THE PRINCIPLES AND METHOD OF OPERATION OF SOME MODERN GAS-FILLED COUNTER TUBES*

by

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SUMMARY

Four types of electrical discharge possible in a gas-filled tube are discussed, and the conditions under which each arises are outlined. The methods of operation of gas-filled counter tubes such as the Remtron, Dekatron and Nomotron are then described.

1. Introduction

Mechanical and electro-mechanical counters have an upper limit of frequency, and beyond that limit it is necessary to use electronic valve counters of some form. Various types of hard valve counters have been described, which are generally, though not invariably, based on the Eccles-Jordan "scale-of-two" circuit. A number of thyratron circuits of a somewhat similar nature have also been used. The latest entries into the field, however, are cold-cathode gas-filled tubes with one anode and a number of cathodes, arranged so that only one anode-cathode gap is conducting at any time. The counting is done by extinguishing one gap and striking the gap adjacent to it for each input pulse, in a manner described later. These devices, too, have an upper limit of frequency which varies with the particular design used, but they appear to be very useful for the range up to 25 kc/s or 30 kc/s.[1]

In order to appreciate the method of operation of these tubes it is necessary to understand something of the nature of electrical discharges in gases, and in this paper that approach has been adopted.

2. Electrical Discharges

If two electrodes are sealed off in an envelope containing gas (usually at a low pressure) and a direct voltage is gradually applied between them, a number of types of discharge may take place.

1. Townsend discharge (dark current)
2. Normal or abnormal glow discharge
3. Arc discharge
4. Corona discharge

With alternating voltages, these phenomena are still present, but may be masked by other effects, particularly at frequencies above 1 Mc/s or so.[2]

2.1. *Townsend Discharge*

With a low applied voltage, no ionization of the gas takes place except that introduced by an external agent, such as cosmic rays, radioactivity, etc. The electrons produced in this way are attracted to the positive electrode (anode), but they may also recombine with positive ions, or attach themselves to the walls of the envelope. Similarly the positive ions move to the negative electrode (cathode) or are lost by recombination or attachment to the walls. As the applied voltage is increased, an increasing proportion of the electrons and ions find their way to the anode and cathode, until saturation is reached when all the electrons and ions are swept away as fast as ionization occurs, and no losses by recombination or attachment occur.

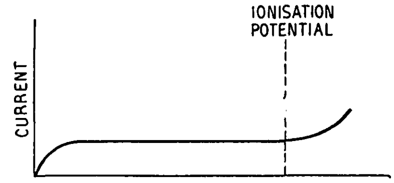

Fig. 1.—The curve of current against voltage for the Townsend discharge. The current is of the order of one microampere.

The next stage is reached when the applied voltage becomes just high enough to accelerate the electrons so much that additional atoms of gas are ionized by collision, the potential required to do this being the "ionization potential." This causes an increased current, but the effect is not cumulative because the electrons

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produced by collision in this way are nearer to the anode than those produced by the external source of ionization, and so have less chance of causing further ionization. The curve of voltage against current thus has the form shown in Fig. 1. The current, known as dark current because it does not produce any visible illumination, is of the order of one microampere.

2.2. *Glow Discharge*

If the voltage is increased further, then under certain conditions a considerable increase in current takes place. The positive ions produced by external ionization are accelerated towards the cathode, and acquire sufficient energy to cause the emission of electrons from the cathode surface. These electrons are accelerated towards the anode by the field near the cathode, causing further ionization. This process does become cumulative, thus removing the necessity for further external ionization. The positive ions produced in this way form a dense positive space charge which extends from the cathode towards the anode; and nearly all of the applied voltage between the anode and cathode appears across this space charge. Thus for the same anode voltage, there is a much greater field close to the cathode than existed before the formation of the space charge, and because of this a smaller potential is needed to maintain this form of discharge than is required to initiate it.

In between the anode and the end of the space charge near the cathode atoms and molecules of gas are continually under bombardment by fast-travelling electrons, causing not only ionization, but also excitation, which leads to the emission of electro-magnetic radiation characteristic of the gas concerned, some of which is within the visible spectrum; hence the term "glow discharge."

A diagram of this type of discharge is shown in Fig. 2, together with the potential and field strength along the length of the tube. Close to the anode, the field strength may rise or fall, depending on the nature of the anode itself.

The presence of the dense positive space charge in the cathode dark space leads to the rapid rise of potential (the "cathode drop") near the cathode surface, then a small fall followed by a slow rise of potential through the positive column, sufficient only to replace those ions lost to the walls of the tube. This rise of potential thus decreases with increasing tube radius.

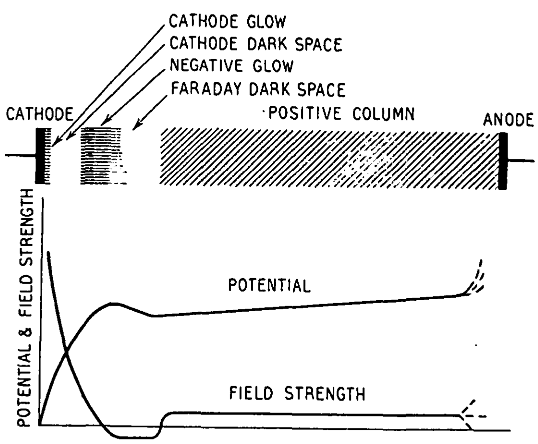

Fig. 2.—The general appearance of the glow discharge, together with the distribution of field strength and potential difference between the anode and cathode.

The conditions for a glow discharge may be summarized as follows:—

(*a*) The positive ions must be accelerated sufficiently to cause electron emission at the cathode. This implies a minimum voltage, and a minimum mean free path.

(*b*) The electrons emitted, in their journey to the anode, must be accelerated sufficiently to ionize further molecules or atoms. This implies again a minimum voltage, a minimum free path, and also an adequate number of atoms present to provide enough collisions.

These conditions are embodied in Paschen's Law, which relates the applied voltage to the product of the pressure and the electrode spacing (for plane electrodes) by the form of curve shown in Fig. 3.

At the point M, the conditions are most favourable for ignition. Here the pressure and distance are such that the anode-cathode spacing is very approximately equal to the mean free path of the electron.* If the pressure is increased the electron mean free path is decreased, while

* The number of electron mean free paths in this space has been the subject of some controversy. Two

(*continued overleaf*)

if the spacing is increased, the field near the cathode for the same applied voltage is also decreased. This explains the rising curve towards B. If either the pressure or the distance is decreased the number of atoms available for collision-ionization is reduced, and the curve rises again towards point A.

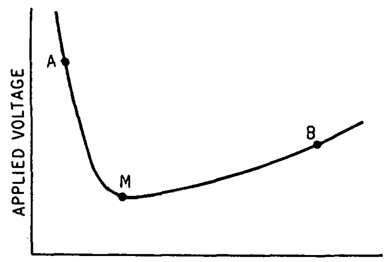

Fig. 3.—The variation of applied voltage necessary to initiate a glow discharge with the product of electrode spacing and gas pressure (Paschen's Law) for plane electrodes.

The above reasoning applies only to the initial breakdown of the gas, and as soon as any appreciable currents flow, the formation of the positive space charge modifies the picture. The applied voltage is now concentrated across the cathode dark space giving rise to a much smaller (in general) distance between the effective anode and cathode. In most cases Paschen's Law, and the reasoning used above, can be applied to this "cathode to virtual anode" spacing in the same way.

For a point such as B, to the right of point M, ignition is very quickly followed by the establishment of the cathode dark space and the associated space charge. The effective anode-cathode spacing is reduced, and consequently the applied voltage (for the same current) decreases, provided the external circuit permits. If the voltage is derived from a battery in series with a resistance, the voltage can only decrease if the current increases, causing increased current density, a greater space charge, and thus a further decrease in the cathode dark space and the applied voltage. The current accordingly increases still further and this process continues until the cathode dark space corresponds to the point M. If the current cannot increase, and is held fixed, then a reduction in the area of the cathode covered by the discharge will lead to an increased current density, a smaller cathode dark space, and again a reduction in the applied voltage. The active area on the cathode thus shrinks and the cathode dark space becomes smaller until conditions corresponding to the point M are reached. The potential at M is known as the maintaining potential, and the discharge is known as "normal glow" discharge.

The characteristic of the "normal glow" discharge is that only part of the cathode surface is covered by the discharge, and the current may be increased with only a very small increase in applied voltage (to account for small changes in the potential drop across the positive column), up to the point where all the cathode is being used. Further increase in current then leads to increased current density, a smaller cathode dark space, and operation at an increased voltage drop. This is characteristic of the "abnormal glow."

For an electrode spacing and pressure corresponding to a point such as A, to the left of point M, the initial ignition voltage is higher than at M. The formation of a space-charge and cathode dark space, with a still smaller effective anode-cathode spacing, would call for a still higher applied voltage, rather than a lower voltage as in the previous case. The whole cathode takes part in the discharge, and increased current is accompanied by increased voltage, as in the "abnormal glow" discharge.

2.3. *Arc Discharge*

If the current in a glow discharge tube reaches sufficient proportions, small portions of the cathode surface become hot enough to give rise to thermionic emission, and the current again increases very greatly. The maintaining voltage drops to a low figure, usually just above the ionization potential for the gas concerned, and currents of from one ampere to hundreds of amperes may be encountered. This is the arc discharge, the precise mechanism of which is still far from completely understood.[6]

well-known authorities[3,4] have held that the number must be nearer fifty than one, basing their arguments on theoretical grounds. Others[5] have produced experimental evidence that the number is close to unity. In a more recent paper[6] one of the two authorities referred to above has thrown some doubt on the validity of the theoretical work, and so the author has felt free to adopt the experimental evidence and quote a value of unity.

2.4. *Corona Discharge*

The corona discharge is a particular case where one, at least, of the electrodes has a sharp radius of curvature, causing a high concentration of electric field at its surface. Typical cases are those of needle-points in air at atmospheric pressure, a long thin wire inside a hollow cylinder at low pressure, and, of course, extra high voltage overhead transmission lines. Corona discharge in air takes the form of bluish tufts or streamers of light, and is accompanied by a hissing sound, and, generally, a smell of nitrous oxide.

3. Multi-cathode Counter Tubes

Multi-cathode gas-filled counter tubes are based on the following principle:—If there are two adjacent cathodes and one anode in a normal glow gas tube, and one cathode is glowing while the other is not, the voltage required to break down the second gap is less than it would be in the absence of the first gap, because of the diffusion of ions out of the first gap into the second anode-cathode space. This reduction in breakdown voltage is termed the ionization coupling voltage. A number of cathodes are symmetrically disposed around a central anode, which is connected through a suitable resistor to a positive voltage so that only one cathode-anode gap will break down, the maintaining voltage of that gap being less than the breakdown voltage for the other gaps. Each input pulse is made to extinguish one gap, and to strike the gap next to it in cyclic order, by various forms of transfer electrode. With ten main gaps, one complete cycle thus corresponds to ten input pulses, and a single output pulse can be taken from one of the cathodes.

There are two types of counter tubes, depending on how the transfer mechanism is arranged. In the Remtron[7] and Dekatron[8] two transfer electrodes are used for each main cathode, and a pair of pulses has to be generated for each pulse to be counted. In the Nomotron[9] cathodes having a directional property are used, and only one input pulse is required for each "count."

4. The Remtron and the Dekatron

These two tubes are somewhat similar in principle. In each case one anode, ten cathodes, and twenty transfer electrodes are used, as shown diagrammatically in Fig. 4. The cathodes are spaced equidistant from the anode, and are screened from each other by mica plates, or by separate metal plates held at a suitable potential. The spacing, gas and pressure correspond to a "normal glow" discharge. If one cathode glows, the maintaining voltage of that cathode-anode gap is insufficient to ignite any of the other gaps, the anode being connected to a positive voltage through a resistor.

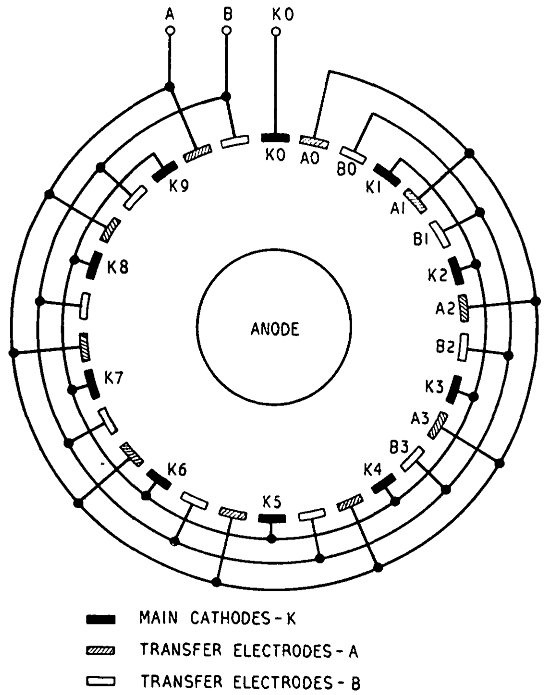

Fig. 4.—Diagram representing the electrodes in the Remtron and the Dekatron.

The transfer electrodes are connected to a more positive potential than the cathodes. If cathode K1 is glowing, and a negative pulse is applied to the transfer electrodes A, the presence of the ions already near cathode K1 will reduce the ignition potential of the gap between the anode and the transfer electrode A1, which will break down before any of the others, and as the anode current is supplied via a resistance, the anode potential will drop, and the anode-cathode gap will de-ionize. If a negative pulse is applied to transfer electrodes B simultaneously with the removal of the negative pulse on A, the glow will similarly transfer from A1 to B1, and thence, when the pulse is removed from the transfer electrodes, to cathode K2. In this way the glow progresses from cathode K1 to cathode K2, to cathode K3, and so round to K0 and K1 again. Cathodes K1 to K9 may be joined together, and cathode K0 isolated to provide one output pulse for each ten pairs of input pulses.

The Dekatron is arranged as shown in Fig. 4, with a central anode and wire cathodes and transfer electrodes around it. The construction is simple, and the operating currents are stated to be low. The maximum speed is quoted as 600 c/s, though possible developments up to 20 kc/s are mentioned.[8]

The Remtron has a circumferential anode with the cathodes and transfer electrodes arranged inside. The operating current is higher than for the Dekatron but lower than for the Nomotron referred to later. Counting speeds up to 16 kc/s are quoted.[7]

The main disadvantage of the Remtron and Dekatron lies in the necessity for a pair of sequential pulses for each count.* The associated circuits (using high-vacuum valves) are quite complicated,[11] and tend to discount the simplicity of the counter tubes themselves. It should however be noted that they can count backwards, if desired; all that is needed is to reverse the order of the pulses to the two sets of transfer electrodes.

5. Directional Cathodes and the Nomotron

The Nomotron (the G10/240E), is essentially a non-reversible tube, and it uses a directional cathode to ensure that the count continually progresses. Its maximum operating speed is quoted as "at least 25 kc/s," and the associated circuits are very simple, the only coupling devices between two tubes in series being a gas trigger tube[9] (the G1/370K), small selenium rectifiers, capacitors and resistors.

In the Nomotron, the anode is essentially circumferential, and the cathodes are arranged around a circle inside the anode, with one transfer electrode in between each pair of cathodes. A simplified diagram is shown in Fig. 5. The gaps between the anode and each cathode or transfer electrode correspond to normal glow spacing, and ionization coupling exists between each pair of electrodes. The transfer electrode is triangular, and this would give a slightly greater coupling to the following cathode than to the preceding one were the cathodes uniform. The cathodes are, however, specially shaped, as will be explained later. The anode is connected in series with a resistance, and each cathode may be connected with a resistor-capacitor time-constant circuit in its cathode, as shown in Fig. 6.

Suppose K1 had been conducting, and the glow has just been transferred to T1 by a negative pulse on the transfer electrodes. The cathode K1 will remain more positive than the other cathodes for a time determined by the cathode circuit time-constant. If the pulse is removed from the transfer electrodes, K1 and K2 will ignite before any of the other cathodes because of the ionization coupling from T1. As K1 is already more positive than K2, K2 will ignite first, and the glow will transfer from T1 to K2.

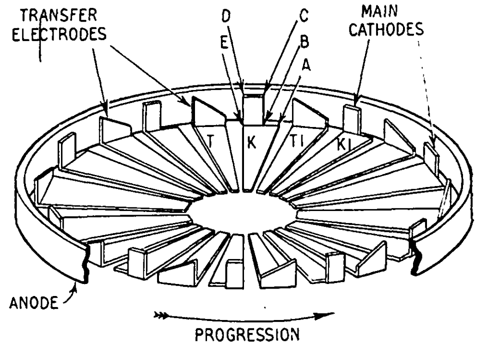

Fig. 5.—The electrode arrangement in the Nomotron.

The cathode K2 will glow first in the portion nearest to the electrode T1, i.e., on the thin edge AB (Fig. 5). As the glow transfers completely and T1 de-ionizes, the current to K2 increases. The glow spreads along the edge and when the edge is covered, the current density increases causing the dark space to get shorter and shorter until it reaches the minimum point M on the Paschen Law diagram. At this point the voltage begins to rise, and the glow spreads on to the turned-over edge (the plate BCDE) of the cathode. This plate has a much greater area than the edge and thus does not saturate at so small a current. Also the plate is slightly nearer the anode than the edge. There is one other difference between the plate-anode discharge and the edge-anode discharge, and that is in the cross-section of the glow discharge. The plate is almost square, whereas the edge is long and

* A newer form of Dekatron has recently been described which needs only a single pulse for each count.[10]

narrow. The loss of ions by diffusion out of this narrow stream is far greater than out of the squarer plate stream, and thus its maintaining voltage is higher. Once the plate-anode discharge is stabilized, the edge-anode gap becomes deionized, and the tube is ready for the next pulse on to the transfer electrodes, and it will be seen that the ionization coupling from K2 is higher to T2 than to T1. Thus, on the next pulse T2 will conduct, rather than K1, which provides the desired directional property to the counting.

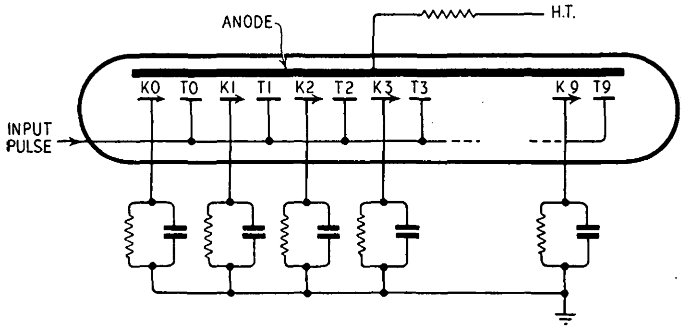

Fig. 6.—Circuit connections for the Nomotron.

The discharge is restricted in all cases to desired portions of the tube by using control plates (or screens) mounted very close to those parts of the electrodes which are not required to take part in the operation. The spacing is small compared with the normal cathode dark space, and this effectively screens these surfaces off. The gas used is a special mixture with a high rate of de-ionization, and this, in conjunction with the restriction of the glow to the active portions of the tube, leads to a high maximum repetition frequency.

6. Conclusion

The three tubes described are good examples of the application of gas-discharge phenomena to counting problems. No attempt has been made to give any detailed circuits, but rather the emphasis has been laid upon the internal operation of the tubes themselves. The fields of electronic counting, switching, and storage of information offer numerous opportunities for the use of such tubes, and of others, based upon the same principles, which may be forthcoming.

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Note added by Author, July 1953.

This paper was written early in 1952. The field of gas-filled counter tubes is a rapidly-expanding one and some of the details given above are now rather out of date. Other tubes have entered the field and those referred to have undergone considerable development. In particular, the Dekatron will now count satisfactorily at 20 kc/s and even higher speeds are planned. The advent of the single-pulse Dekatron, as noted,[10] has simplified the driving circuits considerably.