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COLD-CATHODE GAS-FILLED TUBES AS CIRCUIT ELEMENTS

BY

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THE STRUCTURE AND CHARACTERISTICS OF COLD-CATHODE GAS-FILLED TUBES AND SOME OF THEIR APPLICATIONS

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Cold-Cathode Gas-Filled Tubes as Circuit Elements

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SINCE the discovery by Hull[1] that oxide-coated cathodes could be used as commercially practical thermionic emitters in gas-filled tubes, these tubes have found extensive use. For high-voltage d-c power supplies two-element mercury-vapor rectifiers have almost entirely replaced rotating machines and the earlier high-vacuum tube rectifiers. The addition of a grid to the gas-filled thermionic rectifier yields the thyratron which is used in regulated rectifiers, for the inversion of direct current to alternating current, and as a sensitive relay in numerous industrial control circuits. The discovery by Slepian and Ludwig[2] of the ignitor principle in initiating the arc spot on a mercury-pool cathode provided a ready means for controlling current flow in tubes with mercury-pool cathodes and the ignitron has now shown itself to have a large field of application.

The present paper will concern itself with gas-filled circuit elements of a third type, cold-cathode tubes. The principles of operation of these devices are not new[3] but their wide application has awaited the development of tubes which will operate in low-voltage circuits of, say, 150 volts or less.[4] Functionally, these tubes have much in common with thyratrons but their current-carrying capacity must remain limited because energy dissipation at the cathode of a glow discharge restricts the current which may be drawn without overheating the surface. However, as control devices in that large class of circuits where milliamperes rather than amperes are required, cold-cathode tubes are capable of performing many of the circuit functions of thyratrons and possess several major advantages over tubes of the hot-cathode type.

General Characteristics of the Glow Discharge

The properties of cold-cathode tubes in which we are interested follow immediately from the well-known characteristics of the self-sustaining glow discharge.

Consider two electrodes in a gas at a

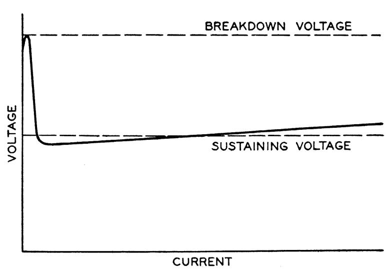

Figure 1. Current-voltage characteristic of typical glow discharge

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1. For all numbered references, see list at end of paper.

reduced pressure. If a low potential is applied between them the few ions which are always present in the gas become multiplied by secondary ionization resulting from impacts of the original electrons and ions with gas atoms and a small current flows through the tube. The gas conduction at this stage is known as the Townsend discharge and the current which flows is called a Townsend current. It is generally of the order of a microampere or less. As the potential between the electrodes is increased the current increases and at some potential, the breakdown voltage, the gas becomes a good electrical conductor. The voltage across the electrodes now assumes a lower value, which we will call the sustaining voltage, at which it remains practically constant and independent of the current, the magnitude of the current being determined by the external resistance of the circuit. Figure 1 shows schematically the current-voltage characteristic of such a discharge tube.

Cold-Cathode-Tube Structure and Characteristics

Figure 2 shows a photograph of a typical cold-cathode tube. The structure consists of three elements, a cathode, an anode, and a control anode. The cathode is a nickel surface coated with a mixture of barium and strontium produced by reduction from the oxides of these metals by positive-ion bombardment in a glow discharge. The anode is a plain nickel wire shielded from the other elements except for its extreme end by a glass sleeve and separated from them by a spacing of about one-half inch. The control anode is placed close to the cathode. In the particular tube illustrated this element is identical with the cathode and therefore these two elements may be used interchangeably. Such construction, however, is not necessary and in other tubes the control anode may be a wire or small surface near the cathode. The gas filling is a mixture of the rare gases, 99 per cent neon—1 per cent argon at a pressure of about 40 millimeters of mercury. Variations in the constitution of this gas mixture may be used to control the electrical characteristics of the device. In such a three-element cold-cathode tube we have to deal with two conduction paths. That between the cathode and the main anode we will call the main gap and that between the cathode and the control anode the control gap. The nominal characteristics and ratings of this tube are given in table I.

Such a tube has many interesting properties as a circuit element. Basically it may be made to perform three distinct circuit functions, those of a relay, rectifier, and voltage regulator. We shall consider these in turn.

The Cold-Cathode Tube as a Relay

Figure 3 shows a typical cold-cathode-tube relay circuit. The supply potential must be greater than the main gap sustaining voltage but less than the main gap breakdown voltage so that no conduction will normally occur. If now a potential exceeding its breakdown voltage is applied to the control gap the resulting ionization will initiate conduction in the main gap and the anode potential will fall to the main gap sustaining voltage, the current being limited by the external circuit impedance. Conduction will continue until the circuit is opened or the anode voltage maintained below the main gap sustaining voltage for a sufficiently long time for the tube to deionize. The control gap current required to cause breakdown in the main gap we will call the transfer current. In magnitude it does not greatly exceed the Townsend currents flowing just below the breakdown voltage. For the tube described it is in general less than one microampere. The cold-cathode tube is thus a very sensitive relay.

The transfer current is a function of the anode voltage. It must obviously be zero at the main-gap breakdown voltage and approach infinity at the main-gap sustaining voltage. Figures 4*a* and *b* show the transfer-current characteristic of the tube illustrated in figure 2 with two different gas fillings. Neon with a one per cent admixture of argon gives a very low transfer current. One hundred per cent argon gives a much higher transfer current and a higher main-gap breakdown voltage.

In using cold-cathode tubes as relays we must consider not only the amplitude of the signal, which together with the control-gap circuit impedance determines the current available for transfer of the discharge, but also its duration. For the Western Electric 313*C* tube it is found that signals of a duration of 200 microseconds are long enough to give reliable operation even when the amplitude of the signal is small. For signals of greater amplitude a shorter signal duration will suffice.

Deionization times are of the order of ten milliseconds, somewhat too long for satisfactory operation on 60 cycles. Tubes with shorter deionization times may be made by using gas filling of pure argon but this may be done only at the expense of increasing the transfer current. Thus while such tubes are faster in their operation as relays they are less sensitive.

The stability and reproducibility of tube characteristics are of interest in circuit design. The important characteristics are the control-gap breakdown and sustaining voltages and the main-gap sustaining voltage. The stability of the main-gap breakdown voltage may vary without detrimental effect on the circuits provided it does not fall to the supply voltage. Several years operating experience with tubes of the 313 type have shown that in general the three characteristics mentioned above will remain within plus or minus five volts of their initial values over several thousand hours of operating life if the current ratings are not exceeded. Deterioration of the tubes or shifts in characteristics on standing are negligible. Variations in initial characteristics will depend upon the degree of manufacturing control and, in general, will not exceed plus or minus ten volts.

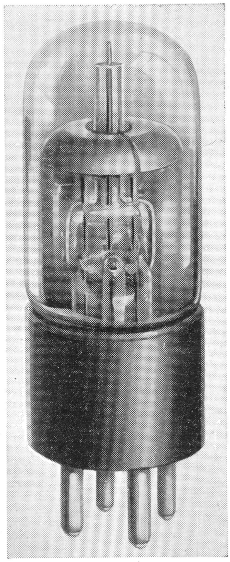

Figure 2. Cold-cathode relay tube

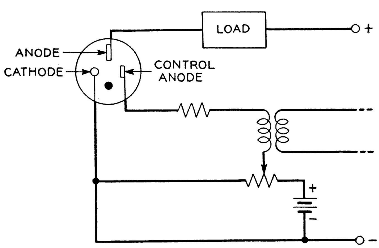

Figure 3. Cold-cathode-tube relay circuit

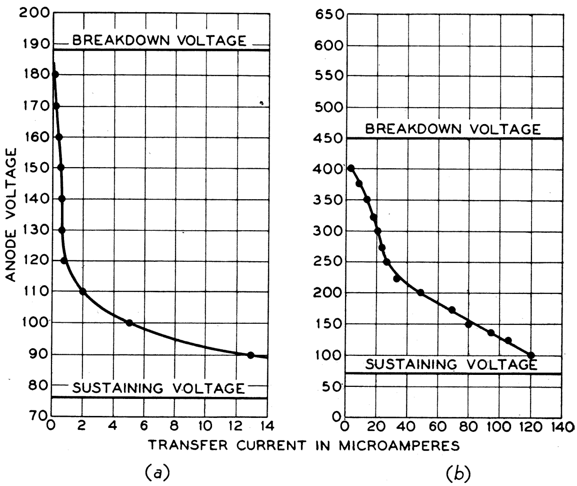

Figure 4. Transfer current characteristic of cold-cathode relay tube

(*a*)—Gas filling; 99 per cent neon, 1 per cent argon, 40 millimeters

(*b*)—Gas filling; 100 per cent argon, 15 millimeters

One limitation on the use of glow discharges as relays should be noted. Oscillation, inherent in the glow itself, and resulting in "noise," makes gas tubes unsuitable to carry voice currents in communications circuits. This restriction, of course, applies to all other gas discharge devices including thyratrons. For control and signalling applications, however, this noise is unimportant.

The Cold-Cathode Tube as a Rectifier

The second circuit function which can be performed by means of cold-cathode tubes is rectification. Rectification requires an asymmetry in the current-voltage characteristic of the rectifying circuit element. When such an asymmetry exists a symmetrical voltage wave applied to the elements results in an asymmetrical current wave in the circuit. The cold-cathode-tube rectifier depends for its operation upon an asymmetrical property of the glow discharge itself. The sustaining voltage is primarily determined by the cathode fall of potential which in turn is largely dependent on the nature of the cathode material. In general low cathode falls are associated with surfaces of low work function. The slope of the current-voltage characteristic depends not only upon the nature of the cathode surface but also upon its

Table I. Characteristics and Ratings of Western Electric 313C Tube

Control-gap breakdown voltage	70 volts
Control-gap sustaining voltage	60 volts
Main-gap breakdown voltage	175 volts
Main-gap sustaining voltage	75 volts
Transfer current at anode voltage of 130 volts	5 microamperes, maximum
Deionization time	
Main gap	10 milliseconds
Control gap	3 milliseconds
Maximum instantaneous cathode current	30 milliamperes
Maximum average cathode current	10 milliamperes
Maximum time of averaging cathode current	1 second
Maximum instantaneous reverse current in main gap	5 milliamperes

area. A small cathode surface produces a steep characteristic. A glow-discharge tube then, with two electrodes one of which is large and coated with a material whose work function is low while the other

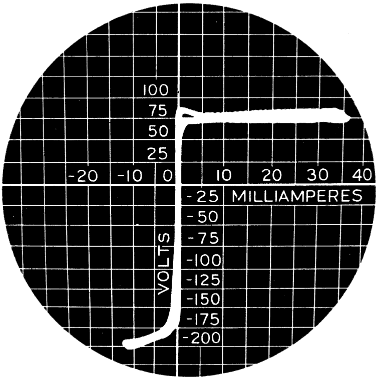

Figure 5. Asymmetrical current-voltage characteristic of cold-cathode rectifier tube

is small and uncoated, will have an asymmetrical characteristic.

The current-voltage characteristic of a Western Electric 313*C* tube connected as in the circuit of figure 6 is shown in figure 5. The trace was obtained by means of a cathode-ray oscillograph, the applied voltage being 208 volts root-mean-square, the load resistor, R_1, 5,000 ohms, and the control-gap resistor R_2, 100,000 ohms. The rectifying properties of the main gap are apparent from this characteristic. The control gap is connected into the circuit only to provide a low starting voltage in the forward direction.

Rectification can also be obtained using two-element tubes, the low starting voltage being produced by designing the tubes so that the anode-cathode spacing is small and the breakdown voltage therefore low. However, cathode sputtering from the small electrode on to the neighboring active surface causes the voltage characteristic of such tubes to be unstable so that three-element tubes are to be preferred.

As rectifiers cold-cathode tubes may be used either to convert an a-c power supply to direct current or to discriminate between positive and negative polarity in a circuit. In power supplies for radio receiving sets several tubes have attained some importance in the past,[5] although unsatisfactory tube life, radio-frequency noise arising from the discharge, and the inherent inefficiency resulting from the large voltage drop have prevented their wide adoption and in recent years their importance has been declining. As polarity detectors, however, cold-cathode tubes have a wide field of usefulness. One extensive application of this type in the communications field will be cited in the latter part of this paper.

The Cold-Cathode Tube as a Voltage Regulator

The voltage-regulating property of the glow discharge is well known. It is based upon the flatness of the current-voltage characteristic shown in figure 1. The sustaining voltage is practically independent of current. Thus in the circuits shown in figures 7*a* and *b* variations in the supply voltage will be practically entirely taken up in the series resistance, the voltage across the tube remaining constant.

Commercial voltage regulators are available which regulate at 60, 70, 90, 110, 130, and 150 volts. All such tubes may be operated in series to obtain regulation at higher voltages. The regulated voltage will in general vary less than five per cent from no load to full load and variations from tube to tube can usually be held to within ± five per cent of the nominal values. The tube illustrated in figure 2 may be used to regulate at either 60 or 75 volts, the sustaining voltages in the control and main gaps, respectively. The two circuit connections are illustrated in figures 7*a* and *b*. In the circuit of figure 7*b* the relay principle has been used to reduce the starting voltage exactly as it is when the tube is used for rectification.

Comparison of Ignitron, Thyratron, and Cold-Cathode Tube

In the introductory paragraph of this paper the functional similarity of the three types of gas-filled control tubes, thyratrons, ignitrons, and cold-cathode tubes, was stressed. These devices have this fundamental property in common. Each one contains a control element, the grid in the thyratron, the ignitor in the ignitron, and the control anode in the cold-cathode tube. Positive potential may in each case be applied to the anode without initiating gas conduction provided the control element is held more negative than some critical value. If, however, this critical value is exceeded, breakdown occurs and the gas becomes conducting. After conduction begins the control element loses all sensible control over the discharge which may be extinguished only by maintaining the anode below the sustaining voltage long enough for the tube to deionize.

Since they have these basic properties in common it is not surprising that the three types of gas-filled control tubes should be functionally similar in their circuit applications. It is scarcely too strong a statement to say that any *type* of circuit set up with one of these circuit elements can also be set up with either one of the others. In spite of this, however, they are not competitive with each other but rather complementary in their functions. This is because, while they are basically similar in principle, their operating characteristics are so widely different that generally in any particular case no doubt will exist as to which device is the *practical* one to use. Table II summarizes in a brief though necessarily incomplete way the comparative characteristics of the three classes of gas-filled control tubes.

The brevity of the table requires that something further be said in explanation.

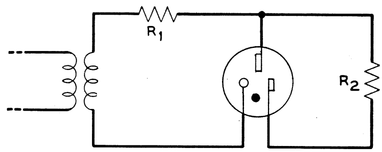

Figure 6. Cold-cathode-tube rectifier circuit

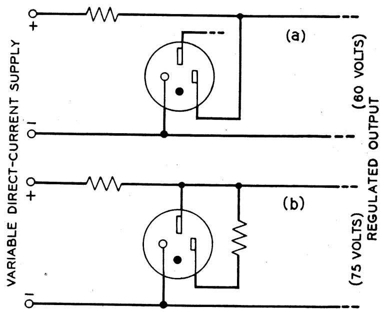

Figure 7. Cold-cathode-tube voltage-regulator circuits

In current-carrying capacity the ignitron is an inherently high-current device, the mercury-pool cathode being capable of supplying thousands of amperes of current. On the other hand, there exists a minimum current for stable operation, of approximately five amperes. Below this current the arc spot will not maintain itself. On the other end of the scale cold-cathode tubes are inherently low-current devices. At currents above about 20 milliamperes per square centimeter the active cathode surface is rapidly disintegrated by positive-ion bombardment. High current capacity then can be obtained only by the use of cathode areas

Table II. Comparison of Gas-Filled Control Tubes

Characteristics	Ignitron	Thyratron	Cold-Cathode Tube
Current capacity	5–10,000 amperes	Up to 100 amperes	Up to 100 milliamperes
Deionization time	10^{-4} second	10^{-4} second	10^{-2} second
Ionization time	10^{-5} second	10^{-6} second	10^{-4} second
Cathode heating time	0	Finite	0
Deterioration in standby service	No	Yes	No
Accuracy of characteristics	Variable	± 2 volts	± 10 volts
Sustaining voltage	15 volts	15 volts	75 volts

NOTE: Where specific values are given these are only approximate and are cited only to make a quick comparison possible.

of impractical size. Existing tubes are capable of supplying peak currents of approximately 100 milliamperes.

In speed of ionization and deionization the ignitron and the thyratron are much faster than the cold-cathode tube. This is because they are low-pressure devices. Argon-filled cold-cathode tubes are faster than those filled with neon-argon mixtures in which the neon predominates. The transfer currents, however, are also much higher so that in the argon-filled tubes sensitivity must be sacrificed in return for speed of operation.

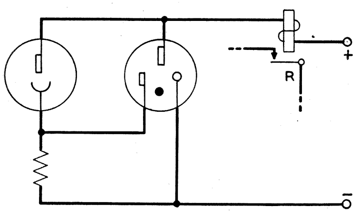

Figure 8. Photoelectric relay

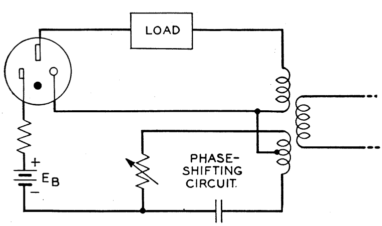

Figure 9. Cold-cathode-tube circuit with phase control

The ignitron and the cold-cathode tube are, except for a brief ionization time, instant starting devices. The thyratron, on the other hand, requires a cathode heating time to bring the cathode to operating temperature. When the thyratron is used as a relay, the cathode must be maintained continuously at electron emitting temperature even though the periods of operation are brief and intermittent. This implies continuous deterioration of the tube even during standby periods. The necessity of supplying cathode power is itself a disadvantage. In service where the operation is intermittent much longer tube life is to be expected with cold-cathode tubes than with thyratrons.

As a voltage-operated device the thyratron is the most sensitive of the three. Its critical characteristic will generally be held within an extreme range of $\pm$ two volts. The variations in breakdown voltage of existing cold-cathode tubes will exceed this by a factor of five. Variability in ignitor rod materials causes ignitron characteristics to be most variable in this respect. For this reason an ignitron is generally controlled by an associated thyratron circuit so that the amplitude of the ignitor current may be made to exceed the critical value by a large margin while the thyratron is used as the voltage-sensitive element.

The sustaining voltage of the discharge is low, approximately equal to the ionization potential of the gas in both the ignitron and the thyratron. In the cold-cathode tube it is higher, approximately equal to the cathode fall of potential. This quantity is characteristic of the cathode material and the gas and is in general lowest for the alkalis and alkaline-earth metals associated with the rare gases. In practical applications the convenience of operation of the cold-cathode tube, since it requires neither filament transformer nor filament power, more than compensates for its lower efficiency resulting from high tube voltage drop.

Circuit Applications of Cold-Cathode Tubes

In cold-cathode-tube circuits as in thyratron circuits the problem of extinguishing the discharge, once it is initiated, must be met. The means available are four in number. The first is the use of an alternating anode voltage. After the removal of the control anode voltage conduction will then continue until the applied anode voltage falls to the sustaining voltage. Reignition will not occur on the next positive cycle if the frequency is low enough to allow the tube time to deionize. The second method is the opening of the anode circuit by a switch or relay contact. Again the length of the interruption must exceed the deionization time. The third is the application of a surge of negative voltage to the anode through a capacitor as in the familiar parallel type inverter circuit. The cold-cathode equivalent of this circuit is illustrated in figure 10 and will be described hereinafter. The fourth is the overshooting of the voltage due to the inductance of the circuit and the dynamic characteristic of the tube when a capacitor is discharged through it. This will be illustrated in considering the relaxation oscillator.

The basic relay, rectifier, and voltage-regulator circuits using cold-cathode tubes have been illustrated in figures 3, 6, and 7. Figure 8 shows a simple cold-cathode photocell relay. Increase of light intensity will cause the relay, *R*, to operate. Means will have to be provided for opening the anode circuit to reset the device for a second operation.

If an alternating voltage is applied to the anode of a cold-cathode tube and an alternating voltage of variable phase applied to the control anode, phase control of the output can be obtained. The circuit is shown in figure 9 and is quite analogous in its operation to phase-control circuits using thyratrons. The bias, E_B, on which the alternating voltage is superimposed should be somewhat lower than the control-gap sustaining voltage.

Figure 10 shows a cold-cathode-tube square-wave oscillator which is the ana-

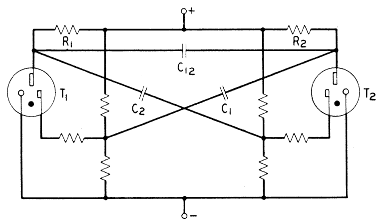

Figure 10. Square-wave oscillator

Note the similarity to the self-excited parallel-type thyratron inverter

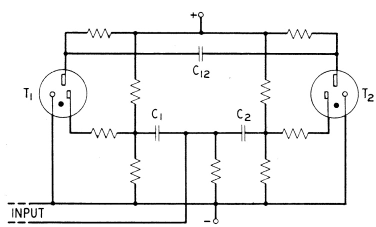

Figure 11. Counting circuit

Note the similarity to the Wynn-Williams "scale of two" circuit

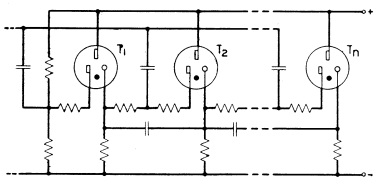

Figure 12. Chain counting circuit

logue of the self-excited parallel-type thyratron inverter. Such a circuit, of course, would not be used for the conversion of d-c power to a-c power since the cold-cathode tube is not a power device. It may be used, however, to generate a block wave to key another circuit. The operation of such a circuit is well known but will be described here since the principles are of general applicability in a variety of other circuits. Assume tube T_2 to be conducting, tube T_1 nonconducting. On the firing of T_1 its anode voltage will drop suddenly from the supply voltage to the sustaining voltage of the tube. This negative surge will be transmitted through the commutating capacitor C_{12}, extinguishing T_2 by driving its anode potential below the sustaining voltage and maintaining it there for a time determined by the time constant R_2C_{12}. A similar surge through C_2 reduces the control anode voltage of T_2 below the control gap breakdown voltage. C_2 charges up through the control gap resistors and T_2 fires when this voltage is again reached. The discharge will thus transfer back and forth between T_1 and T_2 at a rate dependent on the values of the constants in the control anode circuits.

This circuit can be modified as shown in figure 11 so that incoming positive pulses control the transfer back and forth of the discharge. Note that in this circuit the equilibrium potential of the control anodes, as determined by their associated potentiometers, should be below the control-gap breakdown voltage rather than above it as in the preceding circuit. The functioning of this circuit is analogous to that of the familiar "scale of two" counting circuit of Wynn-Williams.[6] For counting closely spaced impulses, of course, the thyratron circuit is preferable on account of the greater speed of operation of the hot-cathode tubes.

A chain of tubes, down which the discharge progresses in steps as successive impulses are fed into the input is shown in figure 12. The drop across the cathode resistor of the conducting tube "primes" the next tube in line so that it, rather than any other, is fired when the next impulse arrives. A potentiometer across tube T_1 gives its control anode an initial priming so that the first incoming pulse fires this tube preferentially. Detailed consideration of the behavior of thyratron circuits of this general class has been given recently by Shumard.[7]

Any glow discharge tube may be used in a relaxation-oscillator circuit. The simplest form of such a circuit is shown in figure 13. Oscillation will generally occur without the presence of the inductance L but its insertion causes the capacitor to discharge to a voltage well below the sustaining voltage rendering certain the extinction of the tube.

A novel use of cold-cathode tubes as relays in a device for the remote control of radio receivers has recently been described.[8] From a circuit standpoint the principal feature of interest in this circuit is the use of a radio-frequency signal on the control gap to fire the tube. As might be expected the peak voltage of the radio-frequency signal required to break the tube down exceeds the d-c control-gap breakdown voltage by a considerable margin.

What is probably the largest use of cold-cathode tubes to date is in an application in telephone communication where they have found extensive use in a four-party subscriber set for selective ringing.[9]

The circuit is illustrated in figure 14. Of the four ringers, two are connected to one side of the line, two to the other, ground being used to complete the circuit. For selective operation of the two ringers on one side of the line a ringing signal is used which consists of an alternating voltage on which is superimposed a direct voltage. The cold-cathode tubes functioning as rectifiers are placed in series with the ringers and are oppositely poled in the two cases. One ringer responds to positive superimposed voltage, the other to negative.

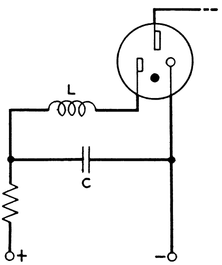

Figure 13. Simple gas-tube relaxation oscillator

One particularly valuable property of the tube in this application not possessed by rectifiers of other types is that as long as the breakdown voltage is not exceeded, the tube represents virtual open circuit to ground. Thus no transmission loss is experienced and no ground noise is introduced into the circuit when the line is used for voice transmission, the talking battery voltage having in general a nominal value of either 24 or 48 volts.

In the older type of equipment a-c relays were used to disconnect the ringers from the line except when ringing voltage was applied. Selection between the positive and negative polarities was obtained by means of mechanically biased ringers.

Summary

Three types of gas-filled control tubes are now in common use. The properties of cold-cathode tubes, the most recent of these to receive extensive application, have been considered and comparisons drawn with those of the more familiar thyratron and ignitron. It is concluded that in its own field of low-current control devices the cold-cathode tube has several inherent advantages which will ensure a wide use for it in the future. These advantages are, the ability to operate without cathode heating power, the ability to start immediately when a signal is applied, and the absence of deterioration in standby service.

A number of typical circuits illustrating the capabilities of the tubes as circuit elements have been described. Several of these are in commercial applications. One, involving some hundreds of thousands of tubes, has been operating for several years and proves beyond doubt that the cold-cathode tube is a valuable addition to the array of control devices available to the circuit engineer.

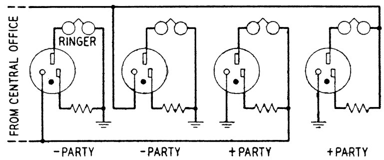

Figure 14. Four-party selective ringing circuit

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