiently used in producing new electrons and ions if they can enter another cathode fall region instead of diffusing outward into the Faraday dark space. This effect is particularly noticeable in the abnormal glow range of currents.

This is illustrated by the curves of Fig. 2 which were taken on a tube containing two parallel plane cathodes with an adjustable spacing between them. Because Fig. 2 is plotted to a linear current scale, current ranges I and II of Fig. 1 are compressed to the left-hand axis. The upper curve is obtained when the cathodes are far apart so that there is no interaction. The lower curve is obtained when the spacing is close enough to give a hollow cathode effect.

The sustaining voltage of a normal glow discharge is dependent upon the anode to cathode distance. To investigate this we can arrange a parallel plane cathode-anode structure with the anode attached to a piece

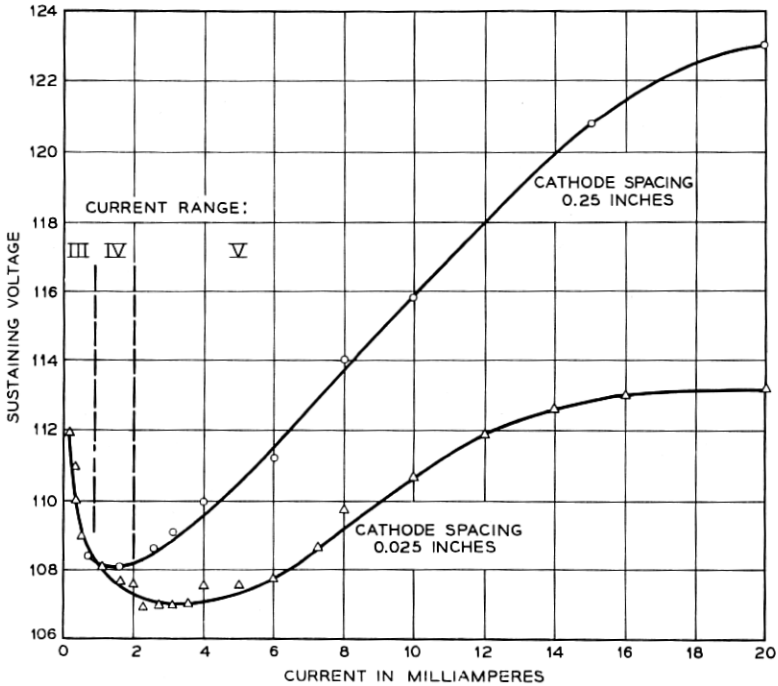

Fig. 2 — Volt-ampere characteristic of parallel plane cathodes at two different spacing.

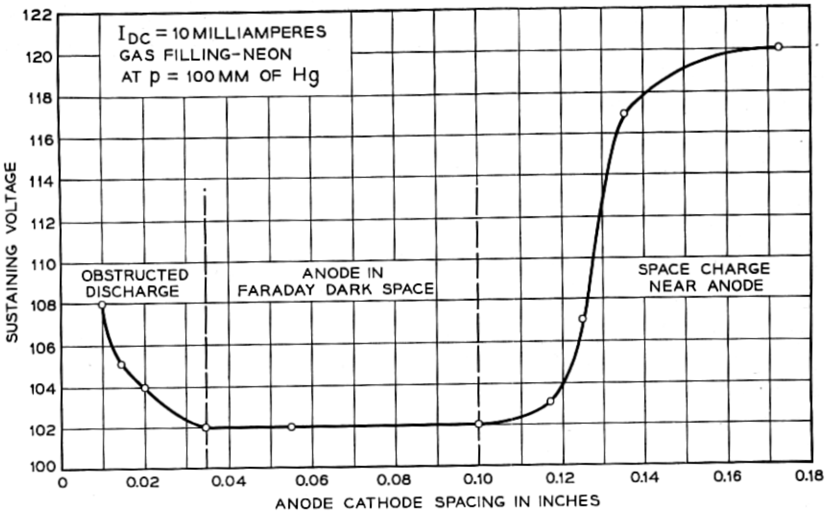

Fig. 3 — Sustaining voltage as a function of anode-cathode spacing.

of magnetic material which can be moved by a magnet external to the tube. Fig. 3 shows a typical set of data obtained in this manner with an operating current in the normal glow range of current. At very close spacings of the order of the negative glow distance, the voltage is higher than normal because some of the electrons released from the cathode are able to strike the anode before dissipating their energy in producing ions and excited particles in the gas. This is referred to as an "obstructed discharge".[3] The voltage must, therefore, be higher because electrons which do produce excitation or ionization must be given extra energy in order to maintain the current. As the anode is moved away from the cathode through the Faraday dark space, the tube sustaining voltage stays at a fairly constant minimum value. This is possible because at close spacings more than a sufficient number of electrons and ions are present in the Faraday dark space to carry the current. As the anode is moved away the Faraday dark space is lengthened. Ions and electrons needed to carry the current diffuse from the cathode region. At sufficiently large distances, however, the ionization density decreases so that not enough ions are present to cancel space charge near the anode. A space charge sheath builds up in the anode region and the sustaining voltage rises with increasing distance.

When the voltage has increased by about 10 to 18 volts depending upon the gas filling, it begins to level off with increase in distance. At about this point, an anode glow may appear in front of the anode. This is due to the fact that some of the electrons have gained suffcient energy for excitation. A slight further increase in anode-cathode distance usually results in the anode glow changing from a uniform layer to a "ball" of glow. When this occurs, oscillations of several volts amplitude appear across the tube terminals. These oscillations result from a sequence of events which is initiated when the electrons gain enough energy in passing through the anode fall region so that they may ionize. A small number of ions generated in this region will, because of their relatively low velocity, enable a large electron current to flow without developing space charge. This then will reduce the voltage appearing across the anode fall and greatly reduce the number of ionizations taking place. As soon as the recently produced ions leave this region the voltage drop across this region increases causing the ionization to build up again. This alternate building up and decaying of ion density results in the observed oscillation which is ordinarily in the frequency range from 0.5 to 20 kilocycles per second.

This oscillation usually cannot be prevented by external circuit means. However, by proper choice of anode-cathode spacing, type and density of the gas filling, and to lesser extent the geometry of the anode, a tube can be made which is free from anode oscillations. The main restriction that this puts on tube design is the limitation of breakdown voltage.

IMPEDANCE

From the previous discussion of transmission requirements it is clear that one of the most important properties of a gas tube is the impedance presented to small ac signal currents superimposed on the steady dc operating current. At low frequencies, these signals cause the voltage across the tube to vary in accordance with the static characteristic. The impedance of the tube to these signals is almost entirely resistive and is equal to the slope of the static characteristic. At higher frequencies, however, there is a lag in the adjustment of the voltage across the discharge to the changes in current. Hence, at these frequencies, the impedance of the tube may have both resistive and reactive components. This is illustrated in Fig. 4.

The small superimposed signals result in current-voltage loci which are ellipses. In current range III at 200 cps, the position of the ellipse corresponds to a negative resistance in series with an inductance. The negative resistance changes rapidly with frequency and as shown at 2,000 cps, it may be positive. Because of the rapid variation of impedance, both with frequency and current, this range of currents is not generally useful for dependable transmission of voice frequency signals.

In the higher current range IV and V the impedance can be represented by a positive resistance in series with an inductive reactance. The resistance increases slowly with frequency as indicated by the elliptical current-voltage loci at 200 and 2,000 cps.

The impedance of a cold cathode tube also varies with anode-to-cathode spacing. This may be studied by means of the same movable-anode parallel-plane tube used to obtain the data of Fig. 3. We again operate the tube in the current range of the normal glow (IV) and, for illustrative purposes, choose a measuring frequency of 1,000 cycles per second. The results are shown in Fig. 5. The resistive and reactive components of tube impedance are independent of anode spacing throughout the Faraday dark space and well into the obstructed discharge region. At large distances where the electron space charge sheath begins to build up in front of the anode, the impedance increases rapidly with distance.

Some useful conclusions about the design of transmission tubes can be drawn from the data of Fig. 5. We can consider the total tube impedance as being made up of the sum of the impedances introduced by the various regions of the discharge. Since large variations in the length of the Faraday dark space do not affect tube impedance, it is concluded that this region has negligible impedance. This means that, so long as the anode-to-cathode distance is short enough to avoid a space charge sheath at the anode, we can concentrate our attention on the cathode fall region. The following detailed discussions of impedance are consequently restricted to the cathode portions of the glow discharge.

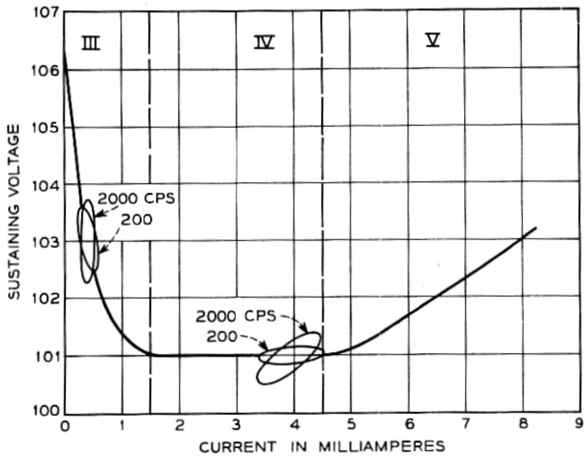

Fig. 4 — Static and dynamic volt-ampere characteristics.

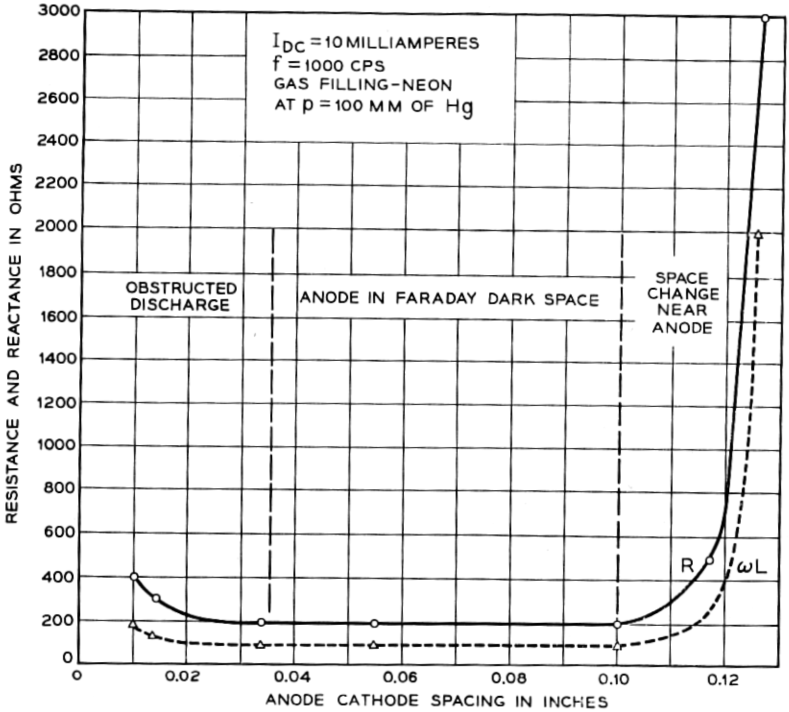

Fig. 5 — Resistive and inductive components of impedance as a function of anode-cathode spacing.

IMPEDANCE OF PLANE CATHODE TUBES

Let us consider first the impedance of a tube with a plane cathode or of a cathode with a radius of curvature large compared to the combined thicknesses of the cathode dark space and the negative glow. An example is the Western Electric 313-C which has a gas filling of 99 per cent neon, 1 per cent argon and a cathode surface of barium and strontium oxides. At a fixed steady current of 25 ma flowing through the starter gap, it is found that the resistive component of the impedance varies with frequency as shown in Fig. 6. In the middle of the voice band it has a value of about 200 ohms. There is also an inductive reactance of about 65 ohms at this frequency. At a fixed frequency, it is found that the resistive component of this type of tube decreases with current approximately inversely as the square root of the current. This is shown in Fig. 7. The

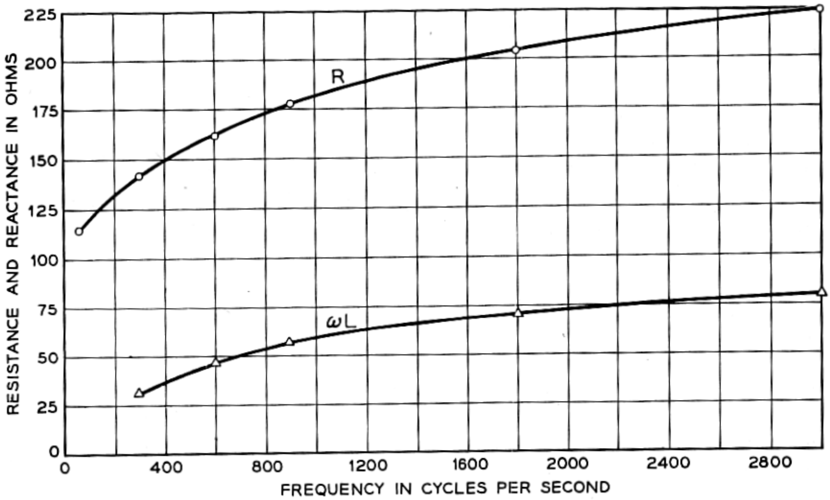

Fig. 6 — Resistive and inductive components of 313-C starter gap impedance as a function of frequency. I_{dc} = 25 mm.

inductive reactance is related to the current approximately as follows:

$$\omega L = B + \frac{C}{I_{dc}}. \tag{1}$$

B and C are functions of frequency.

If we wish to use tubes of this type in central office switching circuits which pass voice frequency currents, we find that even one tube connected between a 600-ohm source and a 600-ohm load gives a prohibitively high insertion loss. The impedance level of the voice frequency circuit may, of course, be raised up to 4,000 or 5,000 ohms. But practical switching circuits might require as many as four tubes in series. Hence, we see that the impedance of tubes of this type severely limits their usefulness.

From Fig. 7 we might argue that to get low resistive components we might continue to increase the direct current flowing through the tube. However, in this range of currents, the life of the tube varies approximately as $1/I_{dc}^3$ while the resistive component varies as $1/I_{dc}^{1/2}$.

Over the range of currents plotted in Fig. 6, the cathode is fully covered with glow. As noted above, the resistive component is

$$R = \frac{A}{I^{1/2}}. \tag{2}$$

If instead of passing a given direct current through a single tube we pass the same current through a parallel combination of n tubes, the resistive component of the combination would be

$$R \text{ comb.} = \frac{1}{n} \frac{A}{\left(\dfrac{I_{dc}}{n}\right)^{1/2}}, \qquad (3)$$
$$= \frac{1}{n^{1/2}} R .$$

The resistive component of the combination is $\frac{1}{n^{1/2}}$ times that of a single tube passing the same total current. This assumes, of course, that the cathodes of the tubes are covered with glow. Obviously this is not a practical method of attaining a low impedance because of the instability of paralleled individual tubes. It does suggest, however, that by increasing the cathode area of a single tube until the glow just covers the full area, a lower impedance is obtained. This has been done experimentally.

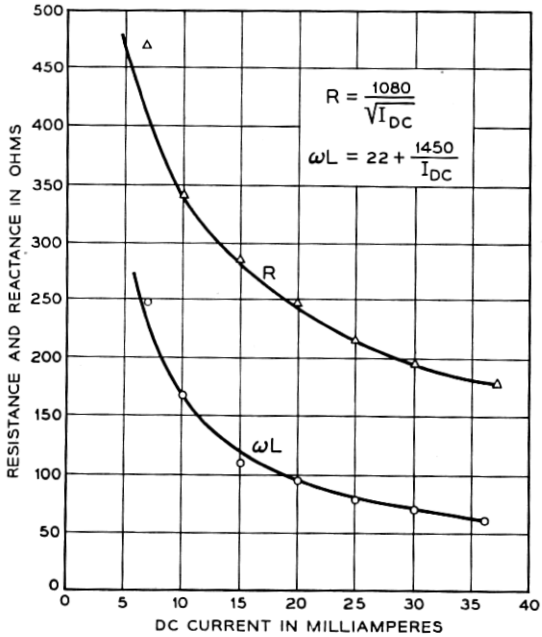

Fig. 7 — Resistive and inductive components of 313-C starter gap impedance as a function of direct current.

Fig. 8 shows the data for a tube of this type which has a cathode area about six times that of the 313-C. This change in cathode area along with the necessary change in anode geometry led to an impedance reduction of about five times. This type of design, of course, gives a large increase in life of the tube but it is undesirable from the standpoint of tube size.

As pointed out above, low impedance can be attained by an increase of the tube current and within limits by an increase of the cathode area. A third parameter which may be varied is the density of the gas filling. At a constant current and with a given cathode area, the resistive component of the impedance decreases with increase in density or the pressure, p, at a fixed temperature approximately in accordance with the relation

$$R \alpha \frac{1}{p^2}. \tag{4}$$

The curve in Fig. 9 was obtained over a limited range of argon fillings with a barium strontium oxide cathode. Since the current density increases approximately in proportion to p^2, the effective cathode area will tend to be reduced unless the total current is kept high enough to cover the cathode fully. Therefore, with a fixed total current there is a limit to either increase in pressure or in cathode area.

In further search for low impedance, a number of different gas fillings have been tried. They have included all the rare gases as well as several mixtures of them. No significant advantages were obtained by the use of other than the more common neon or argon gas fillings.

We therefore see that the ability to control impedance properties of

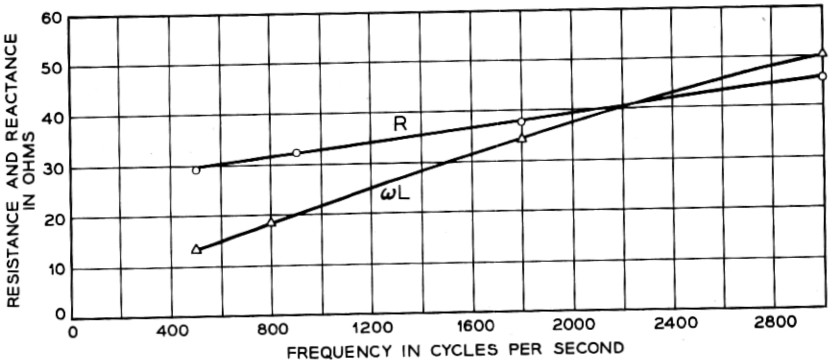

Fig. 8 — Resistive and inductive components of impedance for a large area cathode tube as a function of frequency. I_{dc} = 25 mm.

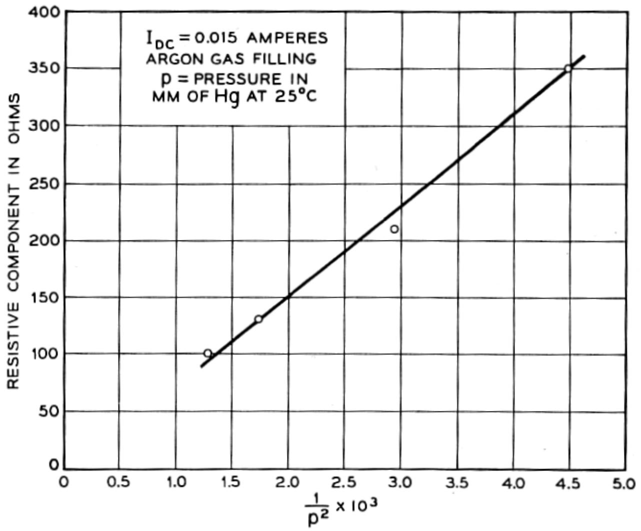

Fig. 9 — Resistive component of impedance as a function of density (pressure at 25°C) of gas filling.

the plane cathode through changes in tube current, cathode area, density and type of gas filling is limited. A reduction by a factor of five or ten times over the values present in commercial tubes is certainly possible. But the possibility of obtaining values of less than +10 ohms or negative values seemed remote. Consequently, development effort was concentrated on the hollow cathode tube described below.

HOLLOW CATHODE TUBES

The static voltage-current characteristic of a hollow cathode was shown in Fig. 2 to be below that of a plane cathode of the same area when operating at currents in the abnormal glow region. It has been found that by proper choice of the cathode dimensions and the kind and density of the filling gas, desirable transmission characteristics can be achieved. The following discussion illustrates the manner in which some of the variables are interrelated.

We will consider a "U" shaped cathode which has been formed by folding a piece of molybdenum sheet in the form illustrated in Fig. 10. The choice of dimensions of the hollow portion will be discussed later. The anode is a cylindrical rod placed in front of the cathode. The anode-to-cathode spacing is selected so that the anode is always within the Faraday dark space and hence does not influence the impedance appreciably. It is assumed that the structure of Fig. 10 is sealed in a bulb which has been carefully evacuated and filled to a fraction of an atmosphere with a rare gas such as neon.

A typical static volt-ampere characteristic of the structure of Fig. 10 is shown in Fig. 11. This curve was taken with a cathode having a hollow portion ⅛″ long and 1/16″ deep with a cathode gap of 0.023″. A neon filling pressure of 58 mm of mercury was used. It can be seen that there is the usual low-current negative slope associated with the transition from breakdown (current range III of Fig. 1). A new characteristic of interest is the second region of negative slope in the abnormal glow range of currents. It has been found that this second region can be made stable with time in a given tube and reproducible from tube to tube. It is also

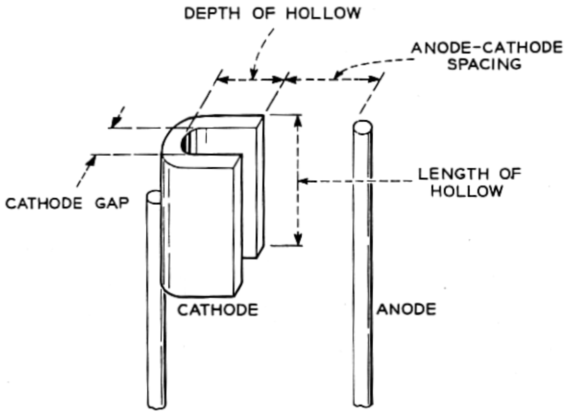

Fig. 10 — Electrode geometry of a hollow cathode tube.

found that the tube impedance has a negative resistance component over the voice frequency range. Thus, this second region of negative resistance offers attractive possibilities as a transmission element.

The impedance of this tube at 300 and 3,000 cps is shown in Fig. 12 for the same range of operating current as Fig. 11. The optimum current for negative resistance and the value of negative resistance are functions of the cathode gap, but so long as the other cathode dimensions are constant the optimum current is relatively independent of the density of the filling gas.

A useful way of studying the interrelation of cathode gap and filling pressure is shown by Figs. 13 and 14. For these data the length and depth of the hollow portion were kept constant at the values of ⅛″ and 1/16″ respectively. Fig. 13 shows the resistive component of impedance as a function of frequency for different filling pressures with a fixed cathode gap.

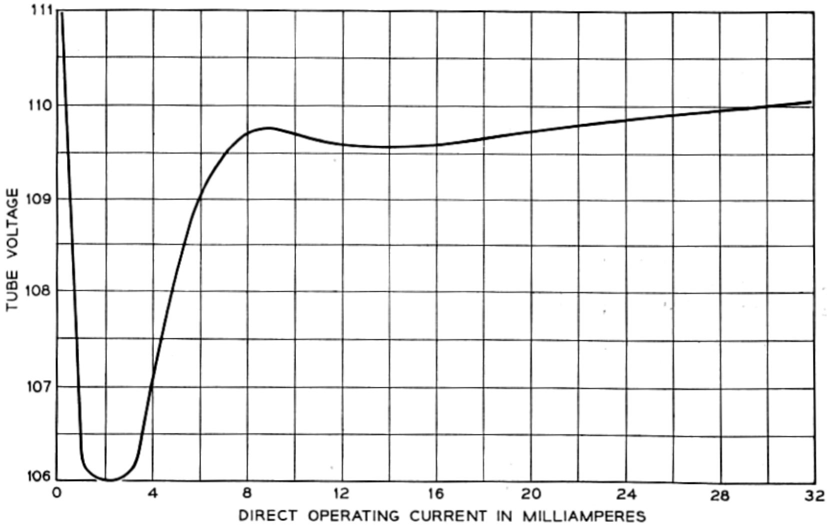

Fig. 11 — Static volt-ampere characteristic of hollow cathode tube.

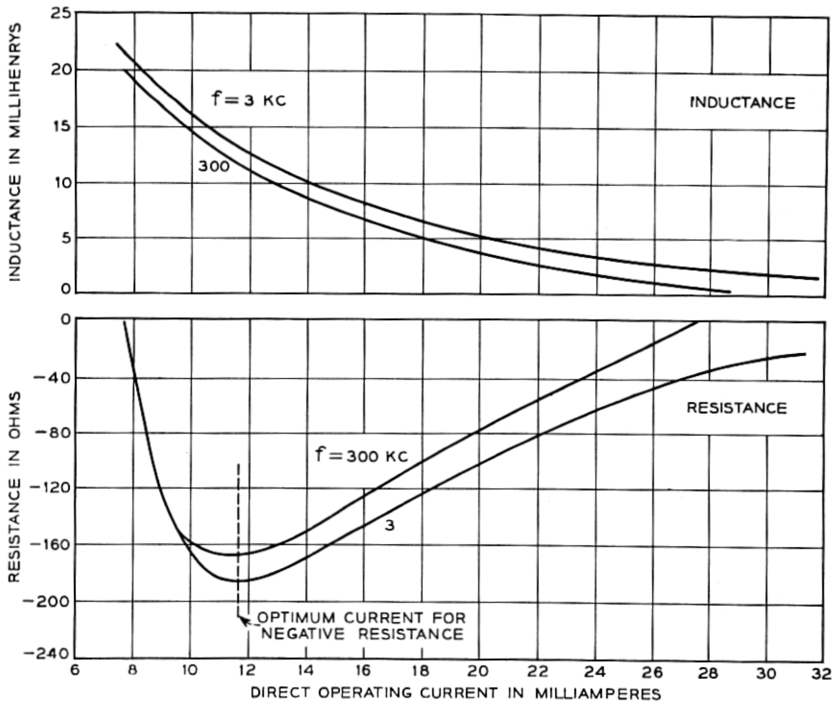

Fig. 12 — Resistive and inductive components of impedance of a hollow cathode tube.

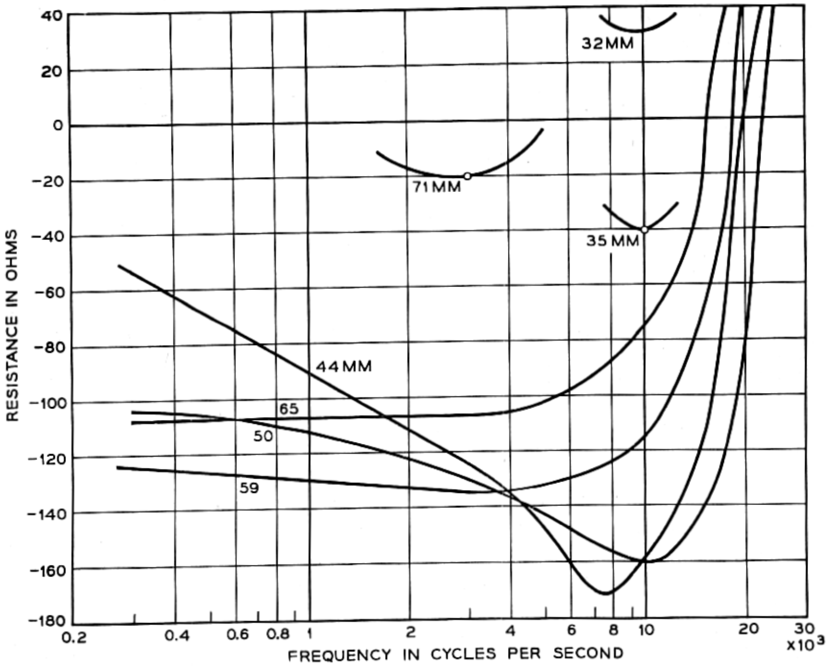

Fig. 13 — Resistive component of impedance as a function of frequency for different neon filling pressures. Cathode gap = 0.024 in.

Fig. 14 shows the variation of the resistive component of tube impedance as a function of frequency for several cathode gaps and at a fixed density of filling gas. For both Figs. 13 and 14, the current was adjusted for optimum negative resistance.

It can be seen from Fig. 13 that the choice of a neon filling gas at a pressure near 60 mm and from Fig. 14 that a cathode gap near 0.024 inch could be expected to yield a negative resistive component of impedance which is reasonably insensitive to filling pressure and which is also constant in value over the voice frequency range. This justifies the choice of cathode gap and filling pressure used in the tube on which the data of Figs. 11 and 12 were taken.

One other parameter of interest is the limit of anode-to-cathode distance. This too is a function of cathode gap and gas density. A typical curve taken for the same cathode geometry and gas filling as used for Figs. 11 and 12 is shown in Fig. 15. It is seen that the negative resistive component is essentially independent of anode distance for a distance of approximately 0.050 inch. This means that the breakdown voltage of

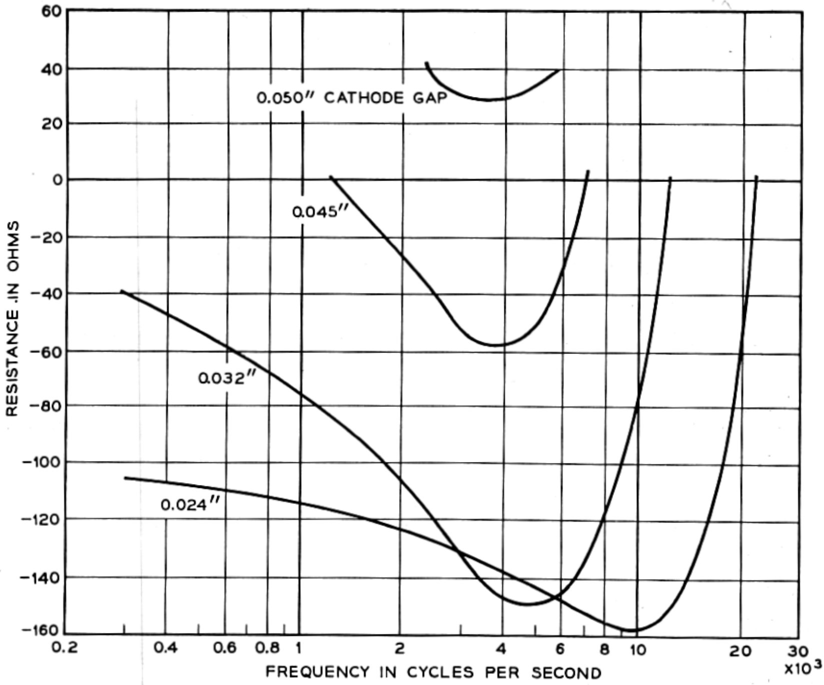

Fig. 14 — Resistive component of impedance as a function of frequency for different values of cathode gap. Neon filling pressure = 50 mm of Hg.

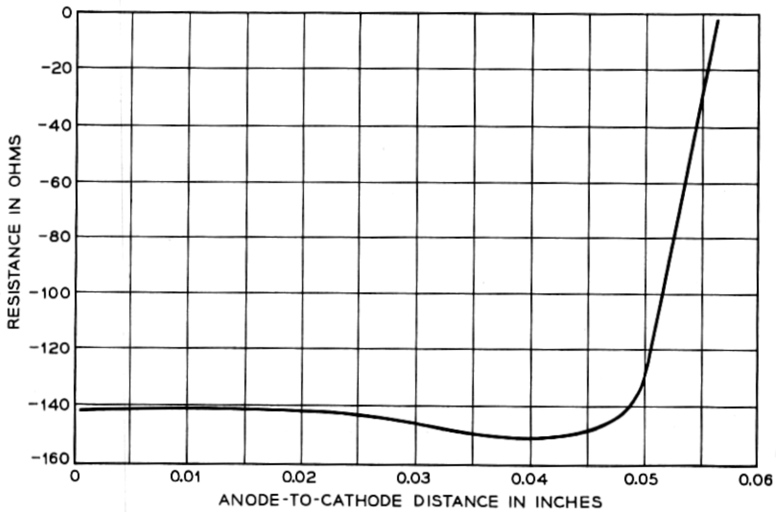

Fig. 15 — Resistive component of impedance as a function of anode-to-cathode distance.

a switching tube can be adjusted by changing this spacing so long as the upper limit is not exceeded.

Although the above discussion is limited to only one adjustable cathode dimension, the cathode gap, other variations are of course possible. The length and depth of the hollow should be at least a few times the width of the cathode gap in order that an efficient hollow be formed. Increasing the hollow length or depth requires larger currents and, if carried too far, the glow may not completely fill the hollow at the optimum current for negative resistance. This is undesirable because the unused portion of the cathode may change its properties with time and produce unstable characteristics. The entire geometry may be scaled to a larger size if the density of the filling gas is reduced by approximately the same factor.

The choice of cathode material is restricted by the high current densities of hollow cathodes. Coatings of alkaline earth oxides or similar materials have too short a life. Pure molybdenum has found to give a satisfactorily low sustaining voltage together with long life and stable operating characteristics. Life tests have shown that tubes can be made which will operate satisfactorily for the equivalent of 20 to 40 years in central office service.

It is seen from the above that by changing the cathode geometry and density of the filling gas a variety of impedance properties can be obtained. The final choice must be determined by the overall transmission requirements. As an example, the transmission performance of a typical tube will now be discussed.

TRANSMISSION PERFORMANCE OF A TYPICAL NEGATIVE RESISTANCE DIODE

The circuit of Fig. 16(a) shows a cold cathode switching tube in series with a transmission path. The voltage across the load resistor R_L under conditions of Fig. 16(a), divided by the voltage across R_L with no tube in the circuit, Fig. 16(b), is one measure of the transmission performance. This ratio, called the insertion voltage gain, is given by

$$\text{I.V.G} = \frac{R_S + R_L}{R_S + R_L + R_t + j\omega L_t}. \tag{5}$$

The derivation of this expression assumes that the transformers are ideal and that the reactance of the condenser C is negligible. Maximum gain occurs at low frequency where the reactive component of tube impedance, $j\omega L_t$, can be neglected. If the resistive component of tube impedance, R_t, is negative, the gain will be greater than unity. The gain approaches an infinite value as the unstable condition is approached where the negative resistance of the tube equals the sum of the source and load resistance. Large values of gain are not practical because this imposes undesirable restrictions on the constancy of the circuit and tube impedances.

Additional restrictions on gain arise from bandwidth and distortion considerations. If it is assumed that both R_t and L_t are independent of frequency over the voice band, it is possible to use the above equation for an approximate calculation of bandwidth. The half-power point occurs at the frequency f_c at which the reactive term equals the sum of the other three terms in the denominator, or

$$f_c = \frac{R_S + R_L + R_t}{2\pi L_t} \tag{6}$$

Since the gain does not fall off at low frequency, the upper cut-off frequency f_c is a measure of the bandwidth. Substituting R_S and R_L from equation (5) into equation (6) gives

$$f_c\,(1 - \text{Low frequency I.V.G.}) = \frac{R_t}{2\pi L_t}\,. \tag{7}$$

Thus for a given tube an increase in gain is accompanied by a decrease in bandwidth.

As shown in Fig. 12 the impedance of a negative resistance tube is dependent on the current passing through it. This will cause some distortion as the signal current swings above and below the average direct current value. The distortion is small so long as the non-linear tube resistance is small compared to the total circuit impedance.

It can be seen from the above discussion that for a given tube the gain, bandwidth, and distortion are all dependent on the source and load impedances. Fig. 17 shows the experimental performance of a typical tube for the special case where source and load impedances were equal. Insertion gain has been converted to power gain in db. The distortion

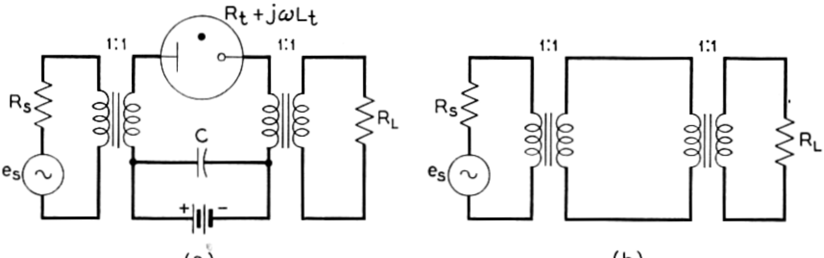

Fig. 16 — Transmission circuits with and without tube.

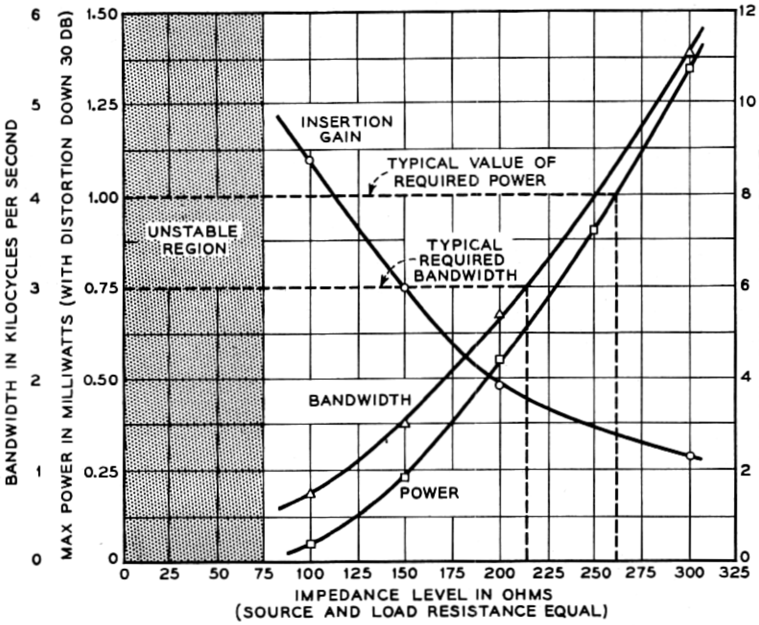

Fig. 17 — Performance curves for experimental cold cathode negative resistance diode.

has been related to the power handling capacity by measuring at each value of source and load impedance, the maximum power output at which the total harmonic distortion is 30 db below the signal.

The noise introduced by a tube affects its usefulness as a transmission element. By designing the tube so that the anode is in the Faraday dark space, anode oscillations are avoided. The remaining noise is at a low level, typical values being 10 decibels above the noise reference level of 10^{-12} watts.

CONCLUSIONS

Cold cathode glow discharge tubes can be made with stable and reproducible impedance characteristics. By proper choice of anode-cathode spacing and pressure of filling gas, it is possible to eliminate oscillation noise associated with the anode region. By properly choosing the density of filling gas and the area of a plane cathode, it is possible to obtain a low positive resistance component of impedance. By proper correlation of cathode geometry and filling gas density, hollow cathodes can be used to obtain a negative resistance component of impedance. Bandwidth, power, distortion, and noise requirements of voice frequency transmission circuits can be satisfied without sacrificing switching characteristics. Cold cathode glow discharge tubes are, therefore, a potentially useful electronic switch for use in series with voice frequency transmission circuits.

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