ELECTRONIC COUNTING CIRCUITS

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PREFACE

In spite of the importance of counting circuitry in modern electronic equipment, it is understood that no book has appeared in the English language specifically on this subject since W. B. Lewis's 'Electrical Counting' was published by Cambridge University Press in 1942. At that time very few counting techniques were known. A paper-backed book entitled 'Elektronische Zählschaltungen' by K. Apel was published in German by Franckh'sche Verlagshandlung, Stuttgart, in 1961. Although numerous papers have been published on counting circuitry, a search of the literature consumes a great deal of time even if the required publications do happen to be available when they are needed. In addition, some papers are not easily read by those who do not already have a reasonable knowledge of the subject. This book has been written to meet the needs of students, designers, servicemen and users of electronic counting equipment who require the theory of operation and practical information on all of the normal types of counting circuit in one volume.

It is assumed that readers have a reasonable knowledge of basic physics and of the operating principles of thermionic valves and transistors. Where other devices (such as trigger tubes and tunnel diodes) are employed in counting circuits, the basic principles of operation of the devices are discussed.

Many of the circuits reproduced in this book are those recommended by the manufacturers of the tubes or semiconductors employed. This should ensure that they are some of the best and most reliable circuits available, since the component manufacturers normally know far more of the advantages and limitations of their own products than anyone else and can make due allowance for these limitations in the circuits they design. A practical approach has been adopted throughout the book and component values are given in most circuits. A fairly large number of references have been included to assist those requiring further information on any particular topic.

The circuits have been classified according to the type of component employed for the counting operation rather than the particular type of circuit (ring, binary, binary coded decade, etc.) used, since it is felt that this approach is a more practical one. Each chapter has been written so that it is essentially complete in itself and may be understood by anyone who is reasonably familiar with the material of the first chapter; this has necessitated a small amount of repetition, but should assist readers who require information on one specific type of circuit. Some of the older types of circuit which are now seldom used have been included to make the book as comprehensive as possible. As in most other fields of electronics, there is a general trend for solid state devices to replace the larger circuits employing vacuum or gas filled tubes and this has inevitably resulted in some types of decade tube becoming obsolete.

The basic principles of counting are discussed in Chapter 1. The various types of counting circuit are described in detail in Chapters 2 to 9 inclusive. Readout devices not covered in the earlier chapters are discussed in Chapter 10. A short survey of nuclear radiation detectors (often referred to as 'counters') is given in Chapter 11 together with some details of the circuits with which they are normally used. An attempt has been made in Chapter 12 to outline some of the more important uses of counting circuits in industry and in instrumentation (other than in computers) and to provide general information on some particular types of application.

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I

Introduction

Enormous advances have been made in all types of electronic instrumentation during the last twenty years, but this progress is most apparent in the design of modern electronic counting equipment. Much of the earlier work on counting circuitry was stimulated by the very great post war developments in nuclear physics and in the applications of radio-isotopes in research, industry and medicine. For these purposes high speed counting equipment is essential. Counting equipment is, however, very useful for many purposes other than that of counting nuclear particles. It is an essential part of most automation processes in modern factories, enables high speed computers to be constructed and when used in laboratory equipment allows many kinds of measurements to be made quickly. The answer is often presented in the form of actual digits to many significant figures. Electronic methods of counting are gradually replacing many of the mechanical systems used in industry, since they are very much faster, more versatile and generally more reliable.

1.1 BASIC COUNTING METHODS

There are two basic types of measurable quantity. The first type consists of a whole number of discrete individual events, for example the number of articles coming off a production line. If each event is converted into an electrical impulse (e.g. by means of a photocell), the number of pulses and hence the exact number of articles can be counted electronically. If the equipment is working correctly, there should be no error whatsoever. The second type of measurable quantity may vary continuously and need not have an integral value; examples of such quantities are time, the rate of flow of a liquid through a pipe and the electrical potential between two points. Such a quantity can normally be converted into electrical impulses, the number of impulses or the frequency of the impulses being a measure of the quantity concerned. The impulses can be counted electronically, but the accuracy of the overall measurement is obviously limited by the fact that a fraction of a pulse cannot be generated. Thus counting equipment can, in principle, be used to make almost any kind of measurement and may be designed to provide outputs which can be used to control even the most complicated machinery.

One of the first methods by which electrical pulses were counted involved the use of an electromagnetic register. This type of register consists of a relay mechanism and a drum on which the digits 0 to 9 are painted. Only one of these digits is visible through the viewing aperature at any time. When a suitable pulse of current is passed through the magnetising coil, an armature is attracted and the drum is moved so that the succeeding digit is indicated. When the drum returns from 9 to 0 at the tenth pulse, a mechanical linkage may be used to cause a second similar drum to move so that the latter indicates the digit 1. The two drums together indicate the number 10. This arrangement may be used to count up to 99 pulses, but more drums may be used if necessary so that larger numbers may be indicated. The type of display from an electromagnetic register is similar to that from the mileage indicator of a car. The registers are described in detail in Chapter 2.

The maximum speed at which an ordinary electro-magnetic register can operate is about 10 to 25 pulses per second. This is much too slow for many applications. Valve counting circuits were therefore designed which would divide or scale down the number of incoming pulses by a suitable factor. The output pulse frequency from the valve circuit could be counted by an electro-magnetic register. If the scaling factor is ten, the valve circuit provides one output pulse for each ten input pulses applied to it. Such valve circuits became known as scalers because they scale down the input pulse rate. The valve scaling circuit and the succeeding electro-magnetic register were often placed in the same unit, the whole of which became known as a scaler. Nowadays any piece of counting equipment which counts each individual pulse is known as a scaler.

A circuit which provides one output pulse for each ten input pulses applied to it is known as a decade counting circuit, or merely as a decade. Valve decades were the first type to be designed, but are relatively large and require a considerable amount of power. Various special tubes with many electrodes have been designed which enable counting circuits to be constructed in a much smaller volume, only one of these special tubes being required in each decade circuit; such tubes are known as decade counting tubes or decade tubes. The three main types of decade tube are the gas filled cold cathode tubes (Chapter 4), the E1T cathode ray tube (Chapter 5) and beam switching tubes (Chapter 6). Most types of decade tube first came into production about 1950. Modern scalers for very high speed operation often employ semi-conductor counting circuits.

1.1.1 Ratemeters

Scalers count each individual pulse separately. Another type of circuit amplifies, shapes and smooths out the incoming pulses and uses the resulting current to deflect a meter. The meter indicates the rate of arrival of the input pulses with a reasonable degree of accuracy. Instruments using this principle are known as ratemeters. They have the advantage that they are rather simpler to use than scalers, since they give direct readings and no time measurements need be made.

1.1.2 Pulses

The units which are counted by electronic circuits are electrical pulses. An electrical pulse consists of a transient change in the potential difference between two points in a circuit or a transient change in the current flowing at a certain point in a circuit. The duration of the pulse may vary from a very small fraction of a microsecond to many seconds, after which the voltage or current returns to its former quiescent value. If the potential at a point in a circuit becomes more positive for the duration of the pulse, the latter is said to be a positive going pulse at the point concerned. At another point in the circuit, the pulse caused by the same initial event may be negative going. An ordinary valve amplifier in a common cathode circuit or a transistor amplifier in a common emitter circuit will invert a pulse; that is, a negative going pulse applied to the input of the amplifier will be converted into a positive going pulse at the output and, of course, vice-versa.

The simplest type of pulse is formed when the voltage (or current) at a certain point in the circuit is switched from its quiescent value to another value and remains constant at this new value until the end of the pulse, when it is switched back to its quiescent value. If the switching process could be carried out instantaneously, the pulse would be a theoretically 'ideal' pulse in which the graph of the voltage (or current) during the pulse plotted against time would be rectangular in form. Such pulses are known as rectangular or square pulses. The difference between the two voltages is the amplitude of the pulse; the only other variable in the case of a rectangular pulse is the duration.

Any actual pulse can only approximate to a rectangular pulse, since the electrical potential or the current flowing at any point takes time to rise or fall to a new value owing to the presence of stray capacitance and inductance in the circuit. The time taken for the voltage to reach its maximum value (or, in the case of a negative going pulse, the time taken for the voltage to reach its minimum value) is known as the rise time of the pulse or as the duration of its leading edge. The fall time is the duration of the trailing edge. The slope of the leading or trailing edge is often important and may be expressed in volts per microsecond or some similar units. The slope of a pulse edge multiplied by the rise or fall time is equal to the pulse amplitude if the edge is linear. Some pulses are more or less triangular in shape and remain at their peak value for only a very short time; in this case the sum of the rise and fall times is equal to the total duration of the pulse. Other pulses may have curved leading or trailing edges and may have a flat or undulating top. Pulse shapes may be determined by means of an oscilloscope which has an adequate frequency response.

An electronic circuit will not count every type of pulse. A pulse with a duration of a microsecond would be too short for the direct operation of an electro-magnetic register or some types of decade tube. On the other hand if a counting rate above 1 Mc/s is to be attained, the input pulses must have a duration of less than a microsecond or neighbouring pulses will partly coincide. Normally a minimum input pulse amplitude and a minimum duration for which this voltage change should be present are specified as the input requirements for any counting circuit. If the amplitude or the duration of the input pulses are too small, the circuit may not count every pulse. Counting circuits may also become unreliable if the input pulses are many times too large, but the amplitude of large pulses is normally adjusted by the input stages of the equipment before the pulses reach the actual counting circuits themselves. In addition there may be upper and/or lower limits on the slope of one or both of the pulse edges.

Circuits are available which will alter the amplitude and the duration of pulses to a value which is suitable for the operation of a given counting circuit; some of these pulse shaping circuits are discussed later in this chapter. In fact the shape of a pulse is altered somewhat by any amplifier, but this alteration can be kept fairly small by choosing an amplifier which gives constant amplification over a suitably wide range of frequencies.

1.1.3 Resolving Time

If two pulses which are closely spaced together in time are fed into a scaler, only one count will be recorded. If the time interval between the pulses is gradually increased, a point will be reached at which the two pulses will just be counted separately. This time is known as the resolving time or the resolution time of the scaler. An instrument with a small resolving time can count at high speeds.

If a counting circuit has a resolving time of, say, 100 μsec, it can count at frequencies up to 10 kc/s without any counts being missed provided that the incoming pulses are evenly spaced in time. The pulses will be evenly spaced if they are derived from such things as an electrical oscillator or from a rotating shaft by means of a suitable pick-up device.

In some cases, however, the incoming pulses have a random distribution in time. For example, the particles from radio-active materials are emitted at random times. If two particles which are spaced very closely together in time enter a Geiger tube, only one output pulse will be obtained from the tube. Thus a Geiger tube has its own resolving time (which is normally of the order of 100 μsec). There is always a certain probability that two particles will enter a Geiger tube within the resolving time of the equipment and the number of nuclear particles counted in a given time will, therefore, always tend to be slightly less than the number which would have been counted if the apparatus had had an infinitesimal resolving time. The percentage of particles not counted (because they enter the Geiger tube at a time which is too close to the time of entry of another particle for each to be resolved individually) will increase as the counting rate increases. The percentage error also increases as the resolving time of the equipment as a whole increases.

The resolving time of a Geiger tube is not normally known accurately, since it varies from tube to tube, with the age of the tube and with the applied voltage. It is normal practice to introduce a resolving time into the counting apparatus which is somewhat longer than the resolving time of the Geiger tube itself, but which is accurately known. The resolving time of the whole apparatus then becomes equal to this resolving time. Although a larger error is thus introduced, it is possible to correct for this error in the case of random pulses by the method discussed below, since the resolving time is now known.

1.1.4 Correction for Losses due to Finite Resolving Time

Let n = the number of counts recorded per second
t = the resolving time of the apparatus in seconds

The counting equipment is effectively inoperative for a time of t seconds following each count which is recorded. Therefore, the total inoperative time per second will be nt seconds and the time during which the apparatus is sensitive is $(1-nt)$ seconds for each second of the counting time. The count rate per second, N, which would have been obtained if the apparatus had had an infinitesimal resolving time is therefore:

$$N = \frac{n}{1-nt} \tag{1}$$

This equation is strictly correct only if the particles which enter the Geiger tube during the inoperative periods do not extend the dead time or if the dead time is determined entirely by the resolving time of the preamplifier probe unit or the scaler. Each particle which enters a Geiger tube during the dead time renders the tube inoperative for a further period equal to the tube dead time. In such a case the corrected counting rate, N, may be obtained from the expression:

$$n = Ne^{-Nt} \tag{2}$$

where t is the resolving time of the Geiger tube and e is the base of natural logarithms. This equation should only be used where the dead time is determined entirely by the dead time of the Geiger tube. In any case, equation (1) which is much simpler than equation (2) is accurate enough for most purposes unless the counting rate becomes greater than about $1/10t$. If equation (2) is expanded, it can be shown to be equivalent to equation (1) if Nt is small compared with unity.

As the actual number of particles entering a Geiger tube per second increases, it can be shown from equation (2) that the count rate will reach a maximum and then decline. A Geiger counter placed in a field of intense radiation can, therefore, indicate a small count rate, since the particles are entering the tube so quickly after one another that the tube is inoperative for a large part of the counting time.

The percentage error introduced at various counting rates for various resolving times is shown in Table 1.1.

Table 1.1

Counts/sec	*Counts/min*	*Resolving time*	*Percentage error*
10^4	6×10^5	1 μsec	1
10	600	1 msec	1
100	6,000	1 msec	10
1	60	100 msec	10

Whilst it is possible to state the approximate maximum rate at which a certain scaling unit will count pulses which are evenly distributed in time, it is obvious from the table that it is not possible to quote a maximum counting rate when the incoming pulses are randomly distributed in time. One can only state the maximum counting rate which will ensure that the percentage of missed counts is kept below a certain value. Any value quoted for the maximum operating frequency of a counting circuit, therefore, refers to the case when the input pulses are evenly distributed in time and when they satisfy the input requirements of the circuit.

If an electro-magnetic register of long resolving time is preceeded by a very fast scaling unit which provides one output pulse for each ten input pulses, it might be thought that the maximum operating speed would be ten times that of the electro-magnetic counter alone. This is, in fact, true for pulses which are evenly distributed in time, but in the case of randomly distributed pulses, the maximum counting speed is increased by a factor of more than ten for the same percentage of missed counts. This is because the randomness of the distribution of the pulses in time is reduced by the first fast scaling unit. The percentage of lost counts for such systems has been computed(1).

The resolving time of a counting circuit can be determined experimentally by feeding pulses of known frequency into the circuit from a pulse generator, but care should be taken to ensure that the pulses conform to the specifications for the input to the counting circuit and that the correct power supply voltages are applied to the circuit. Methods are available for the measurement of the resolving time of Geiger counting equipment by means of radioactive sources[(2)].

1.1.5 The Statistics of Counting Random Pulses

If a source of randomly spaced pulses is counted for a number of equal intervals of time, the results obtained will not be exactly the same in each case, but will fluctuate around a mean value in a statistically predictable manner which is determined by the Poisson distribution. If the time for which each set of counts is taken is increased, the actual differences between the results will tend to increase, but the percentage differences will decrease. In radioisotope measurements it is normally desired to find the mean count rate which would be obtained if the counting were carried out over a long time. It is not, however, always convenient to continue the counting for a long time and in any case this would not give the desired result in the case of a short lived isotope. Statistical methods can be used to determine the number of counts which must be obtained to ensure that the probability of a statistical error being greater than a certain percentage of the count is small enough for the result to be acceptable.

A quantity known as the standard deviation is normally used as a measure of the statistical error likely to be present in any particular case. This is the square root of the average value of the square of the individual deviations from the mean. Although the mean count is not known in practice, the square root of the actual number of counts can normally be taken as being equal to the standard deviation without an appreciable error being introduced provided that the number of counts is not very small.

It can be shown that (in the case of random pulses) there is a 31.7% chance that any actual count will differ from the mean count by more than the standard deviation. If 100 counts are taken, there is, therefore, a 68.3% chance that the statistical error in this one measurement will be less than 10 counts (that is, $\sqrt{100}$). Thus the standard deviation is 10% of the count. In order to reduce the standard deviation to 1% of the count, it would be necessary to take 10,000 counts and there would still be a 31.7% chance (about 1 in three) that the error would exceed 1% of the total number of counts taken. The time necessary to take the requisite number of counts does not enter directly into the statistics.

Although the standard deviation is the most common unit in which statistical deviations from the mean value are expressed, there are two other units which are sometimes used. The probable error is that which has a 50% chance of being exceeded. It is equal to 0.6745 times the standard deviation. The reliable error has a 90% chance of not being exceeded and equals 1.64 times the standard deviation.

It is also useful to note that there is a 95.5% probability that the statistical error does not exceed twice the standard deviation and a 99.7% probability that it does not exceed three times the standard deviation.

The quantities discussed above are useful for checking that the pulses which are being counted are, in fact, randomly distributed in time and that the counting apparatus is not affecting this random distribution. For example, if one finds that a count differs from the mean by more than about 2.5 times the standard deviation, it is almost certain that the equipment is not functioning correctly. The H.T. supply may, for example, be drifting and causing a non-random variation in the counting rate. Similarly a long paralysis time will result in closely spaced pulses being counted as one pulse and the deviations of the results from the mean value will then be less than those which would be expected from statistical considerations.

When a background count is taken and is deducted from the number of counts obtained with a radio-active sample in position, the standard deviation of the resulting net count is equal to the square root of the sum of the squares of the standard deviations of the counts made on the background alone and on the sample plus background. The accuracy with which it is necessary to determine the background count rate depends on the ratio of the counting rate plus background to that of the background alone. If the sample plus background count rate is little different from that of the background alone, approximately the same length of time should be spent on the determination of the background count rate as is spent on the determination of the background plus sample rate. If, however, the sample plus background rate is about one hundred times that of the background alone, the time spent on the determination of the background rate can be about one tenth of that spent on counting the sample plus background. This results in minimum standard deviation of the net count rate for a given total counting time.

1.1.6. Principles of Counting

The operation of any type of counting circuit other than a ratemeter depends basically on some form of switching from one stable state corresponding to a certain number of counts to another stable state which corresponds to one count more than the previous state. The switching is triggered by the arrival of the input pulses.

Our normal counting system is based on a scale of ten because people first learned to count on their fingers (which are sometimes called 'digits'). When we refer to the number 2,350 we are really using an abbreviated form for the expression: $(2\times10^3)+(3\times10^2)+(5\times10^1)+(0\times10^0)$. This system is known as decade counting, or decimal counting, ten different digits being required.

Electronic circuits which count in this manner must have ten stable states in each decade. Each input pulse causes the units decade to advance one position until the tenth pulse returns this decade to the zero state and an output pulse is provided for triggering the second decade which indicates the number of tens. Similarly, the hundredth pulse causes the first two decades to be returned to zero and the third decade to be switched to indicate the digit one. Although decade tube and various other types of circuit have been designed to count in scales of ten, it is not easy to design a simple valve or transistor circuit which has ten stable states. A scale of counting in which fewer digits are employed is more convenient when valve or transistor circuits are to perform the counting operation.

The simplest counting system of all is the binary scale or scale of two. On the scale of two the number quoted previously (2,350) would be represented as 100100101110 which is really an abbreviated form for the expression: $(1\times2^{11})+(0\times2^{10})+(0\times2^9)+(1\times2^8)+(0\times2^7)+(0\times2^6)+(1\times2^5)+(0\times2^4)+(1\times2^3)+(1\times2^2)+(1\times2^1)+(0\times2^0)$.

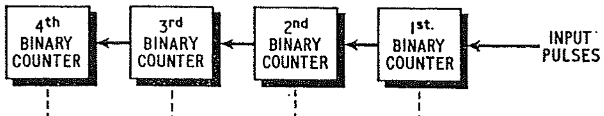
The only digits which appear in any binary number are 0 and 1, because the next number, two, would be represented as a '1' in the next column, that is as 10. In decade counting there is no single digit to represent any number above nine and similarly in the binary scale there is no single digit to represent any number above one. When the binary system is used the simplicity in the number of different digits employed must be paid for in the actual number of digits which are required to represent a given number. The decade method of writing the number 2,350 requires only four digits, but the binary system requires no less than twelve digits.

Scales other than the binary and decade systems are sometimes used in electronic counting. The scale of twelve is useful for converting pence to shillings and, in combination with a scale of five, for converting seconds into minutes or minutes to hours. A scale of three (ternary) has also been used.

1.1.7 Basic Binary Circuits

Hard valves and transistors are normally used in groups of two in counting circuits, each pair forming a bistable binary counting circuit. At any one time only one of the two valves (or transistors) is conducting, the other being cut off. Normally, circuit diagrams are drawn so that the binaries are in the zero state when the right-hand valve or transistor is conducting. The first input pulse will switch the circuit so that the left-hand valve or transistor conducts and the right-hand one is cut off; this state of the circuit is interpreted as a count of one. A second input pulse will switch the circuit back to its zero state.

A single binary circuit can count only up to one, but larger numbers may be counted if the first binary provides one output pulse (each time it is



READINGS				TOTAL COUNT	
4th COUNTER	3rd COUNTER	2nd COUNTER	1st COUNTER	AS A BINARY NUMBER	AS A NORMAL NUMBER
0	0	0	0	0 0 0 0	0
0	0	0	1	0 0 0 1	1
0	0	1	0	0 0 1 0	2
0	0	1	1	0 0 1 1	3
0	1	0	0	0 1 0 0	4
0	1	0	1	0 1 0 1	5
0	1	1	0	0 1 1 0	6
0	1	1	1	0 1 1 1	7
1	0	0	0	1 0 0 0	8
1	0	0	1	1 0 0 1	9
1	0	1	0	1 0 1 0	10
1	0	1	1	1 0 1 1	11
1	1	0	0	1 1 0 0	12
1	1	0	1	1 1 0 1	13
1	1	1	0	1 1 1 0	14
1	1	1	1	1 1 1 1	15
0	0	0	0	0 0 0 0	0 (OR 16)

Fig. 1.1. Four cascaded binary counters forming a scale of 16

reset to zero) for each two input pulses which are fed into it. The output pulses may be fed into a second binary stage which will provide one output pulse for each four pulses fed into the first binary circuit. Such a circuit employing two successive binary stages can count up to three.

The four cascaded binary counting circuits shown in Fig. 1.1 can count up to fifteen. If all of the binaries are initially set to zero, the first input pulse fed to the system will cause the first binary stage to register a count, but the other three stages will remain in the zero state. A second pulse applied at the input will reset the first stage to zero and a pulse will be fed from the first to the second binary; the latter, therefore, indicates a count. As this indication is being given by the second binary, it is interpreted as the binary number 10, that is two. A third input pulse causes the first binary stage to indicate a count and leaves the second stage also indicating a count. Thus the total count is the number 11 which is three. A fourth pulse will reset the first binary to zero, the output pulse from this stage will reset the second stage to zero and a pulse from the second binary causes the third stage to indicate a count. Thus the total count is the binary number 100 which is four. Further pulses cause the units to indicate the counts shown in the table of Fig. 1.1. It can be seen that no two lines are the same and, therefore, the binary system indicates these numbers unambiguously.

Successive binary stages may be added until it is possible to count up to any desired number. If six binary stages are cascaded, the circuit will count up to 63, whilst twelve binary circuits connected in the same way can count up to 4,095. In general, if there are n binary circuits in cascade, the maximum count which can be indicated is (2^n-1).

Each binary circuit acts as a 'divide by two' stage. The four cascaded binary circuits of Fig. 1.1 act as a 'divide by sixteen' circuit. When the total count is 1111 on the binary scale (that is, fifteen), a further input pulse will reset each of the four binary stages to zero. This is analogous to the resetting of a decade scaler to zero when the count was previously 9,999.

1.1.8 Decade Counting Using Binary Circuits

Most people are much more familiar with a scale of ten than with a scale of two. It is, therefore, usually desirable to employ decade circuits where possible in order to avoid human errors and to achieve a somewhat greater simplicity in reading the state of the count. In the case of valve and transistor counting circuits, it is possible to obtain a decade circuit by converting the scale of sixteen circuit provided by the four cascaded binary stages of Fig. 1.1 into a scale of ten. This conversion can be accomplished by the use of a suitable feedback or gating system in which six of the counts shown in Fig. 1.1 are automatically omitted.

In principle it does not matter which particular six counts are omitted provided that an output pulse is obtained from the system for each ten input pulses and provided that each of the ten states is represented in a known and unequivocal way. The ten digits of a decade can be represented by any ten of the binary numbers shown in Fig. 1.1, the information about the state of the count in the circuit being indicated in a binary code. The ten states may be chosen from the sixteen binary numbers in ${}_{16}P_{10} = \dfrac{16!}{6!} = 29{,}059{,}430{,}400$ ways. In most cases, however, the ten states are chosen so that as the decade digit increases, the binary number carrying the information also increases. If this is the case and if the binary zero is always to be used to indicate the zero of the decade, the number of ways in which the ten binary numbers can be chosen is equal to the number of ways in which six binary numbers can be omitted from lines one to fifteen inclusive of Fig. 1.1, no importance being attached to the order in which the six are selected. This number of ways is thus equal ${}_{15}C_6 = \dfrac{15!}{6!\,9!} = 5{,}005$ ways.

In order to show how feedback can modify the scale in which four cascaded binary circuits count, let us consider the effect of taking pulses from the fourth binary and feeding them to the first binary. The circuit will count up to seven in the normal binary manner, but the eighth pulse will cause the fourth binary to be switched and a pulse will be fed from this stage to the first stage. This extra pulse will cause the total count to advance to nine on the binary scale. Another seven pulses will be required to cause the binaries to reach sixteen and to reset themselves to zero. The circuit will, therefore, be counting on the scale of fifteen. In practice it may be necessary to delay the fed back pulse slightly so that it does not arrive at the first binary stage at the same time as the end of the input pulse. In some cases, however, normal delay in the circuit is adequate.

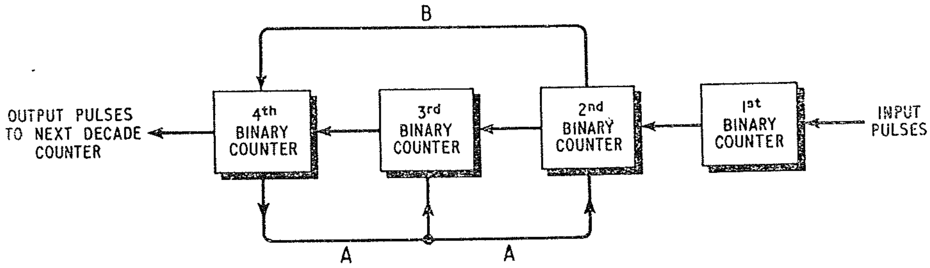


Fig. 1.2 A decade counter using binary counting circuits

If the pulse from the fourth binary had been fed back to the third stage, it would have added four to the total count. Thus the eighth pulse would cause the total count to increase to twelve on the binary scale and another four pulses would be required before the counter would reset itself to zero. It would, therefore, be counting on a scale of twelve.

One of the numerous methods in which four binary stages can be operated as a decade counter stage can be illustrated by the block diagram of Fig. 1.2. The system counts up to nine in the normal binary way, the additional connections marked A and B being ineffective. When the tenth pulse is fed into the system, the first binary counter is switched to read zero and the output pulse from it switches the second binary to indicate a count (actually two counts, since it is the second binary). A pulse from this stage is fed along the connection marked B to the fourth stage. This pulse switches the fourth binary to zero and a pulse from it passes along the wire A so that the second binary is switched to zero. The switching of this second counter would normally provide a pulse to switch the third binary, but the switching of the third binary can be prevented by a pulse fed along *A* from the fourth binary to the third binary. All of the binary stages have thus been reset to zero after ten input pulses have been applied.

The system is so arranged that the fourth binary is not affected by the pulse received direct from the second stage along *B* unless it is actually indicating a count at the time (that is, eight counts, since it is the fourth binary). Thus when the second, fourth, sixth and eighth pulses are fed into the system, the pulse from the second binary to the fourth binary has no effect, since the latter is indicating zero.

The necessity for preventing the simultaneous arrival of an input pulse and the fed back pulse at any stage may somewhat limit the maximum frequency of operation of decade circuits which employ feedback. This limitation can be eliminated by the use of diode gating circuits instead of feedback to convert the scale of sixteen to a scale of ten. A gate is either open or closed according to the potential applied to it from one of the binary stages. Each decade consists of four cascaded binary stages but, when a certain number of input pulses have been applied to the circuit, the switching of one of the binary stages causes a diode gate to open so that a succeeding input pulse can pass through the gate and operate one of the later binaries in the decade. A number of states in the scale of sixteen can thus be eliminated and a scale of ten obtained.

Circuits which employ feedback or gating diodes to convert four cascaded binary stages into decade counters are discussed in Chapters 7 and 8 together with the detailed functioning of these systems and their circuitry. Binary stages arranged to operate as decade counting systems are one of the most commonly used types of high speed counting circuit.

1.1.9 Ring Circuits

One form of counting circuit employs devices which have two characteristic stable states—normally conducting and non-conducting. Such devices include trigger tubes and PNPN four layer diodes. A number of these devices may be connected in the form of a closed ring so that at any time only one of them is conducting. Each input pulse which is applied to the circuit causes the state of conduction to move one place in the ring. Each time the ring returns to the zero state, an output pulse is provided for the operation of the succeeding ring. Rings of ten are common, but any number of stages can normally be employed in the ring. A binary circuit may be constructed by using only two stages in the ring.

An alternative arrangement which was used in some of the earlier decade equipment employs a ring of five and a ring of two tubes (or other devices) in each decade. The input pulses may be fed to both rings so that the position of conduction moves one place in each ring as each input pulse is applied. The ring of two tubes indicates whether the total count is an odd or an even number and when taken in conjunction with the ring of five, the state of the count is determined unambiguously. For example, if the ring of five is in the fourth position, it shows that the count in that decade is either three or eight, since the first position corresponds to a count of zero. If the ring of two indicates an even count, the total count is clearly eight. A pulse is fed to the next decade only when an input pulse is received when both rings are indicating their maximum count. In an alternative arrangement the output pulses from a ring of five are used to trigger a succeeding ring of two. The total number of stages in the two rings is only seven when either of these methods are employed, but a single ring of ten stages is normally preferred for decade counting, since the count in each decade is then determined by the state of only one ring. A circuit comprising a ring of five and a ring of two bistable devices may be referred to as a biquinary decade counter.

1.1.10 Readout

Readout is the means by which the quantity which the equipment has counted is displayed for observers to see. A circuit may provide electrical readout in which case an output in the form of electrical pulses or a voltage or current is available. This output carries information as to the state of the count and can be used to operate other circuits.

Some of the devices used for the switching operations in counting equipment are inherently self indicating. For example, digits are displayed by electromagnetic registers, the glowing gas in trigger and polycathode tubes shows the state of the count, whilst a luminescent strip in the E1T cathode ray decade tube shows the position of the beam. In general, however, such self indicating devices cannot count at the highest possible speeds.

The switching operation of the fastest counting circuits (such as hard valve, transistor, beam switching tube and tunnel diode circuits) does not cause any visible change which can be interpreted as a change in the number of counts. If visual readout is required, some additional components are employed with such circuits to convert the electrical readout from the counting circuit into visual readout.

There are two basic types of readout which can be used to display the state of the count, namely digital and analogue. When a digital readout system is employed, the number of counts is displayed as actual digits. Analogue readout systems show the number of counts in terms of the movement of a meter needle, the movement of a spot of light on the screen of a cathode ray tube or some other physical change in which the actual number of counts is not shown directly.

Electronic scalers are required to count numbers of discrete pulses and not to measure quantities which can vary continuously unless these quantities have first been converted into pulses. Digital readout is, therefore, usually preferred for counting circuits. It has the advantage that it is very easy to read, even in poor light, and errors are, therefore, minimised. In some counting systems a special type of electro-magnetic counter is used to print the number of counts onto a sheet of paper.

Readout from ratemeters is almost always by means of a meter. Digital readout from ratemeters would not be very easy to arrange, as the actual digits are not counted individually; it could, however, be achieved by feeding the output from the ratemeter into a digital voltmeter.

A very common form of readout system involves the use of one additional cold cathode gas filled numerical indicator tube for each decade in the scaler. The indication is given as a glow in the gas contained in the indicator tube. In some types of tube the glow is of such a shape that it forms the digit which is to be indicated. This type of display is particularly useful, but milliammeters graduated from zero to nine are often used in transistor scalers, since they consume no appreciable power and can operate from the low output voltages available. Other possible forms of readout include the use of tungsten filament bulbs, cathode ray or 'magic eye' indicators, neon bulbs and luminescent display panels.

Further information about readout is given in Chapter 10 and in various circuits throughout the book.

1.1.11 Predetermined Counting

In industrial operations it is often necessary to obtain an output pulse after a preselected number of counts. For example, if articles coming off a production line are to be counted and packed in batches of, say, 144, the preselecting switches in the counter can be set to this number and when 144 articles have been counted, the equipment will provide an output signal which will cause the container for the next batch to be moved into position. Many types of predetermined counter also indicate the total number of batches produced since the equipment was last reset. In many types of equipment it is also possible to obtain an output pulse at any selected count before the end of the batch so that the speed of the production machinery can be reduced immediately before the end of the batch; a second pulse can then be used to stop the production momentarily when exactly the desired number of articles has been placed in the batch.

1.1.12 Choice of Counting Circuit

The type of counting circuit which is most suitable for a particular purpose depends largely on the maximum counting speed which is likely to be required, although various other factors such as size, power consumption, cost, the H.T. voltage required, output facilities, etc. may be important. Circuits which are intended for use at fairly low counting speeds can generally be much simpler in design than those used in high speed scalers.

Although an electro-magnetic counter has the disadvantage of having the longest resolving time of any type of counter, it has the advantage that one small, compact and reasonably cheap unit can be used to display up to at least six digits. Most gas filled cold cathode decade tubes can count at speeds up to some thousands per second, but two types can count up to one million pulses per second. E1T decade tubes can count at up to about 100,000 pulses per second. Transistor, hard valve and beam switching tube circuits can be constructed with a resolving time of less than one microsecond and can, therefore, be used for very high speed counting, but the circuitry is rather more complicated than is necessary for the slower self-indicating counting circuits. Valve scalers have the disadvantage that they are large and consume a large amount of power—hence they dissipate much heat. Transistor and other solid state scalers can be made very small, consume little power and are very reliable. Transistor scalers are now the most commonly used type of counting circuit in first class modern equipment designed for the highest possible speeds where economy is not of prime importance, but decade tubes are often preferred for medium speed operation.

Semiconductors are still relatively new devices and it appears that a great deal of development work remains to be done on both the devices themselves and on their circuits, especially those intended for very high speed operation.

In order to construct the simplest and most economical scaling equipment which can operate at reasonably high speeds, it is usual to feed the incoming pulses first into a high speed decade which is followed by simpler decades of longer resolving time. Each ten input pulses to the first decade produce only one output pulse from it. The output pulses are, therefore, separated by longer intervals than the input pulses and can be counted by decades of longer resolving time. The circuits of these succeeding decades can be much simpler and less expensive than the first high speed decade. It is usually desirable to have a uniform type of readout from all decades.

Complete scalers covering several decades are not usually constructed using only hard valves to perform the actual counting operations, since after the first one or two high speed valve decades the circuits can be much simplified by the use of slower decades without any reduction in the maximum overall counting speed. Similarly complete scalers are not usually constructed using only beam switching tubes as the scaling elements, since these tubes are fairly expensive and the circuits are not quite so simple as some of the cold cathode decade tube circuits.

The semiconductor devices used in high speed semiconductor decades are usually quite expensive and the circuitry is more complicated than in low speed semiconductor decades. In such scalers the first high speed circuit is therefore usually followed by a simpler circuit of longer resolving time. This may then be followed by a still simpler decade.

One of the most inexpensive arrangements for use with Geiger counters consists of two gas filled decade counting tube stages followed by a four digit electromagnetic register. The first four digits of the number of counts are read from the register, the number of tens from the second decade tube and the number of units from the first decade tube. This arrangement can be used for counting up to 999,999, but the maximum counting speed is not so very much less than that of a scaler employing decade tubes alone. Most of the slightly more expensive scalers for use with Geiger tubes employ decade tubes alone. Electromagnetic registers make a slight noise each time they operate whereas other forms of counting circuit are completely silent.

Magnetic scalers using materials which have rectangular hysteresis loops can be designed for scaling at speeds up to at least one million pulses per second. They have the advantage that they can be made quite small and that their quiescent power consumption is extremely minute.

E1T and beam switching tubes are sensitive to magnetic fields and it would not be wise to use them near to any apparatus containing a large magnet such as an electro-magnetic isotope separator or some types of nuclear particle accelerators.

High speed counting units containing one or two decades are available commercially. They provide output pulses which are normally used to operate a succeeding slower scaler and are known as prescalers.

1.2 SOME BASIC PULSE CIRCUITS

In most types of counting circuit various circuits are required for pulse shaping, gating, etc. Some of the most commonly used types of these circuits will now be briefly discussed.

1.2.1 The Differentiating Circuit

One of the simplest types of circuit for changing the shape of a pulse is shown in Fig. 1.3. It is known as a differentiating circuit because the output voltage waveform is approximately equal to the waveform which would be obtained by mathematically differentiating the input waveform with respect to time,

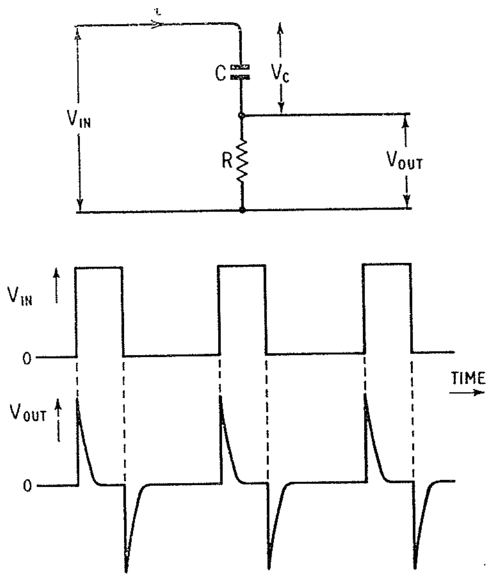


Fig. 1.3 A differentiating circuit

provided that the component values have been suitably chosen. This simple circuit can be used to obtain very sharp voltage pulses from any input pulses which have sharp leading or trailing edges. The differentiated pulses are ideal for synchronisation or for other applications when a sharply defined pulse at a definite time is required.

Let Q = the charge on capacitor C in Fig. 1.3

V_c = the potential across C

$$Q = V_c C$$

Differentiating

$$\frac{dQ}{dt} = C\frac{dV_c}{dt}$$

But dQ/dt is equal to the current i.

$$V_{out} = Ri = RC\frac{dV_c}{dt}$$

provided that the output current is zero.

But $$V_{in} = V_c + V_{out}$$

If the resistance R is steadily reduced so that the potential V_{out} across it is much smaller than V_c, then V_{in} is approximately equal to V_c. Hence

$$V_{out} = RC\frac{dV_{in}}{dt}$$

approximately. That is, the output voltage is a constant multiplied by the differential of the input voltage with respect to time.

If the input pulses are approximately rectangular in shape as in Fig. 1.3, the leading and trailing edges of the differentiated waveform should coincide with each other. In actual practice, however, the output peaks have a finite width which can be reduced by reducing the value of R, but in a practical circuit this will reduce the amplitude of the output peaks. The product RC is known as the time constant of the circuit. The capacitor of a differentiating circuit presents a higher reactance to low frequencies than to high frequencies. The circuit therefore acts as a high pass filter.

In many circuits a capacitor is used to block a d.c. potential (such as the d.c. potential at the anode of a valve). Some form of resistor is connected on the output side of the capacitor, so the circuit will effectively differentiate the input waveform if the time constant of the circuit is short compared with the pulse duration. If the time constant is long compared with the pulse duration, however, the shape of the pulse may not be appreciably affected by the circuit.

In many applications a diode is connected across the output terminals of the differentiating circuit. This will remove either the positive or the negative going peaks from the output according to the way in which the diode is connected.

1.2.2 The Integrating Circuit

The simplest possible integrating circuit is shown in Fig. 1.4. The output voltage approximates to the integral of the input voltage with respect to time provided that the component values are suitably chosen.

$$Q = CV_{out}$$

where Q is the charge on capacitor C

$$V_{out} = \frac{Q}{C} = \frac{1}{C}\int i\,dt = \frac{1}{C}\int \frac{V_R}{R}\,dt$$

since $dQ = i\,dt$

$$V_{in} = V_R + V_{out}$$

If R is made large so that V_{out} is much smaller than V_R,

$$V_{in} = V_R$$

approximately and

$$V_{out} = \frac{1}{C}\int \frac{V_{in}}{R}\,dt$$

approximately. Thus the output voltage is approximately equal to the integral of the input voltage when R is relatively large and when no current is

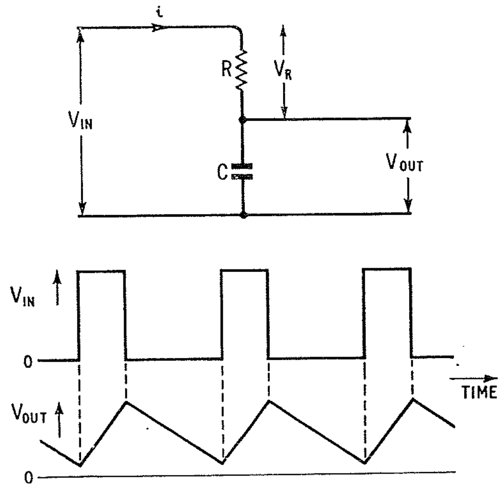


Fig. 1.4 An integrating circuit

taken from the output. It should be noted that only the alternating component of the input waveform is integrated and that the output has the d.c. component from the input superimposed on it. The integrating circuit is a low pass filter.

Much better approximations to a true integrating (or differentiating) circuit can be obtained if the resistor and capacitor are used in the feedback loop of an amplifier. A simple integrating circuit can be constructed in which the capacitor is connected between the grid and the anode of a single valve amplifier; the effective value of the capacitance is thus increased by the Miller effect.

1.2.3 Multivibrators

The name multivibrator was given to a type of two valve oscillator circuit described by Abraham and Bloch in 1918. The name is derived from the fact that the circuit produces rectangular waves which are very rich in harmonics. The same name has since been given to two similar circuits which are not self oscillating, the only difference in the three types of circuit being the type of coupling between the two valves or transistors. Only hard valve and transistor multivibrator circuits will be discussed here, but similar circuits can be constructed using devices such as trigger tubes and tunnel diodes.

The design of multivibrator circuits is complicated by the fact that the valves or transistors normally switch between the cut off state and the fully conducting state and therefore the small signal equivalent circuits are not applicable. For a full analysis of multivibrator design, the reader is referred to one of the books on this subject[3–6].

1.2.4 The Astable or Free Running Multivibrator

The circuit of Fig. 1.5(a) can exist in two basic states, both of which are unstable. The circuit automatically switches continuously from one of these states to the other, thus forming a relaxation oscillator. The feedback is not frequency selective and, therefore, rectangular waveforms are generated. The astable multivibrator circuit is very useful for generating pulses for testing or operating counting equipment. Either the fundamental or one of the harmonics of the multivibrator can easily be synchronised to an incoming signal; this enables the circuit to be used as a frequency divider.

The astable multivibrator may be considered as a valve amplifier which is resistance-capacity coupled to another valve amplifier stage, the output from the second stage being returned to the grid of the first stage via a similar resistance-capacity coupling. The feedback is thus 100%.

If at any time the grid potential of $V1$ decreases, the anode potential of this valve will increase and

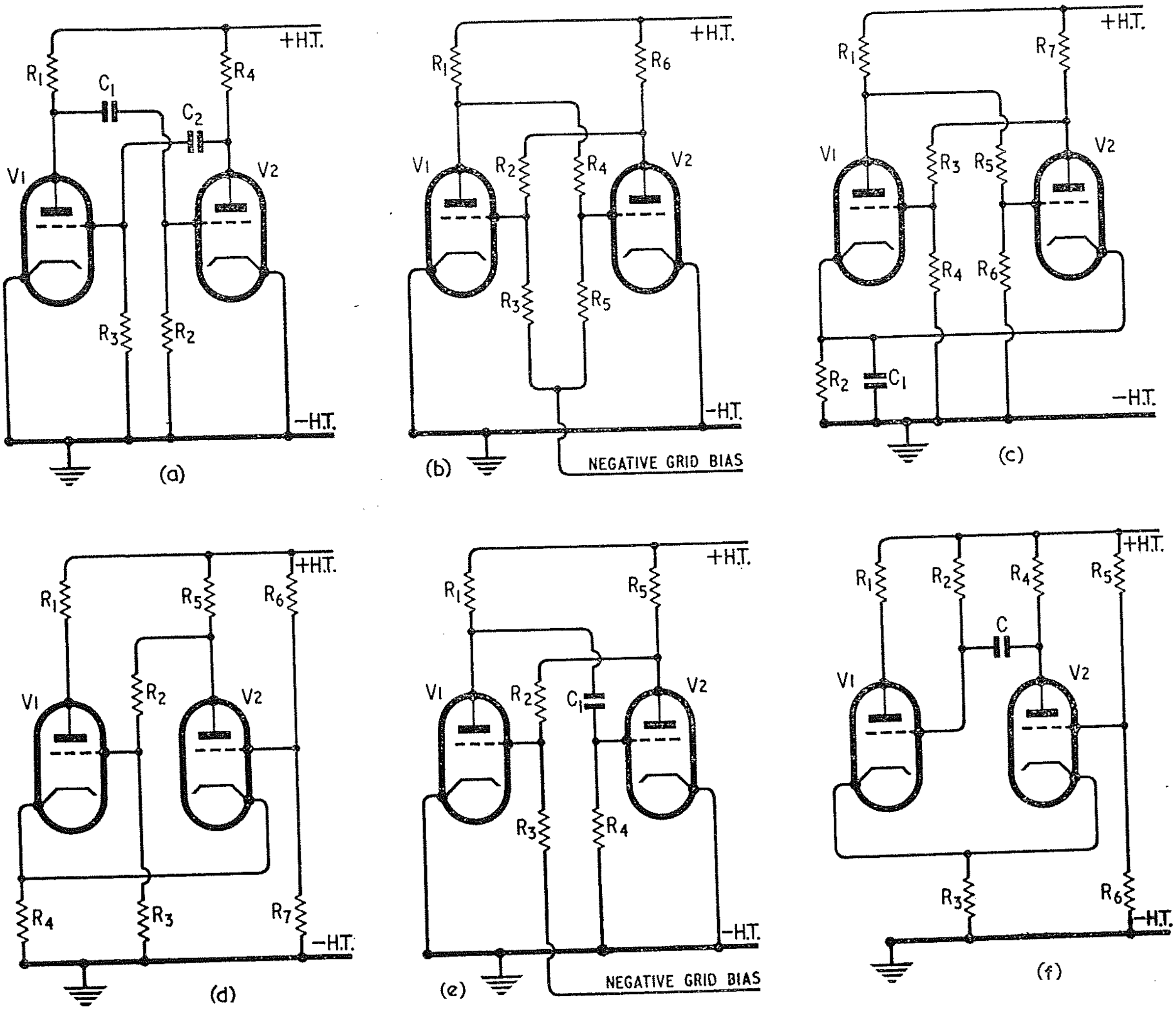


Fig. 1.5 Valve multivibrator circuits. (a) Astable circuit; (b) bistable circuit; (c) bistable circuit with cathode bias; (d) Schmitt trigger circuit (bistable); (e) monostable circuit (flip-flop); (f) cathode coupled monostable circuit

this increase will be coupled to the grid of $V2$. The anode potential of $V2$, therefore, falls and this fall is used to decrease the grid potential of $V1$ further. A cumulative effect thus takes place which results in $V1$ being cut off. The resulting rise in potential of the anode of $V1$ is amplified by $V2$ so that the grid of $V1$ is held well beyond cut off. This process occurs extremely rapidly so that the potential across the coupling capacitors does not have time to change appreciably during the switching.

Immediately the switching has taken place, the capacitor C_1 (Fig. 1.5(a)) begins to charge exponentially from the H.T. line and some grid current will flow in the conducting valve, which $V2$, effectively acts as a low resistance shunting R_2. The time constant for the charging of C_1 is thus reduced from $C_1(R_1+R_2)$ to an effective value of approximately C_1R_1. The potential of the grid of $V2$ will be only a few volts positive above earth potential.

Whilst C_1 is charging, C_2 is discharging through R_3 and is providing a negative potential at the grid of $V1$. The grid of this valve gradually becomes less negative as C_2 discharges and eventually the valve will conduct. This causes the anode potential of $V1$ to fall and the fall is amplified by $V2$ which leads to a cumulative effect similar to the one described previously. $V2$ will quickly be cut off, whilst $V1$ will become fully conducting again. The circuit thus switches continuously between the two states, each valve being cut off in turn. The output may be taken from either anode.

If the values of the components are symmetrical in each half of the circuit, the time for which each tube is cut off per cycle would appear to be identical, that is, the mark to space ratio would appear to be unity. The time for which the circuit exists in one of its states is, however, very dependent on the cut off grid voltage of the non-conducting valve, since the cut off occurs at a part of the exponential discharge curve where the grid voltage is changing relatively slowly towards zero. This effect can be reduced by connecting the lower ends of the grid resistors R_2 and R_3 in Fig. 1.5(a) to the H.T. positive line. The grid voltage of the cut off valve then moves exponentially towards the H.T. supply potential and the cut off voltage will be reached when the grid voltage is changing fairly rapidly. The frequency of operation of the circuit is thus made less dependent on the valve cut off potentials.

The frequency of oscillation of a valve astable multivibrator is given by the approximate equation:

$$f = \frac{1}{(C_1R_2+C_2R_3)\log_e\left(\dfrac{E_b-E_m}{E_o}\right)}$$

where E_b is the H.T. supply potential,

E_m is the anode voltage when the grid potential is zero,

E_o is the grid voltage to cut off the valve under the operating conditions of the circuit.

Various other valve multivibrator circuits can be designed, e.g. one of the couplings may be a common cathode resistor.

1.2.5 The Bistable Multivibrator or Eccles-Jordan Circuit

The circuit of Fig. 1.5(b) differs from that of Fig. 1.5(a) in that there are two d.c. couplings (R_2 and R_4) between $V1$ and $V2$. When the H.T. is first applied, some random change will occur which will result in one of the valves being cut off by the same cumulative process as occurs in the astable circuit. For example, if $V1$ is cut off, $V2$ becomes fully conducting and its anode voltage falls, ensuring that the grid of $V1$ is biased to well beyond the cut off point. The circuit can remain in this condition indefinitely. Similarly, if $V2$ is cut off, the circuit will remain in this condition until it is affected by an incoming pulse. Thus this circuit has two stable states.

If a signal of suitable amplitude and polarity is fed to either of the grid or anode circuits, so that the valve which was cut off commences to conduct, a cumulative effect will occur and the circuit will switch into the other stable state. A second input pulse applied to a suitable point in the circuit can be used to switch it back to its initial state. This type of circuit, therefore, provides one output pulse at one of the valve anodes for each two input pulses fed into it. Thus it is a binary counting circuit.

Fig. 1.5(c) is a similar type of circuit, but a cathode resistor is used to provide the bias required by the tubes. One of the two valves is always fully conducting whilst the other is cut off; therefore the bias voltage present across the common cathode resistor is fairly constant.

A slightly different form of bistable circuit known as the Schmitt trigger circuit(7) is shown in Fig. 1.5(d). In this circuit $V2$ is coupled to $V1$ as in the two bistable circuits described previously, but the output from $V1$ is coupled into the cathode of $V2$ by means of the common cathode resistor, R_4. When $V1$ conducts, the voltage developed across the common cathode resistor is appreciably greater than the grid voltage of $V2$, so this valve is cut off. The circuit is very useful for pulse shaping, for example, for converting sine waves into square waves.

In any bistable circuit it is normal practice to place a small capacitor in parallel with the coupling resistors in order to increase the speed of the switching action and to provide an output of shorter rise time. Bistable valve counting circuits are discussed in Chapter 7.

1.2.6 The Monostable Circuit

A monostable multivibrator circuit is shown in Fig. 1.5(e). It has a capacitive coupling from $V1$ to $V2$ and a resistive coupling from $V2$ to $V1$. When $V1$

is cut off and $V2$ is conducting, the passage of the $V2$ anode current through R_5 produces a voltage drop which ensures that the grid potential of $V1$ remains well beyond cut off. In this state the circuit is stable for an indefinite time.

If a positive going pulse of suitable amplitude is applied to the grid of $V1$ or a negative going pulse to the grid of $V2$, a cumulative action will take place which results in $V1$ conducting and $V2$ being cut off. The discharging current of C_1 flows through R_4 and causes $V2$ to remain cut off for a limited time. As soon as the potential across R_4 falls to a value which is small enough to allow $V2$ to conduct, the circuit will rapidly switch back to its previous stable state. Thus when $V1$ is conducting the circuit is unstable or, more correctly, it is stable for a limited time only and it will automatically switch back to the state in which it is permanently stable. Another input pulse is then required to trigger it.

Monostable circuits are known as flip-flops because if they are flipped by an input pulse, they will flop back to their initial state after a predetermined time. The time interval between the input pulse and the return to the stable state is determined mainly by the values of C_1 and of R_1 and R_4 in series.

A cathode coupled monostable circuit is shown in Fig. 1.5(f). This may be compared with the Schmitt trigger circuit of Fig. 1.5(d). In each case the output of $V1$ is cathode coupled to $V2$. This type of circuit is very commonly used in counting equipment for shaping pulses (see, for example, some of the circuits in Chapter 4). The grid resistor, R_2, is returned to the H.T. positive line for the same reason that the grid resistors of astable multivibrators are sometimes returned to the H.T. line, namely that the time at which the circuit returns to its former state is more precisely determined than if the grid resistor is returned to earth.

It is interesting to note that the astable circuit of Fig. 1.5(a) can be converted into a monostable circuit by merely returning one of the grid resistors to a suitable negative potential.

When an input pulse is applied to a monostable circuit, a positive going output pulse which is approximately rectangular in shape may be obtained from the anode of the valve which is normally conducting, whilst a negative going pulse can be obtained from the valve which is normally cut off. The amplitude and duration of the input pulses which are used to trigger the circuit may vary over quite a wide range, but the amplitude and duration of the output pulses from the monostable circuit are independent of the input pulse characteristics. Monostable circuits are therefore extremely useful for shaping and controlling the duration of pulses. They may also be used to produce a delay (by using the trailing edge of the output pulse) or to put a piece of equipment out of action for a brief pre-set time following the application of an input pulse to the circuit.

1.2.7 Transistor Multivibrator Circuits

Transistor circuits which are exactly analogous to the valve circuits of Fig. 1.5 can be designed. Some typical examples are shown in Fig. 1.6. In each of these circuits one of the transistors is fully cut off at any one instant and the other is fully conducting. A fully conducting transistor is said to be 'bottomed' because the collector potential is little different from the emitter potential (which is often earth potential). If a transistor is cut off, the current passing through it is very small whilst, if it is bottomed, the potential difference across it is small. In either case the power being dissipated in the transistor is small, so it is not usually necessary to employ any components which will give protection to the transistor against possible thermal runaway.

1.2.8 Astable Circuits

A transistor astable circuit is shown in Fig. 1.6(a). If the transistor $T1$ is bottomed and $T2$ begins to conduct, the positive pulse at the collector of $T2$ will be fed to the base of $T1$ and will reduce the current taken by this transistor. The resulting negative pulse at the collector of $T1$ is fed to the base of $T2$ where it causes the collector current to increase. A cumulative effect thus takes place which results in $T1$ being rapidly cut off and $T2$ being bottomed. C_2 begins to discharge through R_3 and the output circuit of $T2$ so that after a time the base potential of $T1$ will fall somewhat and this transistor will

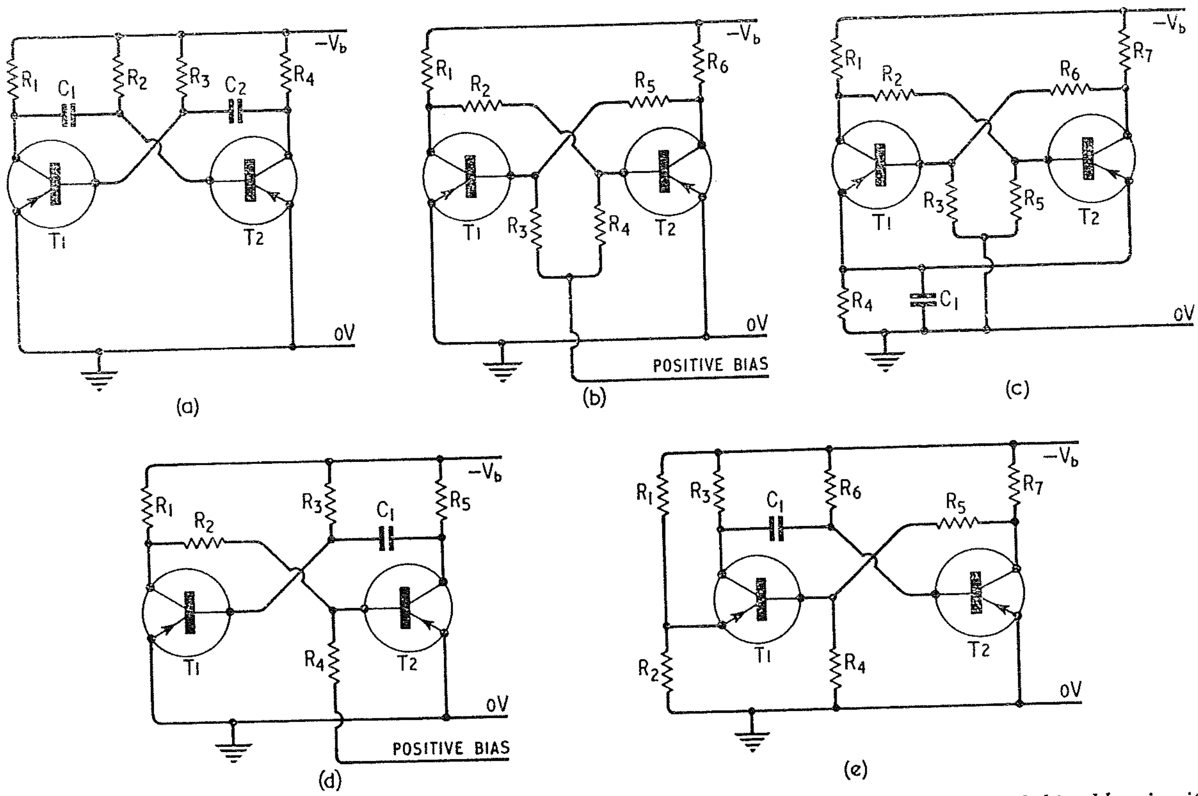


Fig. 1.6 Transistor multivibrators. (a) Astable circuit; (b) bistable circuit; (c) self biased bistable circuit; (d) monostable circuit; (e) monostable circuit

commence to conduct. This will result in a switching action taking place and $T2$ will be cut off.

If $T1$ is initially cut off, the collector of this transistor will be at the full negative supply potential (ignoring the leakage current of $T1$), whilst at the other side of the capacitor C_1 the base of $T2$ will be at about earth potential (actually slightly negative with respect to earth). Thus the right hand side of C_1 is at approximately $+V_b$ volts with respect to the other side of the capacitor. When $T1$ suddenly bottoms, the potential of its collector will become approximately zero. The charge on C_1 cannot change instantaneously and, therefore, the potential of the base of $T2$ becomes $+V_b$ with respect to earth. $T2$ is therefore cut off. As C_1 discharges the potential of the base of $T2$ commences to fall exponentially from $+V_b$ towards $-V_b$ but, as soon as the base reaches approximately the earth potential, $T2$ conducts and the switching process takes place. This occurs when the potential of the transistor base has moved half way from $+V_b$ to $-V_b$. The potential, V, across the discharging capacitor is given by the equation:

$$\frac{V}{V_0} = e^{\frac{-t}{RC}}$$

where V_0 is the potential of the supply from which the charging takes place,
t is the time since the charging commenced,
R is the resistance through which the charging current is passing,
C is the capacitance.

Hence

$$t = RC \log_e \left(\frac{V_0}{V}\right)$$

In order to find the time taken for the base of $T2$ to reach zero volts, a value of 2 is substituted for V/V_0, since C_1 charges half way towards the value which it would reach if the switching action did not occur. The output impedance of $T1$ is usually small compared with R_2 and therefore may be neglected in the equation.

Hence $t = R_2C_1 \log_e 2$ approximately
or

$$t = 0.7R_2C_1$$

When $T1$ has been switched to the conducting state, a time t will pass before $T2$ is switched into its conducting state. Hence the frequency of oscillation of the circuit is given by:

$$f = \frac{1}{0.7(R_2C_1+R_3C_2)}$$

approximately.

The output may be taken from either collector, the pulses being approximately rectangular in shape. The edge of an output pulse caused by a transistor being switched to the conducting state is steeper than that caused by a transistor being cut off, since the cut off time is limited by hole storage effects and circuit time constants. The waveform at the transistor bases has a steep leading edge when the transistor commences to conduct and an exponential trailing edge.

1.2.9 Transistor Bistable Circuits

A simple bistable transistor circuit is shown in Fig. 1.6(b). This circuit is very similar to the valve bistable circuit, since it has two resistor couplings and may be switched from one state to the other by an input signal of appropriate polarity and amplitude applied to either the base or the collector of a transistor. If the cut off transistor is made to conduct or if the bottomed transistor is cut off, the circuit will be switched to the other state.

In practical circuits small capacitors are normally placed in parallel with R_2 and R_5 of Fig. 1.6(b) so that the pulses generated have steep edges. If these components are not used, the high frequency components of the pulses from the collector of one transistor are effectively shorted out by the input capacitance of the transistor to which they are fed.

In the bistable circuit of Fig. 1.6(c), the bias has been obtained by means of a resistor in the emitter circuit. The resistor is decoupled with a capacitor in order to preserve the steep sides of the output waveform.

Various asymmetrical bistable circuits have been designed including some especially interesting ones in which a PNP transistor is employed in conjunction with an NPN transistor. No valve circuits similar to this type of circuit can be constructed.

Transistor bistable circuits, like the corresponding valve circuits, provide one output pulse for each two input pulses. They can, therefore, be used as binary counting circuits and will be discussed more fully in Chapter 8.

1.2.10 Transistor Monostable Circuits

The circuit of Fig. 1.6(d) is stable only when $T1$ is bottomed and $T2$ is cut off. If a suitable input pulse is applied to the circuit, $T1$ will be cut off and $T2$ will conduct. After a short time, however, the circuit will return to its stable state. The time interval before the circuit returns to its stable state is the time taken by C_1 to discharge from the potential of V_b to about earth potential. This interval is given by the following equation which may be derived by the same reasoning as that given in the case of the astable transistor circuit.

$$t = 0.7\ C_1R_3$$

Positive going pulses may be taken from the collector of $T2$ or negative going output pulses from the collector of $T1$. In order that the output pulses shall be as nearly rectangular as possible, it is usual to connect a small capacitor across the resistor R_2.

Another type of monostable circuit is shown in Fig. 1.6(e). This circuit is stable when $T1$ is cut off and $T2$ is bottomed.

1.2.11 The Blocking Oscillator

In the multivibrator two valves or transistors are employed to provide the phase inversion required for the feedback to be positive, but in the blocking oscillator the phase inversion is obtained by the use of a transformer; only one valve or transistor is therefore required. A blocking oscillator circuit may be monostable or astable.

The basic circuit of a free running or astable valve blocking oscillator is shown in Fig. 1.7(a). The percentage feedback is made large. When the circuit is first switched on, the anode current flowing

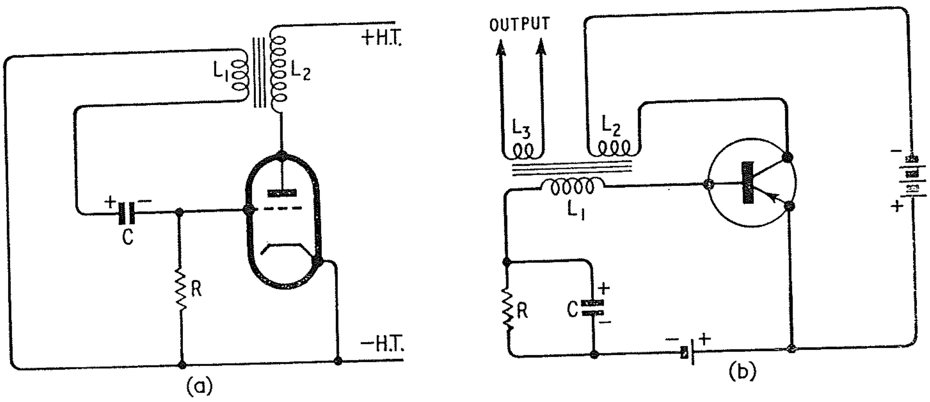


Fig. 1.7 Blocking oscillator circuits

through L_2 increases and induces a voltage in L_1 of such a polarity that the valve grid becomes more positive. Grid current flows through R and the capacitor is charged with the polarity indicated in the circuit. The cumulative effect quickly causes the anode current to reach a maximum, after which the current in L_2 is almost constant so that the potential across L_1 becomes zero. C_1 now biases the grid negatively and, as the anode current commences to fall, L_1 provides a potential which reduces the grid potential still further. The valve is therefore rapidly cut off by this cumulative effect. The capacitor then discharges through R exponentially and the grid of the valve gradually becomes less negative and eventually the valve conducts. The anode current flowing through L_2 causes a positive potential to be applied to the valve grid which increases the anode current still further. The valve is thus quickly driven into saturation again. C_1 charges and the whole process is repeated.

The valve anode potential consists of a negative pulse followed by a positive pulse; it then remains constant until the succeeding negative pulse occurs. The Q of the transformer winding is normally made low so that the oscillations which result from shock excitation of the transformer windings are kept to a small amplitude.

If the grid resistor is returned to a potential which is negative with respect to the cathode potential by an amount greater than the cut off potential of the valve, the circuit becomes monostable. A positive going pulse fed to the grid will trigger the circuit and a pulse of fairly high amplitude may be taken from the anode.

A transistor blocking oscillator circuit is shown in Fig. 1.7(b). The feedback is from the collector of the transistor to the base. When the supply voltages are first connected, the transistor will conduct owing to the negative potential applied to the base relative to the emitter. The transformer windings are arranged so that the increasing collector current flowing through L_2 renders the base more negative and this tends to increase the collector current still further. The transistor is, therefore, quickly bottomed. The capacitor C becomes charged during this time with the polarity indicated in the circuit. When the collector current reaches a maximum, the potential across L_1 falls to zero and the positive potential applied to the base from the capacitor C causes the collector current to be reduced. The effect of this reduction is fed back via L_2 and L_1, thus producing a cumulative effect at the end of which the collector current is cut off. C discharges through R and after a short time the base voltage reaches such a value that the transistor conducts.

A cumulative effect causes the transistor to be rapidly bottomed. The cycle is then repeated again.

Monostable transistor blocking oscillator circuits offer a very economical way of using transistors to drive counting circuits such as cold cathode decade tubes which require a fairly high pulse amplitude, since a fairly large number of turns may be placed on the output winding L_3 of the blocking oscillator transformer to obtain a large amplitude pulse. A low voltage transistor may be used in the blocking oscillator circuit. The transformer is often constructed on a ferrite core.

1.2.12 The Diode Clamping Circuit

A diode is often used in pulse circuits to prevent the potential of a certain point from rising above or falling below a certain voltage. In the circuit of Fig. 1.8 the output from the pulse amplifier $V1$ is fed through the capacitor C. If the time constant CR is small, the pulse will be differentiated. If at

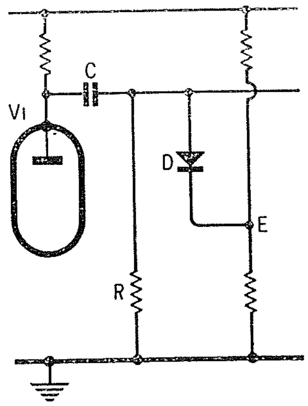


Fig. 1.8 A diode clamping circuit

any time the output potential tends to become more positive than the potential at the point E of the potential divider, the diode D will conduct and the output potential will not rise much above E.

A similar method may be used to prevent the potential at a point in a circuit from falling below a certain potential. In some cases the potential at a point may be clamped to both an upper and a lower value. Unless the pulse amplitude at this point is small, it is then completely determined by the values of the potentials to which the point is clamped. The pulse amplitude may thus be made independent of the characteristics of valves in amplifier stages.

1.2.13 Gating Circuits

An electronic gate is a device which either allows pulses to pass or prevents them from passing; that is, the gate is either open or closed. The simplest form of a gate is a diode in series with a pulse source. If the diode anode is more positive than its cathode, the gate will be open and vice-versa.

Simple gates enable counting circuits to be used for the accurate measurement of time. Pulses from an oscillator pass through the gate when it is open to the counting circuit. The gate may be opened by a beam of light falling on a photocell. If the frequency of the oscillator is known, the time for which the gate was open can be deduced from the number of counts recorded.

1.2.14 The and Gate or Coincidence Circuit

The AND gate is a circuit which will provide an output pulse only when a number of simultaneous input pulses are fed to it. A simple type of AND gate is shown in Fig. 1.9. If a positive going input pulse is applied to D_1, this diode will be biased so that it has a high resistance. If no pulses are applied to D_2 and D_3, these diodes will be biased in the forward direction by the pulse applied to D_1. The diode D_1 forms the upper part of a potential divider, the lower

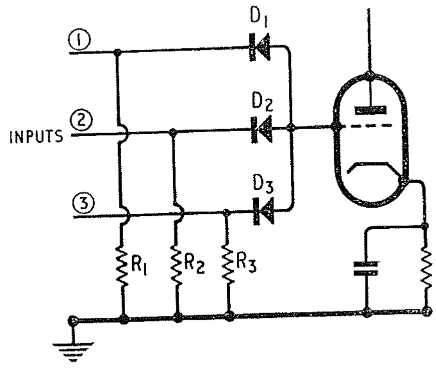


Fig. 1.9 An 'AND' gate

part of which consists of a parallel combination of the other two diodes each in series with a resistor. When D_1 is in its high resistance state, it has a resistance which is much greater than the sum of the forward resistance of one of the other diodes and one of the resistors, R_1, R_2 and R_3. The voltage at the grid of the valve is, therefore, almost unaffected by the application of a positive pulse to D_1 alone. Similarly the application of a positive pulse to any other diode or the simultaneous application of positive pulses to any two diodes will leave the grid potential of the valve virtually unchanged, since the diode or diodes which are receiving no pulse will be held in their low resistance state and will effectively short the valve grid to earth.

If, however, positive pulses are applied to all three of the diodes simultaneously, the grid of the valve will receive a positive potential with respect to earth, since the valve input impedance is much greater than the reverse impedance of the diodes.

Thus the valve receives a positive pulse if, and only if, positive pulses are fed to all three of the diodes simultaneously. Although three diodes are shown in Fig. 1.9, any reasonable number of diodes from two upwards can be used if a greater number of input channels is required. If the incoming pulses are negative going, the connections of the diodes in Fig. 1.9 should be reversed.

Another type of coincidence circuit employs a multi-grid valve such as a hexode in which two of the grids are normally biased so that either would cut off the anode current. The anode current will only flow if positive going pulses are received simultaneously by both of the grids, in which case a negative going pulse is produced at the anode.

The Rossi coincidence circuit employs a number of pentodes which have a common anode resistor of a fairly high value. The number of pentodes used is equal to the number of input channels required. When one or more pentodes conduct, the common anode potential falls to about 20 V. A positive going output pulse is obtained from the anodes if, and only if, all of the pentodes receive simultaneous negative input pulses so that they are all cut off.

A transistor coincidence circuit is shown in Fig. 1.10. Current can only pass through the series connected transistors when coincident negative going pulses are fed to the two inputs. The positive bias is large enough to cut the transistors off in the absence of input pulses.

Coincidence circuits are used in many predetermined counting circuits and are also used in certain radio-isotope measurements. Anticoincidence circuits are also used in isotope measurements; this type of circuit allows a pulse to pass through it provided that a simultaneous pulse is not being received from another source.

1.2.15 The OR Gate

An OR gate provides an output pulse whenever a suitable pulse is applied to any input channel of the circuit. It also serves the purpose of isolating the various input channels from each other.

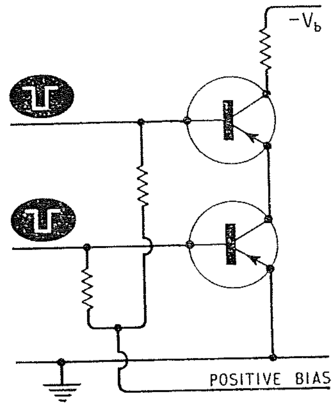


Fig. 1.10 A transistor coincidence circuit

The AND gate of Fig. 1.9 will become an OR gate if the input pulses are negative going. It can be seen that negative going input pulses will pass through the diodes, but will not be able to pass into any of the other input channels without passing through the high reverse resistance of one of the other diodes. If the polarity of the diodes is reversed, the circuit becomes an OR gate for positive going pulses. Other types of OR gate are also available.

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2

Electro-Magnetic Counters

The simplest type of counter is the electro-magnetic register, also known as the electro-mechanical register. The mechanism of this type of counter is very similar to that of a relay. When a current pulse flows through an internal electro-magnet, a soft iron armature is attracted and is subsequently released at the end of the pulse. The armature operates a pawl and ratchet system which in turn moves a small drum on which the units digits are painted. When the units drum moves from 'nine' to 'zero', the drum which indicates the number of tens is advanced one position by means of a mechanical linkage from the units drum. The type of display (as can be seen from Plates 1 and 2) is similar to that of the mileage indicator of a car. The maximum operating speed of electro-magnetic counters varies from about 5 to 50 pulses per second according to type. They have a longer resolving time than any of the other counting systems to be discussed, but are very useful as compact multi-decade slow counters and for adding to faster decades to increase the capacity of the latter by several digits.

Initially electro-magnetic counters were used by the Post Office to register the number of local telephone calls made by a suscriber. The types of four digit Post Office register (type 100A, 100B or 100C) used for this purpose are comparitively cheap, but they have a long resolving time (about 0.1 to 0.15 sec), cannot be reset to zero and have a relatively short life (about 250,000 counts). When such a counter ages, some counts are missed and eventually the unit will completely cease to function. The power required to operate these counters is of the order of 3 W for not less than 50 msec. The most common value of the coil impedance of the electro-magnet is 2,300 Ω, but other values of coil impedance are available. In the past, Post Office registers have been used in many scaling units after high speed valve decades.

Many types of precision electro-magnetic counters are now available which have a very much longer life (over 10^8 counts) and which usually have a somewhat shorter resolving time than the Post Office types. Some types can be reset by means of a switch, a lever or a push-button, whilst others can be reset by the application of a suitable pulse to an additional electro-magnet inside the counter. Counters which are reset to a number other than zero are also obtainable. The number of digits indicated can vary from one up to at least seven. Small electro-magnetic counters are available to indicate time in hours, minutes and seconds. Other types of counter contain two electro-magnets and can be used for forward or reverse counting. Some counters print out the number of counts onto a roll of paper instead of, or in addition to, the normal type of electro-magnetic counter readout. An internal rectifier is fitted in some counters so that they can be operated directly from a pair of contacts placed in series with the counter across the a.c. mains supply.

Electro-magnetic counters are available with a wide range of coil impedances. If a counter with a maximum speed of ten counts per second is to be fed from a transistor circuit, a nominal 20 Ω coil which passes about 0.3 A at 6 V may be suitable. A similar counter fed from a valve circuit requires a coil of a higher impedance; for example, a coil of nominal impedance 5,800 Ω which will pass about 19 mA at 110 V may be suitable. In either case the power fed into the coil is about 2 W for 40 msec.

Counters which have a greater maximum operating speed than ten pulses per second will normally require a pulse of larger power for a shorter time. If a counter employs magnetic reset, a pulse of about 8 W for 200 msec is required in most cases to reset the unit. The pulse current and voltage must, of course, be approximately matched to the coil impedance. It should be noted that in many cases the coil ratings are for pulsed operation only, and overheating may occur if the power is applied continuously to the coil for a few minutes.

It is possible to design magnetic counters for operation at quite high speeds (over 10 kc/s), but the amount of movement is microscopic and the construction often resembles that of a moving coil loudspeaker. In such systems the moving parts must be very light in weight in order to achieve high speeds and, therefore, wear may be excessive. Readout is normally effected by means of a beam of light.

An interesting system has been described by Bennett[1] which consists of a continuously running motor and a light electro-magnetically operated clutch. When an input pulse actuates the clutch, the motor moves a pointer which indicates the units and tens. A further four digits are displayed on small drums which can be reset. The system can operate at over 50 pulses per second and showed no signs of wear after 10^8 counts at this speed.

Counting at speeds above 100 pulses per second can normally be carried out much more satisfactorily by the use of purely electronic devices (at least in the first decade) than by electro-magnetic counters, since the latter have inertia and are subject to wear. At the moment it seems most unlikely that much further effort will be made to design counters which employ moving parts for operation at frequencies in excess of about 100 pulses per second.

2.1 PREDETERMINED COUNTERS

Electro-magnetic predetermined counters are manufactured by a number of companies and are very useful for industrial batching operations, etc., where the maximum counting rate does not exceed about 25 impulses per second. The counters are preset to the desired number and each input pulse will then reduce the number indicated by unity until the zero position is reached, when a set of contacts inside the counter will be operated. This set of contacts can be used to cause any desired operation to be performed and (if the unit is equipped with magnetic reset facilities) the counter can be automatically preset to the same number as before. Alternatively the resetting can be carried out manually. Contacts may also be fitted to some types of predetermined counters so that a warning is given at a certain number of counts before the zero is reached.

In the Sodeco preset counter shown in Plate 2, the preset number can be made to appear by pushing the button at the front of the instrument. If the button is pushed and turned through 90°, the hinged cover above the numbers may be opened and the knurled drums which are located under the cover can be adjusted until the desired number appears. These counters are available with various coil impedances and also with internal rectifiers for operation from a.c. mains.

2.2 CIRCUITS FOR DRIVING ELECTRO-MAGNETIC COUNTERS

If an electro-magnetic counter is to be operated from a pair of contacts which periodically close, the counter may be merely connected in series with the contacts and a suitable source of a steady potential. Care should be taken that the contacts are closed for a time which is long enough to ensure satisfactory operation of the counter, but not for the coil of the counter to become overheated.

A considerable amount of sparking can occur at the contacts in series with the counter owing to the voltage induced in the coil of the counter when the current ceases to flow through it. This sparking can damage the contacts, especially if they are small, and will eventually lead to counting errors. There are a number of methods by which sparking at contacts can be reduced, but their efficacy varies considerably with the type of coil and the type of contacts employed[2].

It has been found that one of the most satisfactory methods of spark suppression in many types of counter involves the use of a resistor and a capacitor in series across the contacts. The optimum values of the resistor and capacitor vary widely with the type of counter. A 110 V Sodeco TCe counter rated at 10 pulses per second may employ a 0.2 μF capacitor and a resistor of 2.5 to 5.5 kΩ for spark suppression, whilst a 20 Ω counter of the same type can be used with a 0.5 μF capacitor and a 68 Ω resistor. Larger capacitors and smaller resistors are required for counters designed to operate at up to 25 pulses per second. Full details of the optimum values of spark suppression components for use in this type of circuit have been published(2).

Various other methods of spark suppression are possible. For example, a resistor of about 5 kΩ may be connected in parallel with the counter coil. A capacitor may also be required in parallel with both the resistor and the coil(2).

If a counter coil is rated at between about 20 and 160 V, a voltage dependent resistor may be connected across it to short circuit the voltage produced in the coil when the contacts open. The Mullard voltage dependent resistor type E299DE/P232 is suitable for coils rated at 20 to 48 V, the E299DE/P338 for 60 V coils and the E299DE/P342 for 72 to 110 V coils. This method of spark suppression is not normally so satisfactory as that using a series resistor and capacitor connected across the contacts.

In magnetically reset counters the sparking at the resetting contacts may be reduced by the same methods, but the optimum values of the components are somewhat different to those required for spark suppression at the contacts in series with the main counter coil(2).

If the contacts are small and they must have a long life, only a small current should be passed through them. Some form of electronic switch should therefore be employed to amplify the small current passing through the contacts to a value which can operate the counter. The circuit of Fig. 2.1 shows a valve circuit which may be used for driving an electro-magnetic counter from two contacts. The current which passes through the contacts *S* is negligible. This circuit is based on a Sodeco publication(3) for their ranges of TCe counters. The valve is normally biased to cut off, but when the contacts are closed, the grid becomes less negative so that an anode current can flow and operate the counter. The value of the resistor R should be adjusted so

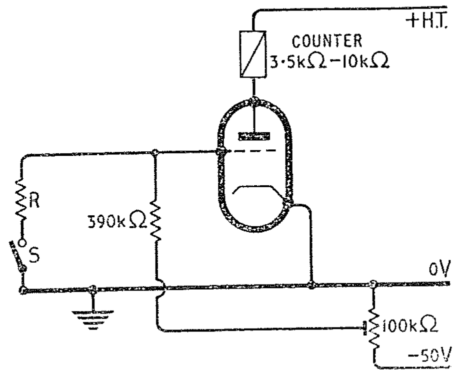


Fig. 2.1 The operation of a counter from a pair of small contacts

that a suitable current passes through the counter when the contacts are closed. If counting rates not exceeding ten pulses per second are required, a counter rated at 3.5 to 10 kΩ at 15 mA may be employed with an E90CC double triode; one section of the valve may be used or both sections may be connected in parallel. For higher counting rates or for counters requiring more current, a valve which can pass more anode current should be used. For example, a 6AQ5 may be used with a counter coil rated at 5.8 kΩ, 38 mA; the screen grid should, of course, be connected to a suitable positive potential.

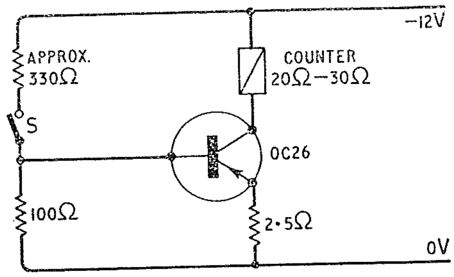


Fig. 2.2 A transistor circuit for the operation of a counter from a pair of small contacts

A similar circuit employing a transistor and a counter coil of much lower impedance is shown in Fig. 2.2(4). When the contacts *S* are closed, a current of about 30 mA passes through them and in the base circuit of the transistor. The amplifying action of the transistor allows a current of about 0.5 A to flow through the counter. The component values should be chosen so that the collector current is normally almost zero, but when S is closed, it should rise to a value suitable for the operation of the counter and the potential between the collector and emitter should fall to a very small value. In either of these states the heat being dissipated in the transistor is small.

In many applications it will be required to operate an electro-magnetic counter from input pulses which have a duration longer than those required to operate the counter. In this case a differentiating circuit followed by an amplifier can be used, a typical case being shown in Fig. 2.3[3]. If the input pulses are negative going, a phase inverting stage, $V1$ (shown dotted), will be required, but if the input pulses are positive going and of a suitable ampli-

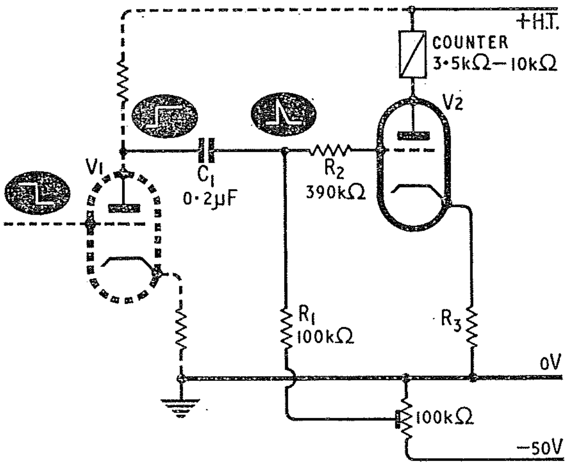


Fig. 2.3 A circuit for the operation of a counter from long input pulses

tude, they may be fed directly to C_1. When the long input pulse is differentiated by C_1R_1, it will be turned into a short positive going pulse which is fed to the grid of $V2$. Thus the anode current flows through $V2$ and the counter for a time which is little longer than that necessary for the operation of the counter. This ensures that the heat generated in the coil is minimised and enables a fairly small valve to be used. The value of C_1 and/or of R_1 may be adjusted to obtain a pulse of a suitable length for the operation of the counter used. The cathode resistor R_3 should be chosen so that the anode current of $V2$ remains below the maximum permissible value for the valve when the grid is earthed. R_2 limits the grid current. The type of valve and the value of the counter coil impedance may be similar to those of the circuit of Fig. 2.1, but as there is no possibility of the valve $V2$ conducting for more than a small fraction of a second, it may be possible to use a valve with a smaller anode current rating than that used in Fig. 2.1.

A similar circuit employing a transistor[4] is shown in Fig. 2.4. The negative going input pulses are differentiated by C_1R_1. The value of R_1 must

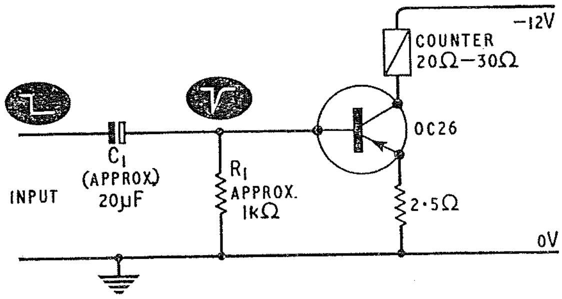


Fig. 2.4 A transistor circuit for the operation of a counter from long input pulses

normally be fairly small and thus C_1 must be fairly large in order to obtain a suitable pulse duration. C_1 is normally an electrolytic capacitor.

2.2.1 Monostable Circuits

If the input pulses are of short duration, a monostable circuit can be used to increase their length to a certain predetermined value which is great enough to ensure reliable operation of the counter. If the maximum speed of the counter is to be attained, a monostable circuit is in any case desirable, since it can supply pulses of the optimum waveform (that is, rectangular). A suitable monostable circuit which has been designed for Sodeco counters is shown in Fig. 2.5[3]. In the quiescent state the left hand triode is conducting whilst the right hand triode is cut off; the current through the counter is therefore very small. A negative input pulse will trigger the circuit and cause the right hand triode to conduct. The circuit will return to its quiescent state after a preset time which is almost independent of the duration of the input pulse. The duration of the pulse applied to the counter may be altered by changing the value of C. Under suitable circumstances this circuit may be used to operate Sodeco

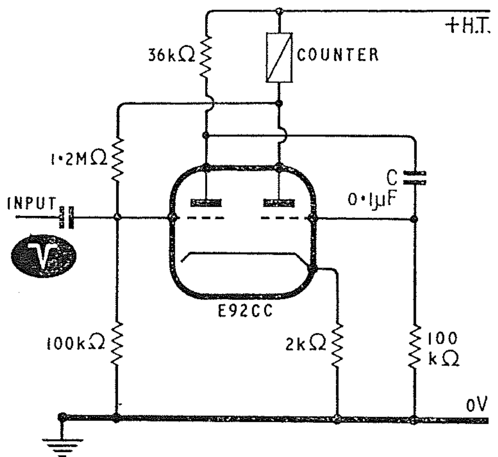


Fig. 2.5 A monostable circuit for the operation of an electro-magnetic counter

counters at speeds exceeding 25 pulses per second. Units consisting of the above circuit plus a suitable power supply are available commercially[(3)].

Some types of counter may require a higher operating current than that provided by the circuit of Fig. 2.5. In this case a valve which has a higher cathode current rating should be used to feed the counter, as in the monostable circuit of Fig. 2.6. In the quiescent state $V1$ is conducting and $V2$ is cut off. A negative going pulse of about 1 V applied to the grid of $V1$ for at least 200 μsec will trigger the circuit. When $V2$ conducts, the current passing through it

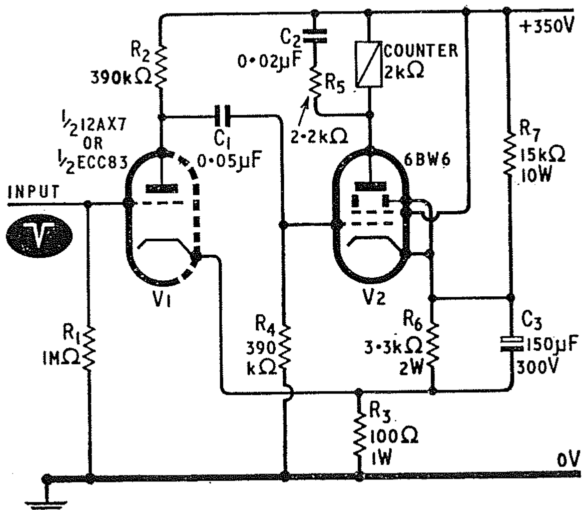


Fig. 2.6 A monostable circuit providing large current pulses

also passes through the common cathode resistor R_3 and so provides the positive feedback required to cut off $V1$. As C_1 charges, a point will be reached at which $V2$ is cut off and $V1$ conducts again. The capacitor and resistor in parallel with the counter coil suppress the voltage pulse when $V2$ is cut off. The value of C_1 may be adjusted to obtain the desired pulse duration. With the value shown, the pulse is applied to the counter for about 25 msec. If a Post Office register is being used, the value of C_1 should be increased to about 0.1 μF, since a Post Office register cannot record more than about ten counts per second. The pulse which passes through the counter has a rectangular top with a peak value of approximately 100 mA. The circuit will oscillate if the bias supplied to the cathode of $V2$ is not great enough to cut the anode current off, but if the bias is excessive, large input pulses will be required to

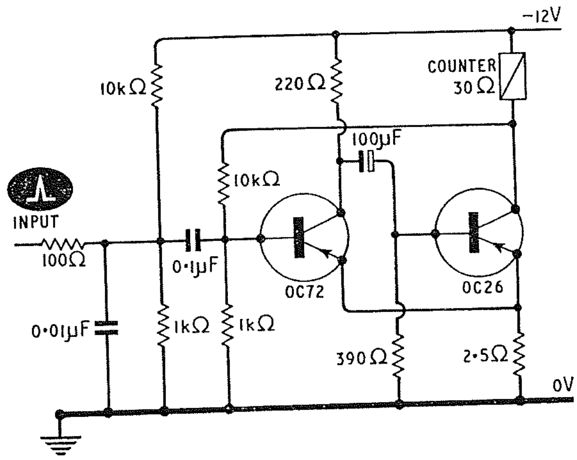


Fig. 2.7 A transistor monostable circuit

trigger the circuit and the current pulses passing through the counter will be reduced in amplitude.

A monostable transistor circuit for operating Sodeco counters is shown in Fig. 2.7[(4)]. In the quiescent state the OC26 transistor is cut off and the OC72 transistor is conducting. The circuit may be triggered by feeding a suitable positive going input pulse to it or by merely connecting the input to earth by a pair of contacts. The OC72 transistor is cut off by the pulse and the voltage across its 220 Ω collector resistor disappears, thus allowing the OC26 transistor to conduct. The double feedback system from the OC26 collector to the OC72 base and from the OC26 emitter to the OC72 emitter enables a rectangular pulse with steep sides to be obtained for the operation of the counter. The duration of the pulse may be altered by changing the value of the 100 μF capacitor or of the 390 Ω resistor in the OC26 base circuit.

Thyratron tubes have been used considerably in the past for the operation of magnetic counters, but

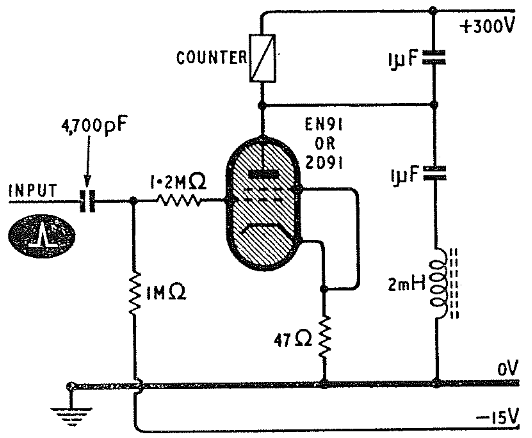


Fig. 2.8 A thyratron circuit for the operation of an electro-magnetic counter

hard valve and transistor circuits are generally more reliable since a thyratron may occasionally fail to extinguish. One type of thyratron circuit which may be used is shown in Fig. 2.8. The capacitance and inductance connected in series between the anode and earth result in the thyratron being extinguished about 50 msec after the commencement of the pulse.

It is sometimes convenient to use a valve, transistor, trigger tube or thyratron circuit to operate a small relay, the contacts of the relay being used to control the current to the counter. A small relay can be actuated by a smaller current than a magnetic counter and thus allows more latitude in the design of the driving circuit. A low power monostable circuit operating from a stabilised supply has been used to operate a relay in many scalers, a separate unstabilised supply being used to supply power to the counter through the relay contacts.

Other circuits for driving electro-magnetic counters are included in Chapter 4 (Figs. 4.37 and 4.38) and Chapter 5 (Fig. 5.21).

2.3 SINGLE DIGIT UNITS

Sodeco single decade counting units (the 1TD series) indicate only one large digit, but are very flexible units for counting circuitry[5]. The single drum on

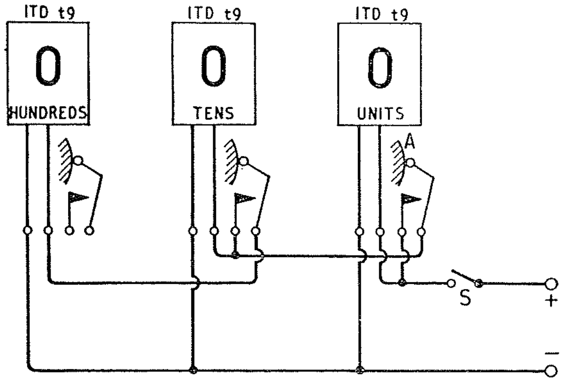


Fig. 2.9 Forward counting with single digit units

which the digits are painted revolves about a vertical axis in contrast to most other types of electro-magnetic counter. The single digit counters are designed for operation at input frequencies of up to either 10 or 25 pulses per second according to type; the slower type require input pulses of about 3 W for 40 msec and the faster type about 6 W for 20 msec. These counters are easy to read at a distance, since the digits are 7/16 in high. Each input pulse advances the drum by half a digit, the count being completed at the end of the pulse. Any unit

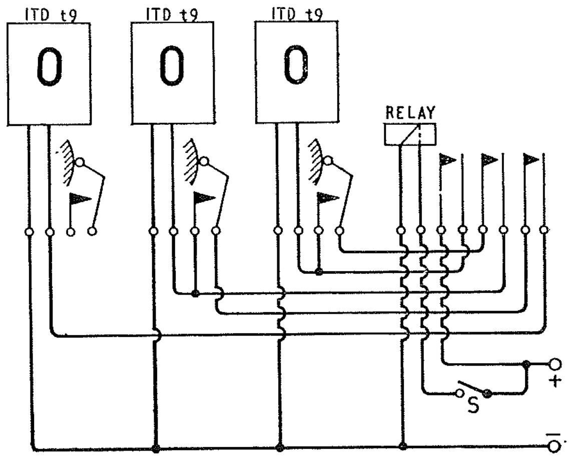
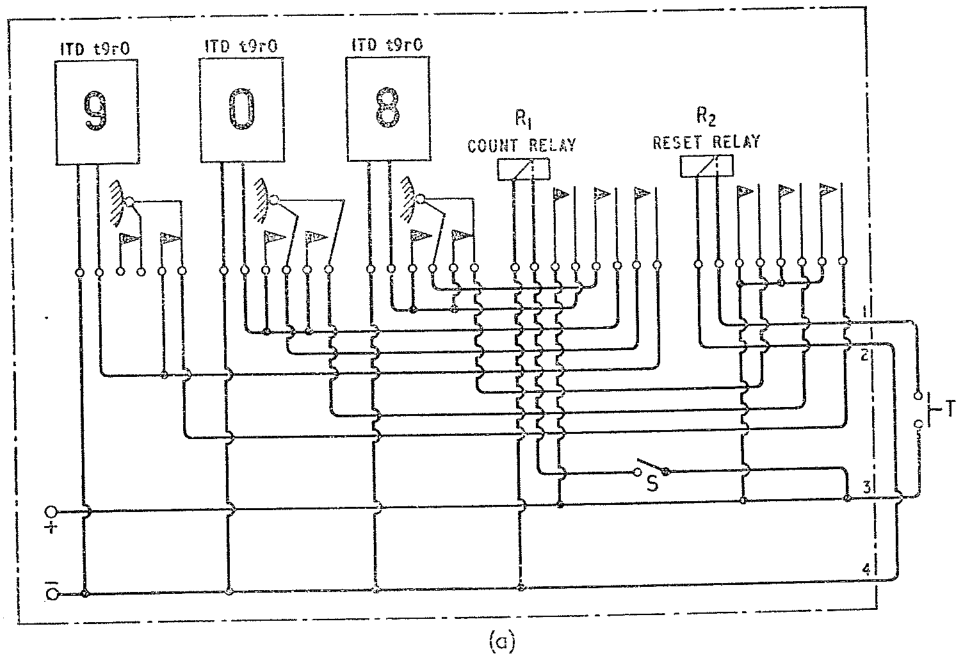


Fig. 2.10 Forward counting with constant loading of the pulse generator



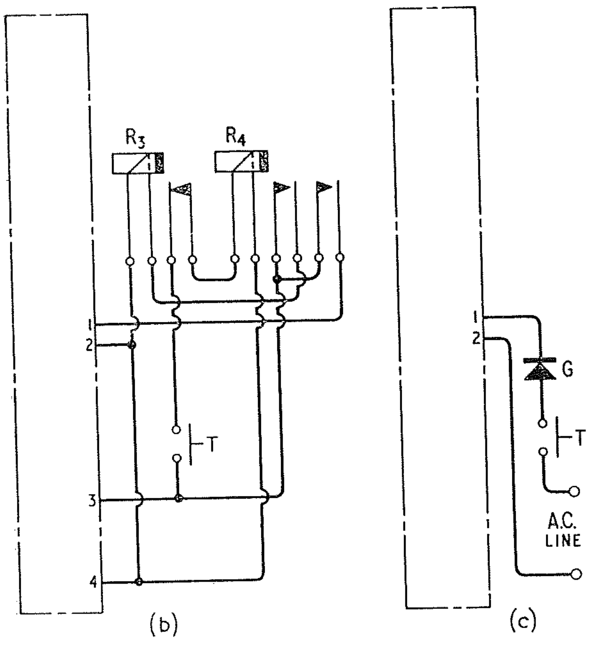


Fig. 2.11 Forward counting with zero reset by means of an additional normally closed contact at position 0

which is continuously energised will, therefore, show an intermediate count.

A number of the single digit counters may be mounted adjacent to one another to indicate a number greater than nine. If they are connected as shown in Fig. 2.9, the additional contacts on the drum of the units counter (marked *A*) may be used to send a pulse to the tens counter each time the units counter moves from 9 to 0. The additional contacts on the highest decade are unused. The counters required for this circuit are coded as ITD t9; other types of single digit counters have different contacts or count backwards.

The input pulses are fed into the units decade, but each tenth pulse must not only operate this decade but also the tens decade. Each hundredth pulse must operate all three decades. If the pulses are derived from a valve or transistor amplifier (such as those already discussed), it is desirable that the amplifier should have a constant load of one decade, especially for counting at higher speeds. This can be achieved by the use of a relay as shown in Fig. 2.10.

The single decade units are not provided with any reset mechanism. They can, however, be reset by the application of pulses to each decade in turn until the digit indicated by each is nine; one additional input pulse to the units decade will then reset the whole system to zero. Rapid resetting can, however, best be accomplished by the use of ITD t9r0 counters which have a normally closed contact which opens in position 0 in addition to the normally open contact which closes in position nine. The circuit shown in Fig. 2.11(a) is reset by pushing the button *T* a number of times until all decades are in their zero state. Each pulse advances all decades which are not indicating zero. If the button is replaced by the circuit of Fig. 2.11(b), the two relays act as a mechanical interrupter and provide the required pulses for resetting the decades automatically when the reset button is pushed once. Alternatively the resetting pulses may be obtained from the a.c. mains by adding the circuit of Fig. 2.11(c) to that of Fig. 2.11(a).

Various other circuits showing how the single decade units may be used for the transmission of numbers over a distance, addition and subtraction with forward counting decades, predetermined counting, remote predetermined counting, etc. have been published[5].

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3

Single Cathode Gas Filled Counting Tubes And Their Circuits

Counting circuits using simple cold cathode gas filled tubes can operate at rates which are at least ten times greater than that of fast electromagnetic counters. Most gas filled tubes have the property of self indication; that is, the number of counts can be read by merely observing which particular tube is glowing in each decade, no additional components being required for readout. This property of self indication also simplifies the servicing of faulty units. Cold cathode tubes are extremely reliable in operation and the absence of heaters simplifies the circuitry, reduces the power consumption and results in less heat being generated than in valve counting circuits. Cold cathode tubes are especially useful in industrial automation for many processes, including counting.

3.1 SIMPLE COLD CATHODE TUBES

Simple cold cathode tubes have two or more electrodes and are normally employed in ring circuits. They have two characteristic stable states, namely conducting and non-conducting. Any number of tubes may be employed in a ring, only one of them conducting at any one time. If the tube which indicates the digit zero is initially passing a current (and therefore glowing), the arrival of an input pulse will cause the next tube, which indicates the digit one, to glow and the zero tube to be extinguished. A second pulse applied at the input will cause the glow to be transferred to the next tube. If the last tube in the ring is glowing, the next pulse will ignite the first tube and the last tube will be extinguished. In addition an output pulse will be passed to the next ring. A counting decade may consist of a vertical row of ten trigger tubes mounted on the front panel of the equipment, each tube being placed behind a small window on which the appropriate digit is marked. Similar decades can be placed side by side. Cold cathode binary counting stages are also used.

The multicathode tubes described in later chapters permit the use of simpler circuitry than is possible when single cathode tubes are used, but the circuits employing simple tubes are more flexible, can easily be adapted for a large variety of particular requirements and can operate from lower H.T. voltages. Cold cathode tubes are very reliable in operation. Most multicathode tubes pass a small current and the output voltage available from them is very limited. Single cathode tubes passing 25 mA or more can be used in counting equipment and fairly high output voltages can be obtained from them; such tubes can be used to operate a relay or electro-magnetic counter directly without any intermediate amplification. On the other hand some trigger tubes can be operated at low currents.

Any desired counting scale can be constructed using single cathode tubes, but this is not usually possible with multicathode tubes. Unsatisfactory operation can occur in gas filled polycathode tubes if the discharge remains at one cathode for a long time owing to sputtering of the cathode material, but trigger tube circuits do not suffer from this effect if they are properly designed.

Cold cathode tubes consist of two or more electrodes placed in a glass envelope which is filled with a suitable gas mixture, usually one or more of the inert gases at a pressure of less than one tenth of an atmosphere. If the voltage applied between the anode and cathode of such a tube is less than a certain value, known as the striking voltage, the current which flows is very small (about 10^{-10} A) and is known as the Townsend current. When the applied voltage reaches the striking voltage, the current suddenly increases and is then usually limited only by the internal resistance of the source of applied voltage. The voltage across the tube falls from the striking voltage to a value which is known as the maintaining or running voltage. This is the normal operating voltage of the tube. Under these conditions the discharge is clearly visible, the colour being determined by the nature and pressure of the gas contained in the tube. The current flowing is given by the equation

$$I_a = \frac{V_b - V_m}{R_a}$$

where V_b is the supply voltage
V_m is the maintaining voltage
R_a is the resistor in series with the tube.

The maintaining voltage remains almost constant over an appreciable range of current and suitably designed cold cathode tubes can, therefore, be used as voltage stabilisers. As the cathode current rises, the discharge covers a larger area of the cathode. If the current is increased beyond the maximum permissible value, the anode to cathode potential will first rise and then fall as an overheated spot on the cathode results in thermal emission. Operation at such currents, however, will normally destroy the tube.

Once the discharge has commenced, it is necessary to reduce the voltage applied to the tube below the maintaining voltage for a time which is not less than the tube deionisation time in order to extinguish the discharge. A voltage at least equal to the striking voltage must then be applied to the tube to cause it to conduct again. If the anode voltage is reduced below the maintaining voltage for a time less than the deionisation time, the tube will ignite again when the maintaining voltage is re-applied. The deionisation time varies somewhat with the anode current and the re-applied voltage, but is normally some milliseconds.

Once a discharge has been initiated in a gas filled tube, the positive ions produced form a space charge extending from the cathode towards the anode. This increases the voltage gradient in the cathode region and results in the maintaining voltage being considerably below the striking voltage.

The initiation of the gas discharge when a voltage is applied to any cold cathode tube is dependent on the presence of some ions in the gas. Once the discharge has commenced, the bombardment of the cathode by the positively charged ions formed in the discharge causes electrons to be emitted from the surface of the cathode and these electrons produce more ions as they pass through the gas.

The cathodes used in cold cathode tubes may be divided into two main types. The first type of cathode is coated with a material of low work function which emits electrons easily; materials with a work function of about 2.5 V such as barium or potassium are used. Tubes in which this type of cathode is used have relatively low maintaining voltages of about 60 to 100 V, but the cathodes are subject to deterioration in use. The second type of cathode has a higher work function (about 5 V) and the tubes in which they are used normally have a higher maintaining voltage. Cathodes of the second type usually consist of pure molybdenum or nickel. During the manufacture of tubes employing this type of cathode, material is sputtered from the cathode by heavy ionic bombardment so that the cathode surface is very pure. In addition the sputtered material on the glass envelope binds any impurities in the gas to the wall of the tube. Such tubes are extremely reliable when operated within their ratings, but cannot be used at low anode to cathode voltages.

3.1.1 Priming

If a discharge is to be rapidly initiated when the appropriate voltage is applied to the tube, a limited number of ions must be present in the tube at all times. A few ions per minute are formed in a trigger tube by cosmic rays and by the radiation from stray radioactive atoms which are present in all materials, but more ions are needed if the discharge must always be initiated rapidly. On the other hand, the presence of an excessive number of ions in the gas before ignition will lower the striking voltage and affect the functioning of the tube. Artificial methods for increasing the number of ions present in cold cathode tubes are known as priming.

If a coated cathode of low work function is employed (such as in the Z701U tube), priming may take place by means of light shining on the cathode. This photoemission can occur at wavelengths less than about 5,000 Å, but the glass used in the manufacture of the tubes does not cut off much of the light with a wavelength above 2,900 Å. Such tubes may take a long time to ignite (up to ten minutes) if they are operated in a completely dark room and if no other form of priming is employed. Tubes which have a cathode of low work function should not be operated in bright sunlight or so many ions may be formed that the striking voltage is considerably lowered. Some tubes employing coated cathodes contain a little tritium gas or other radioactive material which provides the ionising particles required for rapid striking even in complete darkness. The amount of radioactive material used is so small that there is no danger even if the bulb of the tube is broken.

Photoemission will not occur from cathodes of the second type which have a high work function unless ultra-violet light of wavelength less than about 2,500 Å falls on them[1], but light of such a wavelength cannot pass through the glass of a normal tube. Such tubes are quite unaffected by bright sunlight, but some method of priming must be employed if the initiation of the discharge is to take place almost immediately after the application of a potential greater than the striking voltage.

One of the most common methods of priming involves the use of an auxiliary anode or cathode. A constant current of a few microamps flows through the gas between the auxiliary electrode and one of the other electrodes so that ions are always present in suitable numbers. If a priming cathode is used, the tube can be extinguished by raising the cathode potential without the priming discharge being affected, but a negative supply line is required. Tubes with a priming anode can be extinguished by lowering the main anode voltage without the priming discharge being affected. In some tubes a priming anode and a priming cathode are used, the auxiliary discharge taking place between these two electrodes. The ionisation time is affected by the magnitude of the priming current, but the maintaining voltage is independent of this current. Primed tubes which use pure metal cathodes have a very constant striking potential and are unaffected by the ambient lighting.

3.2 COLD CATHODE DIODE COUNTING CIRCUITS

One of the simplest cold cathode diode circuits is shown in Fig. 3.1[2]. Let us assume that the left-hand tube, $V1$, is conducting and the right-hand tube, $V2$, is cut off. The voltage developed across R_1 (due to the current flowing through this resistor to $V1$) is such that the voltage across $V2$ is less than the striking voltage of this tube. Thus the system is stable. The capacitor C_2 is charged so that the anode of $V2$ is positive with respect to the anode of $V1$ by an amount equal to the potential difference across R_2.

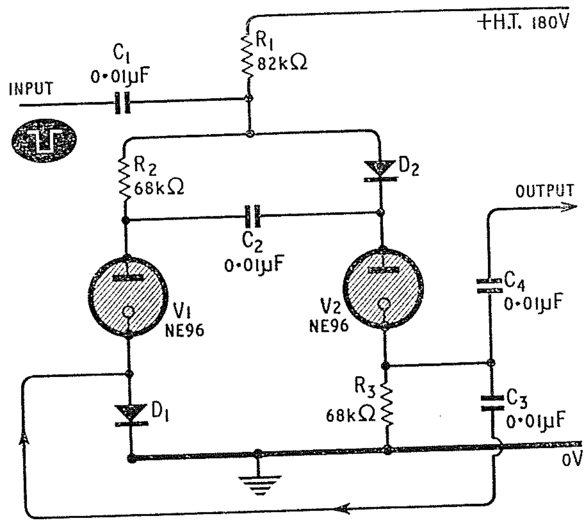


Fig. 3.1 A simple binary counter using cold cathode diodes

If a negative going pulse is now applied at the input, the anode voltage of $V1$ falls below the maintaining voltage and the tube is extinguished. The current through R_1, therefore, decreases and the anode voltages of both tubes will tend to rise. In addition, a sudden rise of anode voltage will occur at

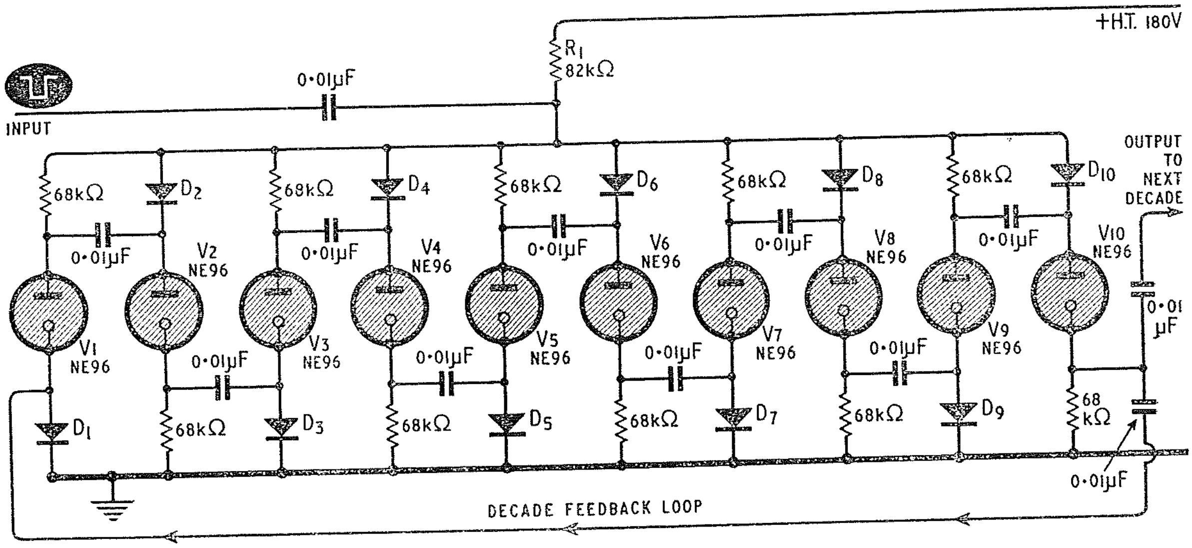


Fig. 3.2 A ring of ten cold cathode diodes for decade counting

the end of the input pulse. C_2 is prevented from discharging rapidly by the reverse resistance of D_2 and, therefore, it holds the anode of $V2$ at a positive potential with respect to the anode of $V1$. $V2$ will, therefore, strike preferentially to $V1$ as the anode voltage rises. When $V2$ commences to conduct, the voltage across $V1$ is kept below the striking voltage by the voltage drop across R_1. The glow is thus transferred from $V1$ to $V2$ and a count is registered.

When $V2$ is conducting, no current flows through R_2 and hence the voltage across C_2 equals the voltage across the diode D_2 – which is small, since the current passes through this diode in the forward or low resistance direction. The capacitor C_3 is charged owing to the flow of current through R_3. The polarity of this charge is such that the cathode of $V1$ is negative with respect to the cathode of $V2$. If a second negative going pulse is now applied at the input, the anode voltages are reduced as before and $V2$ is extinguished. C_3 is prevented from discharging quickly by the high reverse resistance of D_1 and, therefore, the cathode of $V1$ is held at a negative potential with respect to the cathode of $V2$. $V1$ will, therefore, strike preferentially to $V2$, as the anode to cathode voltage is greater. The second pulse thus resets the binary circuit to its initial or zero state in which $V1$ is glowing. The capacitors C_2 and C_3 must be large enough to hold most of their charge during the switching operation, but should not be so large that the maximum counting speed is appreciably reduced.

A number of binary circuits can be cascaded as discussed in Chapter 1 but, when cold cathode tubes are used, it is normally much more convenient to construct a ring counter such as that shown in Fig. 3.2. One common anode resistor, R_1, is employed and the coupling capacitors are placed alternately in between the cathodes and anodes of successive stages as shown. The principle of operation of this circuit is exactly the same as that of Fig. 3.1, but there are ten tubes in the ring instead of two. Any even number of tubes, however, could be used in the ring.

If $V10$ is glowing when an input pulse is received, a positive going output pulse will be produced which may be used to operate a ring of ten similar tubes, in which case the arrangement will count up to one hundred. Alternatively the ouput pulses (after amplification and phase inversion) may be used to operate an electro-magnetic counter.

If the position of the coupling capacitors are altered in Fig. 3.2 so that there is cathode coupling between $V1$ and $V2$, anode coupling between $V2$ and $V3$, cathode coupling between $V3$ and $V4$, etc., the circuit will count backwards as the glow is transferred from the right-hand tube in the circuit towards the left-hand tube.

A very similar cold cathode diode ring circuit is shown in Fig. 3.3 in which all of the capacitors are placed in the cathode circuits of the tubes. Any number of tubes may be used in this type of circuit. When $V1$ is conducting, the right-hand side of C_2 is negative with respect to its left-hand side. If a negative going pulse is now applied to all of the anodes, $V1$ is extinguished and the junction of D_1 and R_2 becomes more negative as the current through R_2 declines. C_2 cannot discharge rapidly through the high reverse resistance of the diode D_2 and the negative pulse from the junction of D_1 and R_2 is applied to the cathode of $V2$. This results in $V2$ striking preferentially to other tubes when the common anode voltage rises at the end of the input pulse.

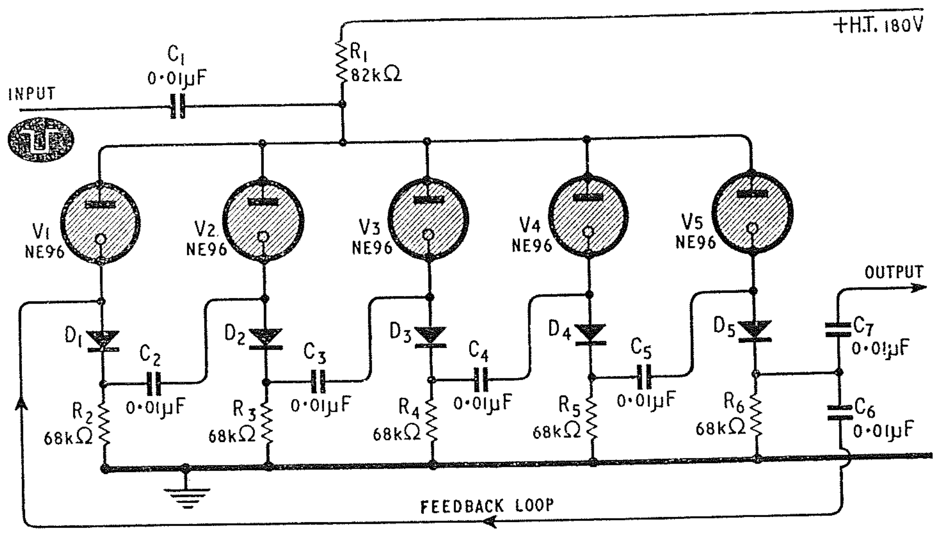


Fig. 3.3 A ring of five diodes with cathode coupling

Cold cathode diodes are not used as counting elements in modern equipment, since similar circuits can be constructed using the more versatile trigger tubes or PNPN semiconductor devices. The maximum speed of cold cathode diode ring circuits is usually of the order of 1 kc/s. Changes in the striking voltage of the diodes during life tends to reduce reliability and the amplitude and duration of the input pulses are quite critical.

3.3 TRIGGER TUBES

A trigger or relay tube is very similar to a cold cathode diode but, in addition to the anode and cathode, it possesses at least one additional electrode known as the trigger or starter. This electrode may normally be considered as an additional anode, although in a few tubes (such as the Z804U) the trigger has a negative potential and acts as an additional cathode. The trigger is normally placed near to the cathode and either in or near to the main anode to cathode gap. The voltage which must be applied to the trigger electrode to initiate a discharge is much less than that required by the main anode. In normal operation the potential applied between the main anode and the cathode of a trigger tube is less than the striking voltage but is greater than the maintaining voltage of the tube. If a suitable positive pulse is applied to the trigger electrode, a current will flow between this electrode and the cathode and the gas between the electrodes will be ionised. Enough ions will be formed for the striking voltage of the main gap to be lowered almost to the maintaining voltage. The greater the trigger current, the greater the amount by which the striking voltage is lowered. Thus the trigger pulse can initiate conduction in the main anode to cathode gap and it can be said that the discharge has been transferred from the trigger gap to the main gap. For a given value of anode—cathode voltage, a certain minimum trigger current is required to enable the main gap to take over the discharge. This is known as the transfer current.

Once the main gap has commenced to conduct, the tube can be extinguished only by reducing the potential between the main anode and cathode below the maintaining voltage of the tube for a time which is not less than the deionisation time. No alteration of the trigger voltage will extinguish a discharge in the main gap; the action of the trigger electrode is not reversible in the way that the grid of a normal thermionic valve can reversibly control the anode current of the valve.

3.3.1 Trigger Tube Characteristics

The discharge in a trigger tube may be initiated between any two of the three electrodes and may flow in either direction, although some of these modes of operation will damage the tube. The breakdown characteristic of a tube which is initially non-conducting can be conveniently represented by the type of quadrant diagram shown in Fig. 3.4. No discharge will take place in the tube if the anode and trigger voltages measured with respect to the cathode can be represented by a point inside the curve unless the operating point has previously been outside the curve and the discharge has not since been extinguished. At certain points within the loop the discharge can be maintained but not initiated. Owing to the spread of the characteristics from tube to tube, it is necessary to draw two curves one inside the other in the tube data sheets. If the operating point is taken outside the outer curve, a discharge will take place in all tubes to which the curves apply, but no discharge can be initiated in any tube by applying a potential which can be represented by a point inside the inner loop. At operating points between the two loops, some tubes will strike whilst others will not.

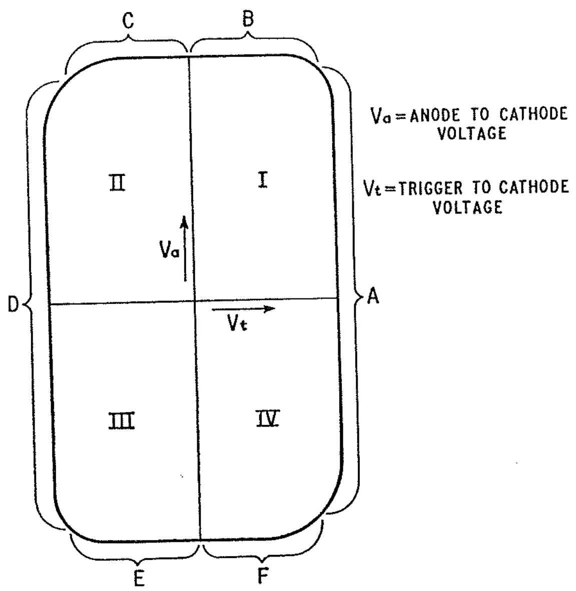


Fig. 3.4 Breakdown characteristics of a trigger tube

If the trigger potential is increased at a small anode potential in Fig. 3.4, the loop will be crossed in the region marked *A*; a discharge then commences between the trigger and cathode. It should be noted that the trigger striking potential is almost independent of the anode potential. If the anode voltage of a trigger tube is increased so that the operating point cuts part *B* of the curve, however, a discharge will be initiated between the anode and cathode. In section *C* of the curve the discharge is from anode to trigger, whereas in section *D* it is from cathode to trigger. If the anode is at an appreciable negative potential, it can also act as a cathode. In section E of the curve the discharge is from the cathode to anode and in section F from the trigger to anode.

Almost all trigger tubes are designed for operation with positive anode and trigger potentials. The operating point should, therefore, be within quadrant I of Fig. 3.4 before ignition takes place. After ignition has occurred, the operating point will return to a point well inside quadrant I owing to the voltage drop in the anode and trigger resistors. A few trigger tubes (such as the Z804U) operate in quadrant II with the trigger negative with respect to the cathode. No tubes should be operated so that the curve is crossed in quadrants III or IV or they may be damaged.

The characteristics of a trigger tube are affected by a thermal hysteresis effect when the tube has been passing a fairly high anode or trigger current for a short time. The characteristic may be changed by as much as 30 V when a tube has been passing its maximum rated anode current for about one minute.

The ionisation time of a trigger tube may be defined as the interval between the application of a pulse to the trigger electrode and the flow of the full anode current. It is the sum of the following three times:

1. *The Statistical Delay*. This is the average delay between the application of the trigger pulse and the time when an ionising particle enters the trigger to cathode gap and initiates the discharge. It depends on the method of priming and the amount by which the trigger potential exceeds the minimum trigger striking voltage.
2. *The Formative Delay*. This is the time taken for the trigger to cathode discharge to be established. It is dependent on the amount by which the trigger potential exceeds the minimum trigger striking voltage.
3. *The Transition Time*. This is the time taken for the trigger discharge to ionise the main gap so that a large anode current can flow. This time is inversely proportional to the trigger current and the anode voltage. The total ionisation time may vary between about 20 μsec and 10 msec according to the type of tube and the applied potentials.

   The ionisation and deionisation times of trigger tubes limit the maximum frequency at which trigger tube counting circuits can be operated.

3.3.2 Trigger Tetrodes

Trigger tetrodes have two independent trigger electrodes instead of one. A suitable voltage applied to either of the trigger electrodes will initiate conduction. Such tubes can be used in circuits which will count in either direction.

The basic characteristics of trigger tubes are discussed in more detail in various publications [3-7], whilst the fundamentals of electrical discharges in gases are discussed in the book by Penning[8].

3.4 TRIGGER TUBE COUNTING CIRCUITS

All trigger tube counting circuits must employ components in the trigger circuits which will cause the tubes to strike under the combined influence of the input pulse and the bias voltage from the previous conducting stage. In addition some means of extinguishing each tube must be included. There are three types of coupling circuit which have been used to extinguish a glowing tube in a counting circuit when the succeeding tube has ignited. In one type of circuit separate anode resistors are employed with a coupling capacitor between the anodes. If a non-conducting tube ignites, its anode becomes more negative and this negative pulse is fed through the capacitor to the anode of the tube which was initially conducting. The pulse extinguishes this tube. A second type of circuit employs separate cathode resistors, but no anode resistors; the extinguishing capacitor is connected between the cathodes. This type of circuit is exactly the same in principle as the first type, except that cathode coupling is employed.

The third type of extinguishing circuit uses a common anode resistor for two or more tubes. The cathode of each tube is returned separately to the H.T. negative line via a resistor in parallel with a capacitor. If the non-conducting tube strikes, the increased voltage drop across the common anode resistor causes the tube which was initially conducting to be extinguished. This type of coupling is most commonly employed, since the positive voltage at the cathode of the conducting tube can conveniently be used for biasing the succeeding tube. The circuit does, however, require a fairly high value of H.T. supply, since both anode and cathode resistors are used.

3.4.1 Practical Binary Circuits

One of the simplest binary or ring of two counting circuits using trigger tubes is shown in Fig. 3.5[9]. It uses two subminiature Hivac XC18 trigger tubes with common anode resistor coupling. R_1, R_2 and R_4 provide a positive bias for the trigger electrode of $V1$ and R_9 and R_{10} provide the bias for $V2$. This bias voltage is not great enough to cause ignition of the tubes by itself but it enables an input pulse of much smaller amplitude to be used to ignite the tubes than if no bias were provided.

When the H.T. supply voltage is first applied to the circuit, a pulse is applied to the trigger of $V1$

via C_1, R_2 and R_3. C_1 presents a much lower impedance to the pulse than R_1 and, therefore, the trigger electrode of $V1$ will become momentarily more positive than its normal working voltage (which is not reached until C_1 is fully charged). This positive pulse ignites $V1$ which indicates zero counts.

If a positive pulse of suitable amplitude and duration is now applied at the input, it is conveyed to both trigger electrodes via C_2R_3 and C_5R_8 respectively. The pulse causes $V2$ to ignite, but leaves $V1$ (which is already passing a current) momentarily unchanged. C_4 is initially uncharged and, therefore, $V2$ takes a current which reduces the common anode potential to the maintaining voltage of this tube. C_3 has charged whilst $V1$ was conducting and maintains the cathode of $V1$ at a positive potential. The potential across this tube is, therefore, less than the maintaining voltage and it is extinguished. Thus the discharge has been transferred from $V1$ to $V2$ and a count has been registered. A second similar pulse at the input will cause the discharge to return to $V1$ by exactly the same mechanism, since the circuit is symmetrical with respect to $V1$ and $V2$, except for the presence of the starter capacitor C_1 in the trigger circuit of $V1$. On the binary scale, $V1$ indicates the digit zero and $V2$ indicates the digit one. The quiescent potential of a conducting cathode is about +70 V.

A binary circuit will normally be required to provide a steeply rising output pulse which can operate a succeeding binary counting stage so that numbers greater than one can be counted. The cathode voltages of the tubes in the circuit of Fig. 3.5 change only relatively slowly owing to the effects of the capacitors C_3 and C_4 and it is, therefore, not possible to obtain a steeply rising output pulse.

If, however, the circuit of Fig. 3.5 is modified to that of Fig. 3.6, suitable output pulses can be obtained for the operation of a succeeding binary counting stage[9]. The circuit of Fig. 3.6 is basically the same as that of Fig. 3.5 except that it is designed to provide a fast rising output pulse of about 30 V amplitude from the cathode of $V1$ each time this tube ignites. A negative pulse is also formed each time $V1$ is extinguished, but a pulse of this polarity will not ignite a trigger tube in a succeeding binary counting circuit.

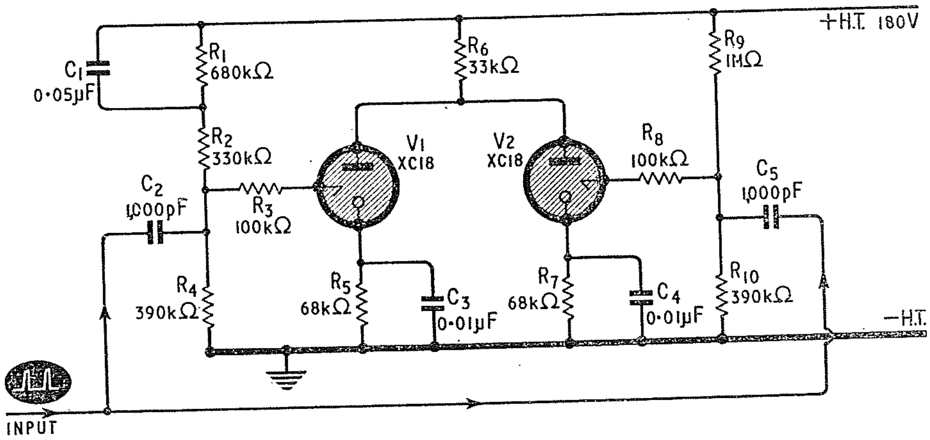


Fig. 3.5 A simple binary counter using XC18 trigger tubes

The Hivac XC23 tube can pass a much larger current than the XC18 tube. If a pair of XC23 tubes are used in the circuit of Fig. 3.6 and the component values are suitably adjusted, the circuit can be used to operate a relay at every alternate input pulse[9].

Although binary circuits require fewer trigger tubes to count over a certain scale than ring circuits, the latter are usually preferred because they provide decade readout. It is possible to construct binary scales of ten employing five trigger tubes per decade. It is interesting to note that some of the earliest trigger tube counting circuits employed transformer interstage coupling.

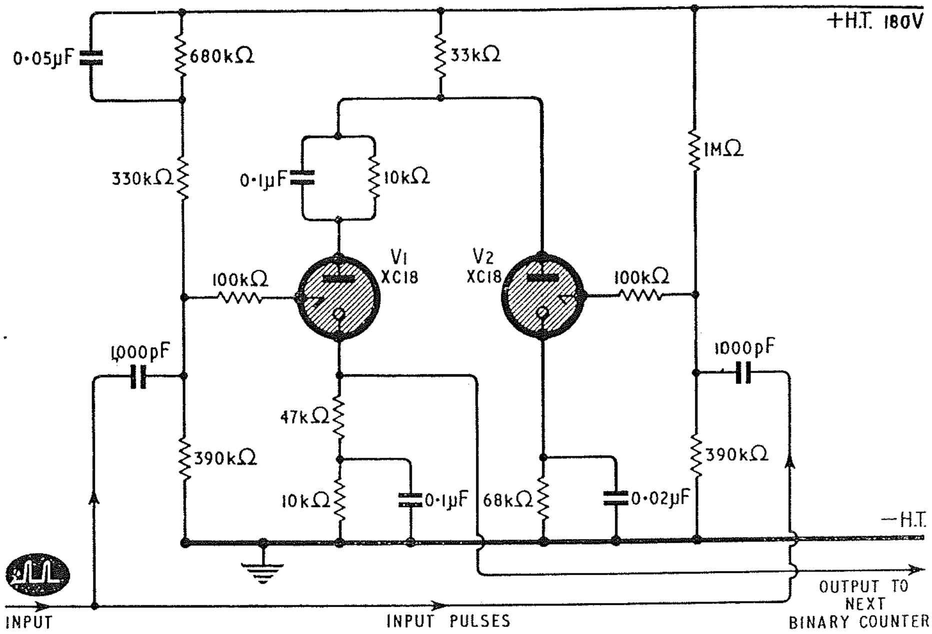


Fig. 3.6 A simple binary counter which output provides output pulses for a succeeding stage

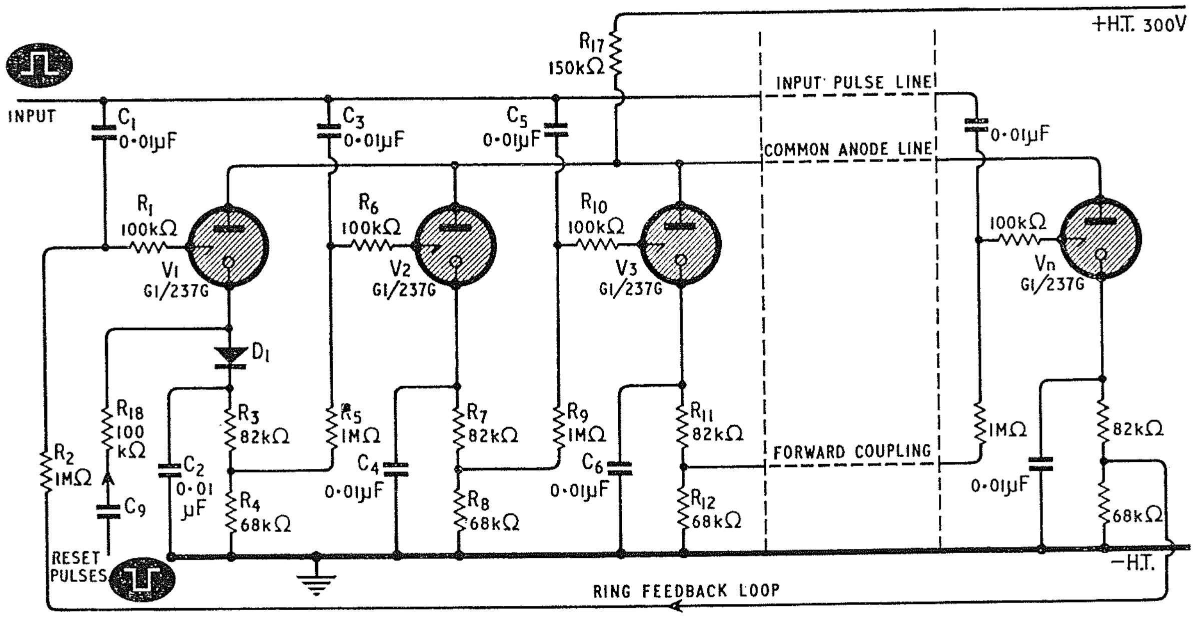


Fig. 3.7 A ring counter using G1/237G tubes

3.4.2 Trigger Tube Ring Counters

A typical example of a trigger tube ring counting circuit is shown in Fig. 3.7 using the S.T.C. G1/237G subminiature trigger tubes[10]. Any number of additional stages may be inserted between the two dotted lines, but rings of ten are most common. At any one time only one of the tubes in each ring is conducting. Each positive going input pulse (of amplitude between 50 and 60 V) is applied via capacitors and resistors to the trigger electrodes of all the tubes in the ring. The amplitude of the input pulses alone must not be great enough to trigger the tubes into the conducting state.

If at any time $V2$ is conducting, a voltage will be present across R_7 and R_8. This voltage will be held fairly constant for a short time by the charge stored in C_4 if the current passing through $V2$ changes. No current is passing through the other tubes and, therefore, the remaining cathode capacitors, C_2, C_6, etc. are uncharged. The voltage across R_8 is applied via R_9 and R_{10} to the trigger electrode of $V3$. When a positive pulse of a suitable amplitude is applied at the input, the trigger of $V3$ will already be more positive than any of the other trigger electrodes by an amount equal to the voltage drop across R_8. Therefore $V3$ ignites, but the other tubes are unaffected by the input pulse.

The capacitor C_6 is uncharged at the instant $V3$ ignites and, therefore, the common anode potential will be reduced to a value equal to the maintaining voltage of $V3$ above earth potential. The cathode of $V2$ is held at a positive potential for a short time by the charge of C_4. The anode to cathode voltage of $V2$ is, therefore, less than the maintaining voltage of this tube which is thus extinguished. The cathode potential of $V3$ rises exponentially as C_6 charges. The anode voltage of this tube will, therefore, also rise exponentially with the same time constant so that the potential across $V3$ remains constant at the maintaining voltage.

The discharge thus passes from $V2$ to $V3$. In exactly the same way it can be made to pass from $V3$ to the following tube (which is not shown in Fig. 3.7) and hence forward around the ring at one step for each input pulse. The circuits of Figs. 3.8 to 3.13 inclusive all operate on the same basic principle.

If a negative going resetting pulse of at least 100 V in amplitude is applied to C_9 of Fig. 3.7, the cathode of $V1$ will become momentarily more negative and the extra voltage appearing across this tube will cause it to ignite. The tube which was previously conducting is extinguished by the same process as in normal counting. The pulse voltage biases the diode D_1 in the high resistance direction and the pulse is not by-passed to earth by C_2. If D_1 were omitted, C_2 would prevent the pulse from causing any rapid change in the potential of the cathode of $V1$.

An H.T. supply potential of about 300 V is suitable for the circuit of Fig. 3.7, but if a higher potential is used R_{17} may be increased by about 1,000 Ω for each volt of H.T. above 300 V. The anode current (about 1 mA) will then be unaffected.

The G1/238G can also be used in the circuit of Fig. 3.7; it is a very similar tube to the G1/237G, but the tolerances are somewhat greater. These tubes may not operate satisfactorily if the ambient illumination is less than about 2 ft-candles (20 lx). They should be mounted by means of a metal clip located at about the centre of the tube and connected to the trigger electrode.

If separate anode resistors are used for each tube in this type of circuit instead of the common anode resistor, the tubes will still strike successively, but no tube will be extinguished until the anode supply voltage is reduced by an extinguishing pulse.

3.4.3 Z700U and Z700W counters

The circuit of Fig. 3.8 shows a chain counter employing the Mullard Z700U (equivalent to the Philips Z70U) or Z700W (equivalent to the Philips Z70W) primed trigger tubes[5, 6, 11]. The components shown by the dotted lines are employed only when a reversible counter is required; the Z700W tube which has two trigger electrodes should then be used. The characteristics of the Z700U and the Z700W are virtually identical except for the fact that the Z700W has two trigger electrodes and a rather higher transfer current. The chain counter of Fig. 3.8 can be closed by a feedback loop to form a ring circuit. Two feedback loops are required in reversible ring counting circuits (as in Fig. 3.10).

Both the Z700U and the Z700W have priming cathodes to ensure reliable ignition even in complete darkness. This electrode is connected to the H.T. negative line via an 18 MΩ resistor. In normal operation a current of about 3μA should pass through this resistor no matter whether the main gap is conducting or non-conducting.

In Fig. 3.8 single cathode resistors are used so that the whole of the cathode voltage of any stage is applied to the trigger electrode of the next stage. Otherwise the operation of the circuit is the same tube shown in Fig. 3.8. The anodes and also the cathodes of each pair of Z700U tubes are connected together. The circuit is unchanged except that the two trigger electrodes of each stage are present in separate tubes. A count is indicated by a stage when either of the two tubes is glowing.

The maximum operating frequency of Z700U and Z700W circuits is 2 kc/s to 5 kc/s, depending on the component tolerances and the stability of the supply voltage. The amplitude of the input pulses should be 100 V and the duration about 20 μsec. The

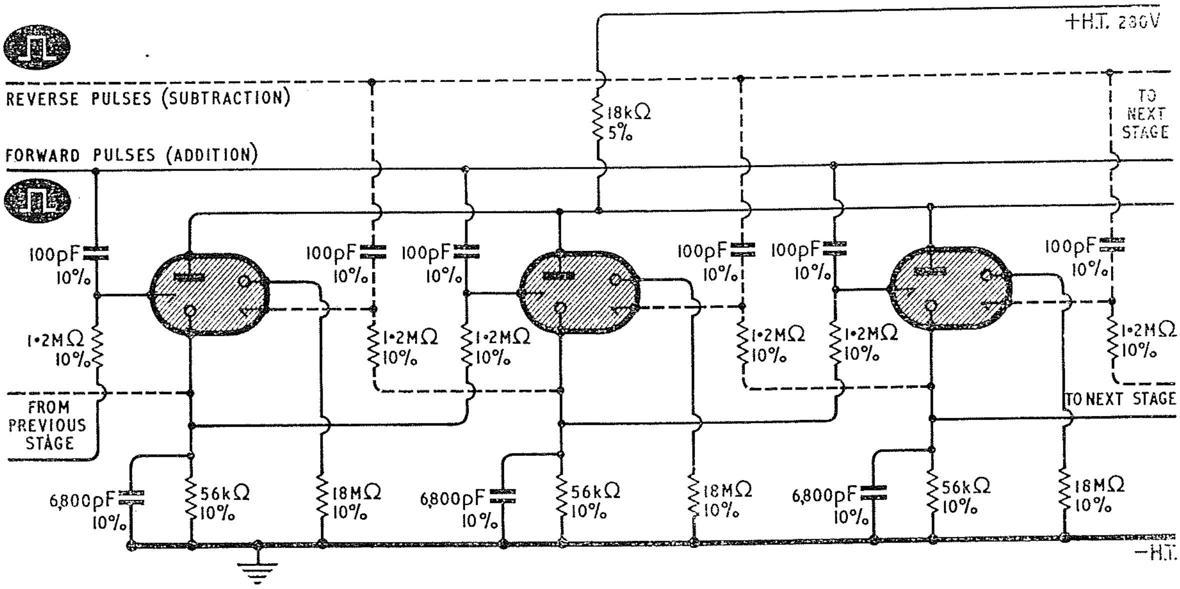


Fig. 3.8 A chain counter using Z700U trigger tubes. A reversible counter can be constructed if Z700W tubes are used with the additional components shown dotted

as that of the circuit of Fig. 3.7. The cathode current of the conducting Z700U or Z700W tube should be between 2 and 4 mA.

If the additional components shown by the dotted lines of Fig. 3.8 are used with Z700W tubes, it can be seen that the circuit is symmetrical with respect to the forward and reverse directions. Suitable pulses applied to the forward input line will cause the circuit to count in the forward direction, whilst similar pulses applied to the reverse input line will cause the glow to be transferred in the opposite direction. Forward and reverse pulses should not be applied simultaneously.

It is also possible to construct a reversible counter by using one pair of Z700U tubes for each Z700W maximum counting speed is attained with an H.T. supply potential of 300 V, with a common anode resistor of 27 kΩ ±5% and with 4,700 pF ±10% cathode capacitors. The supply voltage must not exceed 310 V.

A similar circuit employing a common cathode resistor instead of a common anode resistor has been published(6). Details of a biquinary decade counter which employs a ring of five combined with a ring of two are also available(6).

3.4.4 Z701U Counters

The Z701U is a subminiature low voltage trigger tube equivalent to the Z71U. It can be used in the

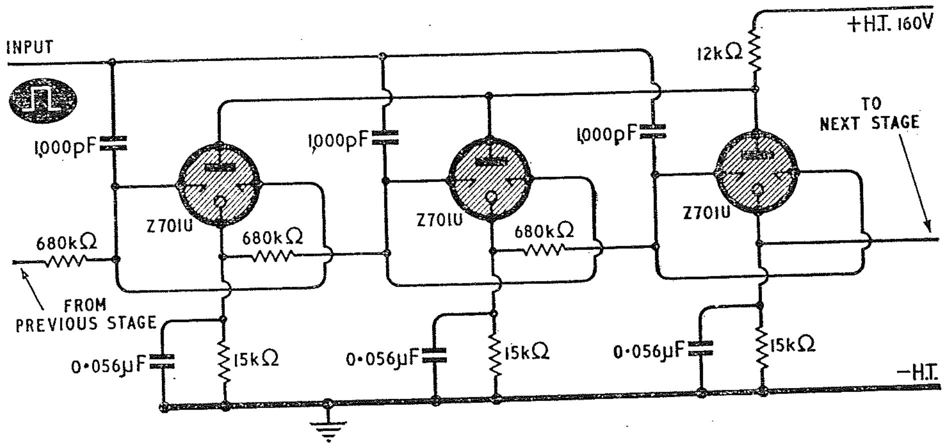


Fig. 3.9 A chain counter using low voltage tubes

circuit of Fig. 3.9 for forward counting(5, 11) and can also be used for reversible counting by employing the techniques shown in Fig. 3.8 with the circuit values of Fig. 3.9. The H.T. supply potential required (160 V) is lower than that required by most similar circuits. The input pulse should be of 60 V amplitude and about 25 μsec in duration. The cathode current of the conducting tube should be between about 3 and 7 mA. The Z701U should not be operated in total darkness, since photoemission is the only form of priming. The maximum frequency of operation of the circuit of Fig. 3.9 is about 2 kc/s.

3.4.5 GPE175M Bidirectional Counter

Fig. 3.10 shows a two decade reversible ring counter using Ericsson GPE175M tubes(12,13). For simplicity only two stages are shown in each ring, the other stages being indentical with those shown. The two GTE175M tubes are used to couple the two decades. The GPE175M has two trigger electrodes and a priming cathode. The maximum counting speed of the circuit shown is about 650 pulses per second and the recommended operating current of the tubes is 2.5 mA. This is, therefore, the quiescent current for each decade.

The trigger electrodes are clamped by means of semiconductor diodes to prevent their potential from falling below +100 V; this is necessary to prevent the triggers from acting as cathodes. The input pulses tend to bias the diodes in the high resistance direction and are, therefore, not short circuited by them. In addition to the +100 V supply, a −100 V supply is required for the auxiliary priming cathodes of the tubes.

If *V*9 is conducting and a forward pulse is received, both *V*0 and *V*10 will be triggered simultaneously, since their trigger electrodes receive both the bias voltage from the cathode of *V*9 and also the forward input pulses. *V*0 remains glowing and *V*9 is extinguished by the process discussed previously for the circuit of Fig. 3.7. As *V*10 ignites, it provides a pulse from its cathode which is fed to the forward pulse line of the next decade. The count in the second decade is, therefore, advanced by one. A capacitor is connected from the anode of *V*10 to earth. When this tube is triggered the charge of the capacitor quickly passes through the tube giving a sharp pulse. The high value of the anode resistor results in the circuit being self extinguishing.

If *V*0 is glowing, a positive bias is applied to the trigger electrode of *V*11 and also to the right-hand trigger of *V*9 which is used for reverse counting. If a pulse is now applied to the reverse input of the first decade, it is fed to both *V*9 and *V*11 and ignites these tubes. The ignition of *V*9 causes *V*0 to be extinguished, since these tubes are in the same ring. *V*9 remains glowing, but *V*11 feeds a pulse to the reverse pulse line of the next decade and then extinguishes itself. The second decade is now indicating one count (that is ten pulses) less than it did previously whilst the first decade indicates nine instead of zero. Thus the pulse applied to the reverse line

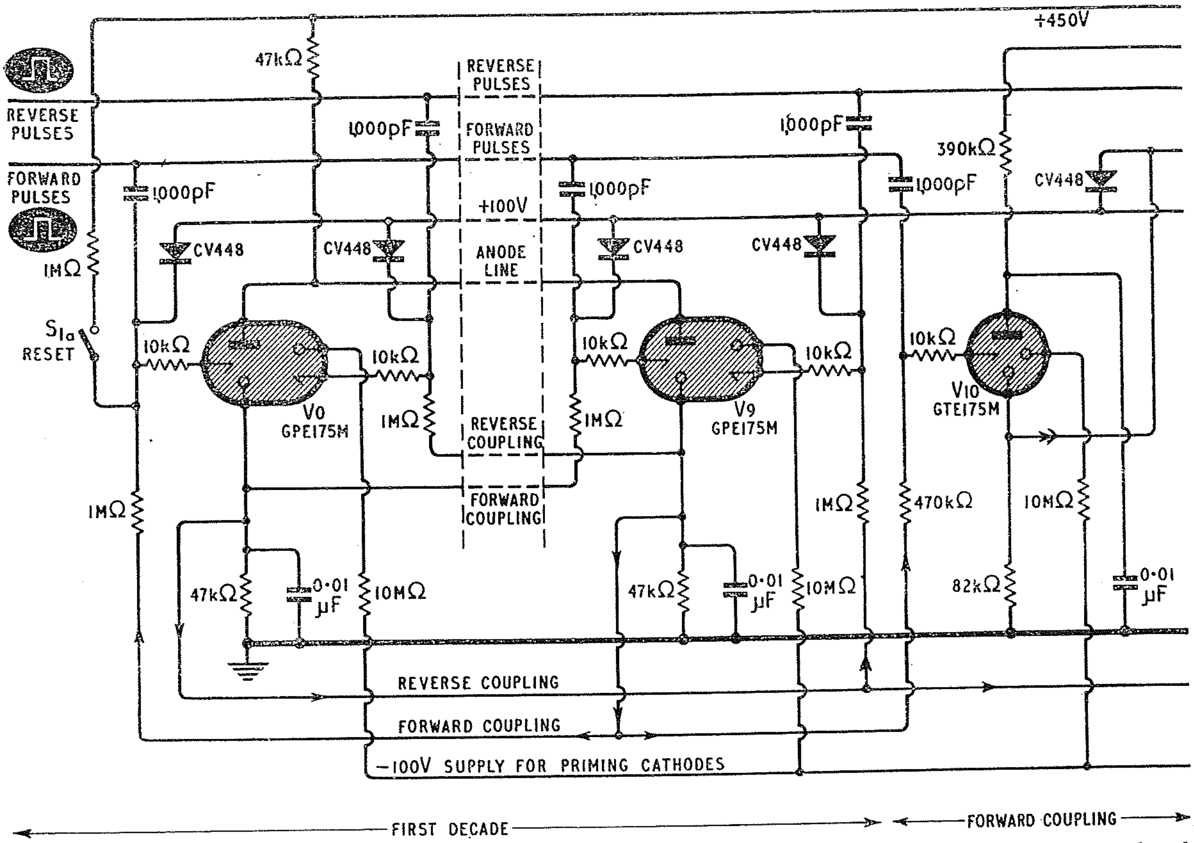


Fig. 3.10 A two decade

has caused the total count, therefore, to be reduced by unity.

The input pulses applied to the circuit of Fig. 3.10 should be of 85 to 95 V in amplitude and about 200 μsec in duration.

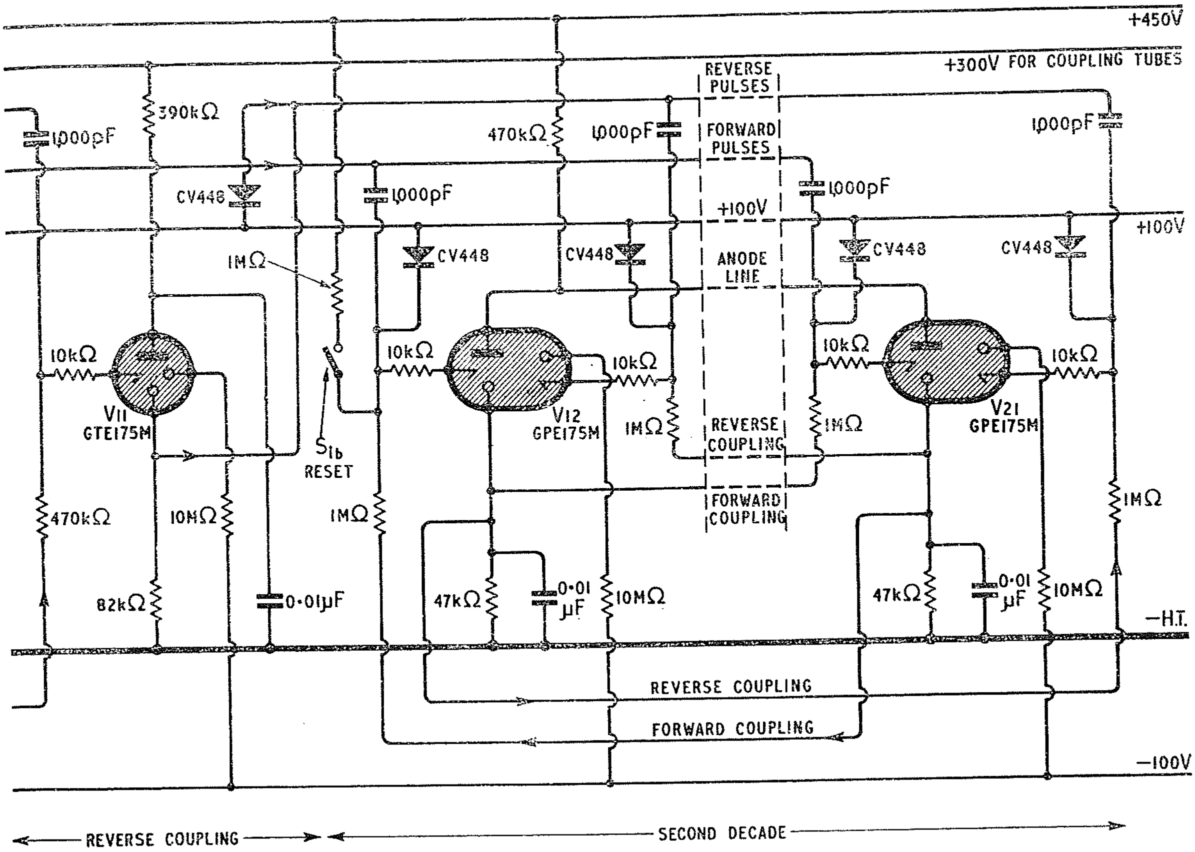
Tubes with only one trigger electrode can be used in the coupling circuit. Two GTE175M tubes (Ericsson) which have one trigger electrode each may be used. Alternatively two GPE175M tubes may be used with the two trigger electrodes of each tube connected together; the whole circuit can then be designed using only the one type of tube.

If the reset switches S_{1a} and S_{1b} are momentarily closed, positive pulses will be applied to the trigger electrodes of $V0$ and $V12$. These tubes will, therefore, be ignited and the tubes which were glowing previously will be extinguished by the same processes as in normal counting. Thus both decades are returned to zero. S_{1a} and S_{1b} would normally be ganged together.

Another very similar bidirectional counting circuit using XC24 (Hivac) tubes for decade counting and XC18 tubes in the coupling circuits between decades has been published[9]. The Z700W bidirectional counter of Fig. 3.8 can also be adapted for multi-decade counting if the necessary coupling circuits are added.

3.4.6 ER3 Ring Counter

The ER3 trigger tube (Elesta) may be used in the reversible ring counting circuit shown in Fig. 3.11[14]. Two trigger electrodes are provided and also an auxiliary priming anode. The type ER1 tube has similar electrical characteristics to the ER3 tube, but possesses only one trigger electrode and has no priming anode. It is, therefore, somewhat slower than the ER3 and cannot be used in reversible counters unless two ER1 tubes are used in each stage. The circuit values for ring counters using the



bidirectional trigger tube counter

ER1 should be similar to those of Fig. 3.11.

The maximum counting rate of the ER3 circuit increases somewhat with the number of tubes in the ring, but the maximum possible rate is of the order of 2,000 pulses per second. The use of rectangular shaped input pulses of about 120 V in amplitude and 20 μsec duration is important if the maximum counting speed is to be attained. The current taken by the circuit is about 15 mA.

3.4.7 Digital Readout from Trigger Tube Circuits

Although trigger tubes are inherently self indicating, it is usually much more convenient to use one digital indicator tube per decade to display the state of the count than to observe the ten trigger tubes in each decade themselves. The indicator tubes display one digit each as a neon glow. They have one common anode and the current passes from this to any one of ten cathodes. Each of the cathodes has the shape of one digit. One cathode is covered by a red glow when the tube is operating. Further details of digital indicator tubes are given in Chapter 10.

The digit which is being displayed at any specified time is determined by which cathode is passing current at that time. The selection of this cathode is carried out by the counting circuit itself. Each trigger tube in the decade circuit is connected to one of the ten indicator tube cathodes. When a particular trigger tube is conducting, the circuit must be arranged so that the corresponding cathode of the indicator tube is at a lower potential than that of the other indicator tube cathodes. The tube then indicates the appropriate number corresponding to the number of the trigger tube in the ring.

A typical circuit is shown in Fig. 3.12; it uses Z700U trigger tubes and the Z520M numerical indicator tube (Mullard)[15].

The Z700U trigger tube *V*10 in the input circuit of Fig. 3.12 converts any incoming pulses into pulses

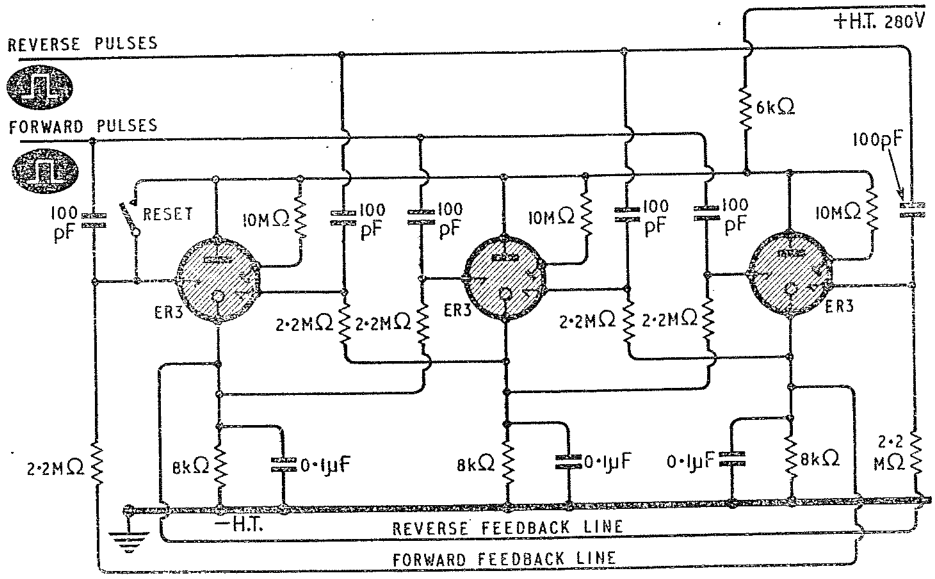


Fig. 3.11 A reversible chain counter using ER3 tubes

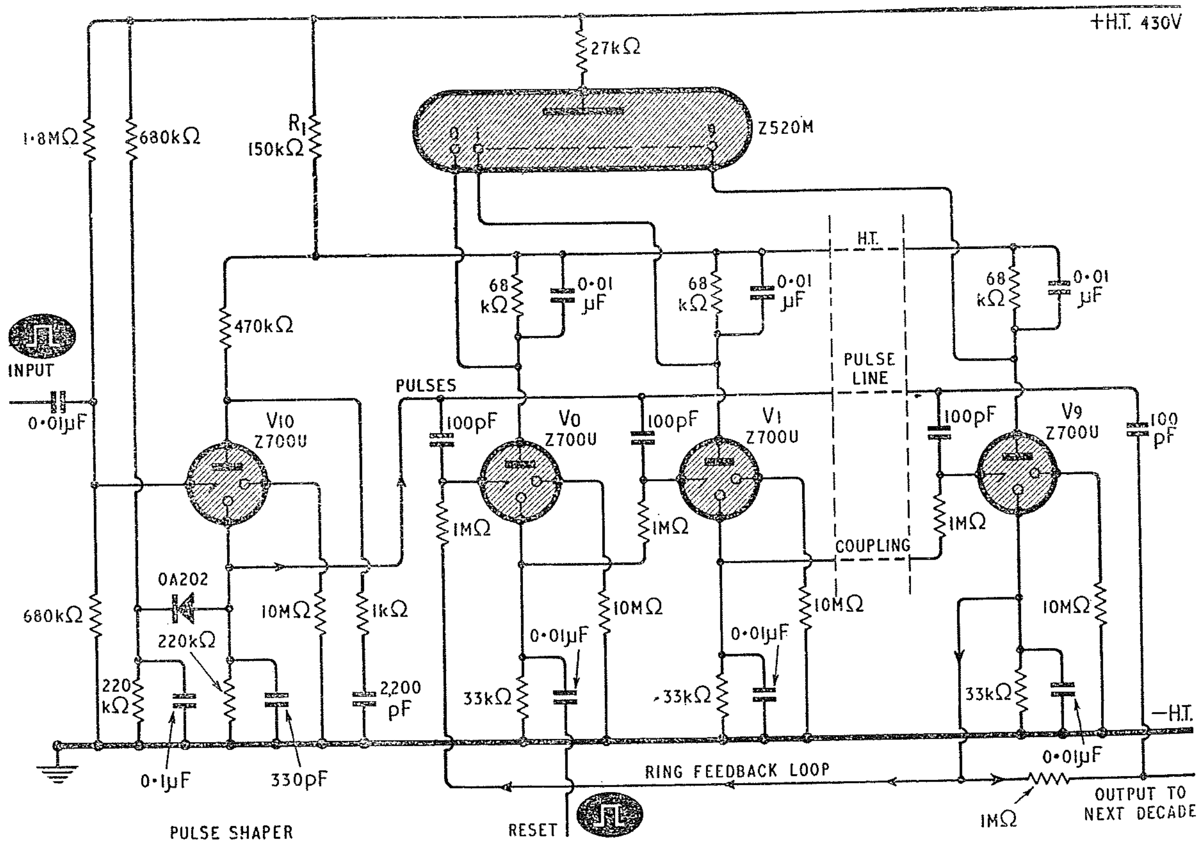


Fig. 3.12 A Z700U decade counter with Z520M readout

of a suitable amplitude and duration for the operation of the other ten Z700U tubes which perform the counting operation. Pulses from the cathode of *V*10 are fed along the pulse line to the trigger electrodes of the counting tubes via 100 pF capacitors. The *V*10 circuit has a capacitor between the anode of the tube and earth and is, therefore, self extinguishing.

The counting tube anodes are fed through the common anode load resistor marked R_1 (150 kΩ). In addition a smaller resistor (68 kΩ) is included in the anode circuit of each individual tube. These resistors are necessary for the operation of the indicator tube, but are by-passed by capacitors so that they do not affect the counting operation itself. The cathodes of the Z520M tube which are not shown in Fig. 3.12 as being connected to any particular trigger tube anode are actually connected to the trigger tubes in between *V*1 and *V*9; these trigger tubes have been omitted for simplicity.

If a trigger tube is conducting, its anode will be at a lower potential than the anodes of the other counting tubes owing to the flow of anode current through the 68 kΩ anode resistor. There will therefore be a greater voltage between the Z520M anode and the cathode of the Z520M which is connected to the conducting trigger tube than between the Z520M anode and any other cathode. Thus the cathode which is connected to the conducting trigger tube becomes the preferred cathode for the discharge and the Z520M indicates the corresponding number.

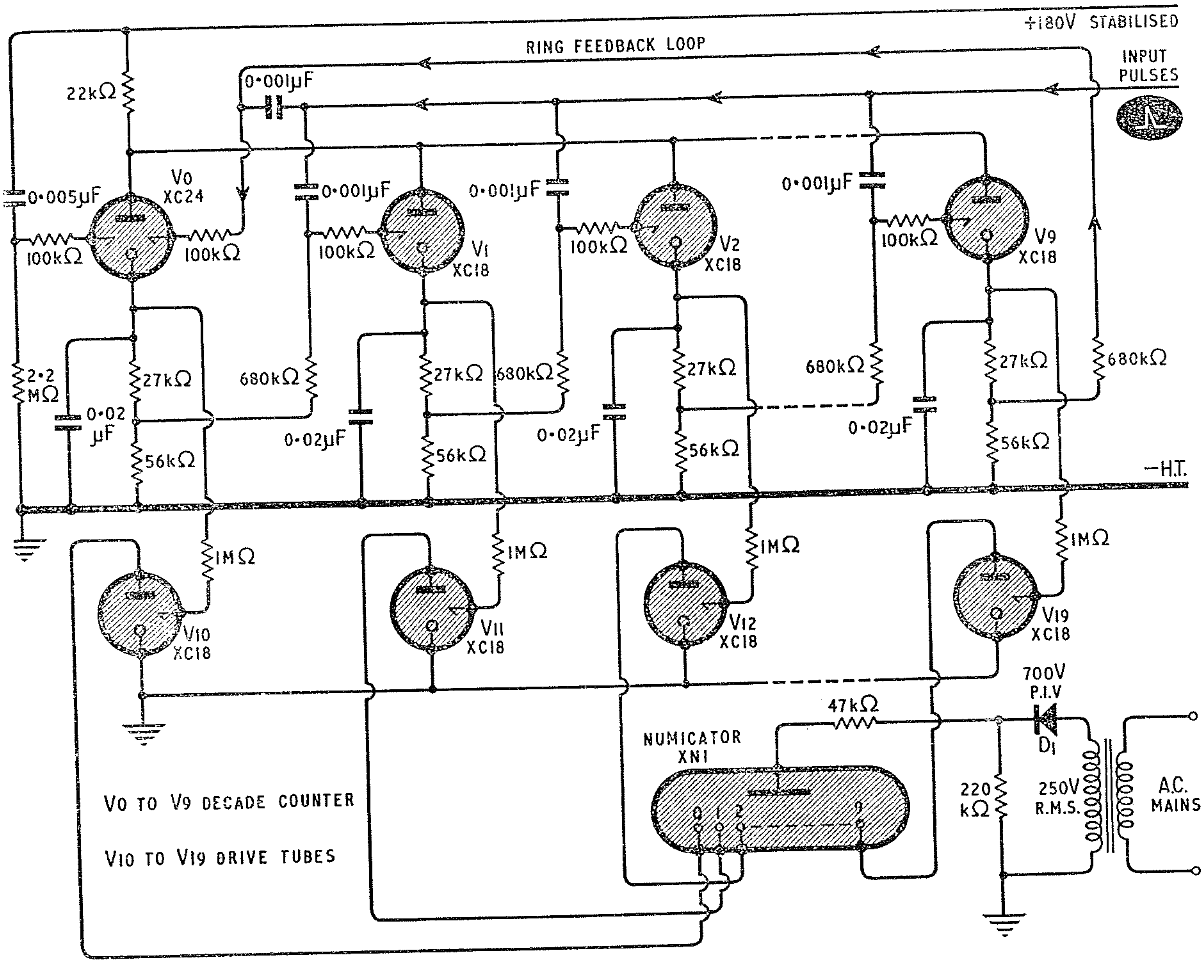


Fig. 3.13 A decade scaler with Numicator readout

The common anode resistor, R_1, enables a tube to be extinguished when the discharge is transferred to a succeeding tube by the same mechanism as that discussed previously in connection with the circuits of Figs. 3.5 and 3.7.

If a suitable negative pulse is applied to the cathode of $V0$ via the 0.01 μF capacitor, the discharge will be transferred to $V0$ and thus the decade will have been reset.

The maximum counting speed will be similar to that of the circuit of Fig. 3.8. If desired, Z700W tubes could be used for reversible counting with the Z520M as indicator. A circuit similar to that shown in Fig. 3.12 should be used with the additional trigger electrodes of the Z700W tubes arranged so that the circuit is symmetrical in both the forward and reverse directions.

3.4.8 Numicator Readout

A somewhat different type of circuit is shown in Fig. 3.13 in which XC18 trigger tubes in a decade ring counter are used in conjunction with a 'Numicator' type XN1 digital indicator tube (Hivac) for displaying the state of the count[(9)]. The first counting tube, $V0$, is an XC24 with two trigger electrodes. One of these electrodes is used for igniting the tube when the circuit is first switched on so that a count of zero is indicated. A pulse travels from the H.T. line through the 0.005 μF capacitor for this purpose. The other trigger electrode of $V0$ is biased from the cathode of $V9$ in the usual way.

The conducting counting tube has a cathode potential of at least 80 V positive with respect to earth. This voltage is applied to the corresponding XC18 drive tube ($V10$ to $V19$) which is triggered. A current passes from the Numicator anode to the appropriate cathode and hence through the drive tube which has been triggered.

The Numicator is supplied with an unsmoothed half wave rectified supply. The Numicator and drive tube are therefore extinguished during the non-conducting periods of the half wave rectifier. If a count is registered by the decade ($V0$ to $V9$) during the time the rectifier D_1 is non-conducting, the new state of the count will be shown as soon as D_1 passes a current during the next half cycle. If a count is registered by the decade whilst D_1 is conducting, two digits may be shown simultaneously for a very small fraction of a second. The true count is shown on the next cycle of the mains voltage. If a d.c. supply were used for the Numicator and the drive tubes, these tubes would not be extinguished when the next drive tube was ignited.

The maximum counting rate of the circuit is of the order of 250 pulses per second, but the Numicator cannot indicate at this speed owing to the wave form of its power supply. A clear indication is, however, given as soon as the counting process ceases.

3.4.9 GTR120W Circuit with Digital Readout

Fig. 3.14 shows a counting circuit[(12)] using the very economical subminiature GTR120W trigger tubes[(16)] with GR10G (Ericsson) digital readout.

The H.T. supply to the circuit of Fig. 3.14 should be 475 ±25 V. A suitable means of obtaining the other required voltages from the H.T. line is shown using two GD150M stabilisers. The trigger electrodes of the counting tubes are returned to the +150 V line so that no reverse trigger current can flow when the cathodes become positive, since this would damage the tubes.

This circuit differs from the trigger tube ring circuits discussed previously in that separate anode resistors are used for each counting tube and extinction of the tubes takes place by means of the 0.04 μF capacitors connecting the anodes of the tubes. No cathode resistors or capacitors are used.

A GTE175M trigger tube is required for coupling the circuit to the next decade. When the tube which indicates zero counts ($V0$) is ignited, a current flows through the choke L_1 and a positive pulse is passed to the GTE175M which ignites. This tube provides a positive output pulse from its cathode for the operation of the succeeding decade.

The positive going input pulses should have an amplitude of between 80 and 100 V and a duration of at least 100 μsec. The maximum counting speed is about 100 pulses per sec. The cathode current of the conducting GTR120W should be about 4.5 mA and the illumination should not be less than 5 ft-candles (50 lx).

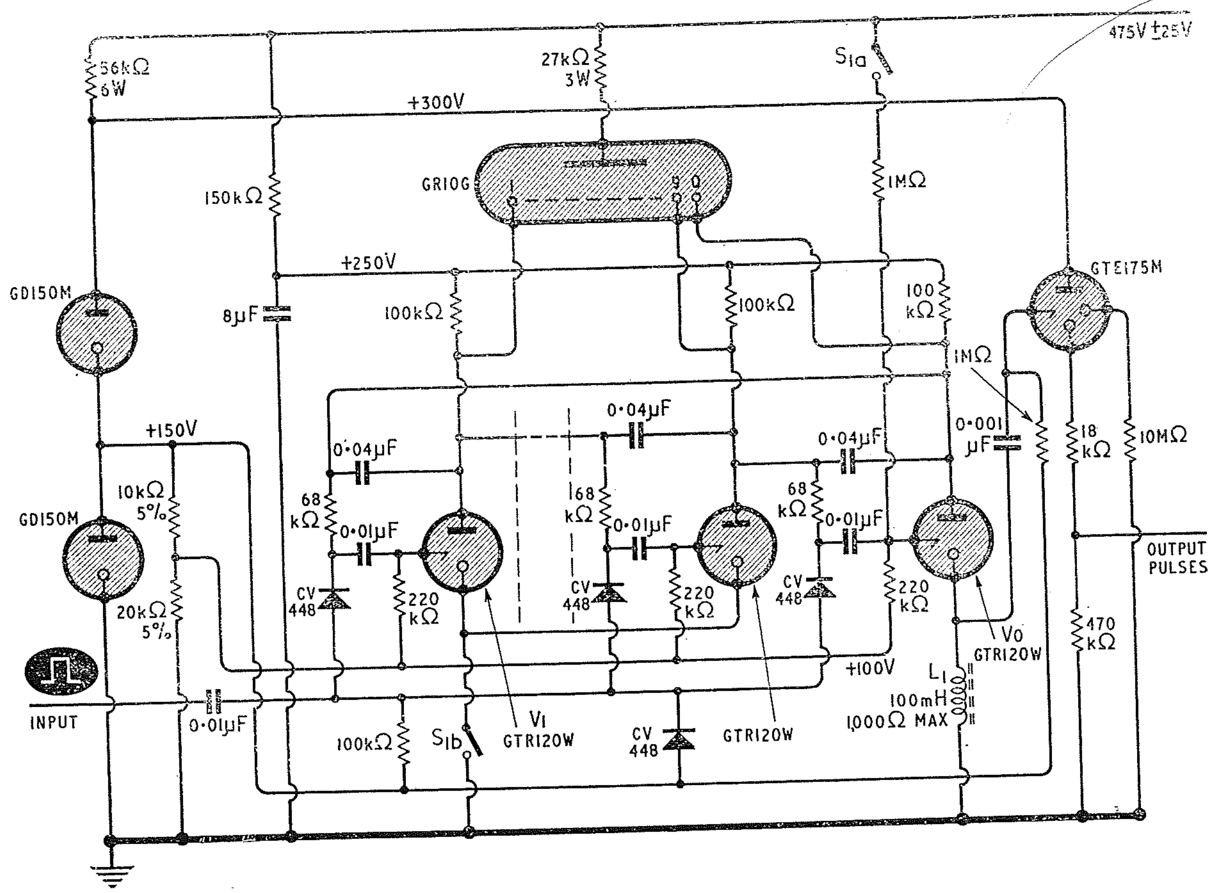


Fig. 3.14 A GTR120W ring counter with GR10G readout

3.4.10 Photocoupling

Another type of digital display circuit for trigger tube counters involves the use of an ORP60 photoconductive cell in each cathode circuit of a Z510M numerical indicator tube[6]. Each photoconductive cell is mounted close to the base of the corresponding trigger tube so that its resistance falls when the trigger tube is ignited. The corresponding cathode of the Z510M tube then passes a current through the photoconductive cell and the appropriate digit is indicated.

3.4.11 Trigger to Trigger Coupling

When the trigger electrode of a tube is connected to the cathode through a resistor of large value, the electrode will assume the potential of the cathode when no discharge is passing, but will rise in potential when the anode current commences to flow in the tube. If a tube with two trigger electrodes is employed, the one electrode can be used to initiate the discharge, whilst the second trigger can be used to provide a suitable bias voltage for the trigger electrode of the succeeding tube.

A circuit employing this principle is shown in Fig. 3.15[17]. Cerberus GR20 tubes are used in this reversible counting circuit which provides digital readout. Suitable pulses for the next decade are provided by the coupling tubes *V*11 and *V*12 shown in the lower part of Fig. 3.15.

If *V*1 is ignited, the potential of the two trigger electrodes of this tube is raised by the flow of the trigger current through the 22 MΩ resistors to earth. The right-hand trigger electrode of *V*1 thus provides a bias for the left-hand trigger of *V*2. When a pulse is received at the 'add' input, the combined effect of the pulse and the bias causes *V*2 to ignite. When *V*2 is conducting, the right-hand trigger of *V*1 is primed and a pulse applied at the 'subtract' input will cause *V*1 to ignite. The tubes in the ring are extinguished by the action of the common anode resistor (10 kΩ); the anode circuit is similar to Fig. 3.12.

When *V*10 is conducting, the right-hand trigger of *V*12 and the left-hand trigger of *V*1 will be biased positively. A pulse at the 'add' input will initiate the discharge in *V*12. The flow of current through the cathode resistor of *V*12 will provide a pulse which (in conjunction with the bias) ignites *V*1 and also operates the next decade. The *V*12 circuit is self extinguishing, owing to the capacitor in its anode circuit. This tube obtains its anode current from a tapping on the common anode resistor feeding the ring circuit. When *V*1 is ignited by the pulse from *V*12, the anode potential of *V*12, therefore, falls somewhat with the anode potential of the tubes in the ring. This enables *V*12 to be extinguished more rapidly than if it obtained its anode supply directly from the H.T. line. The reverse coupling tube, *V*11, operates in a similar way.

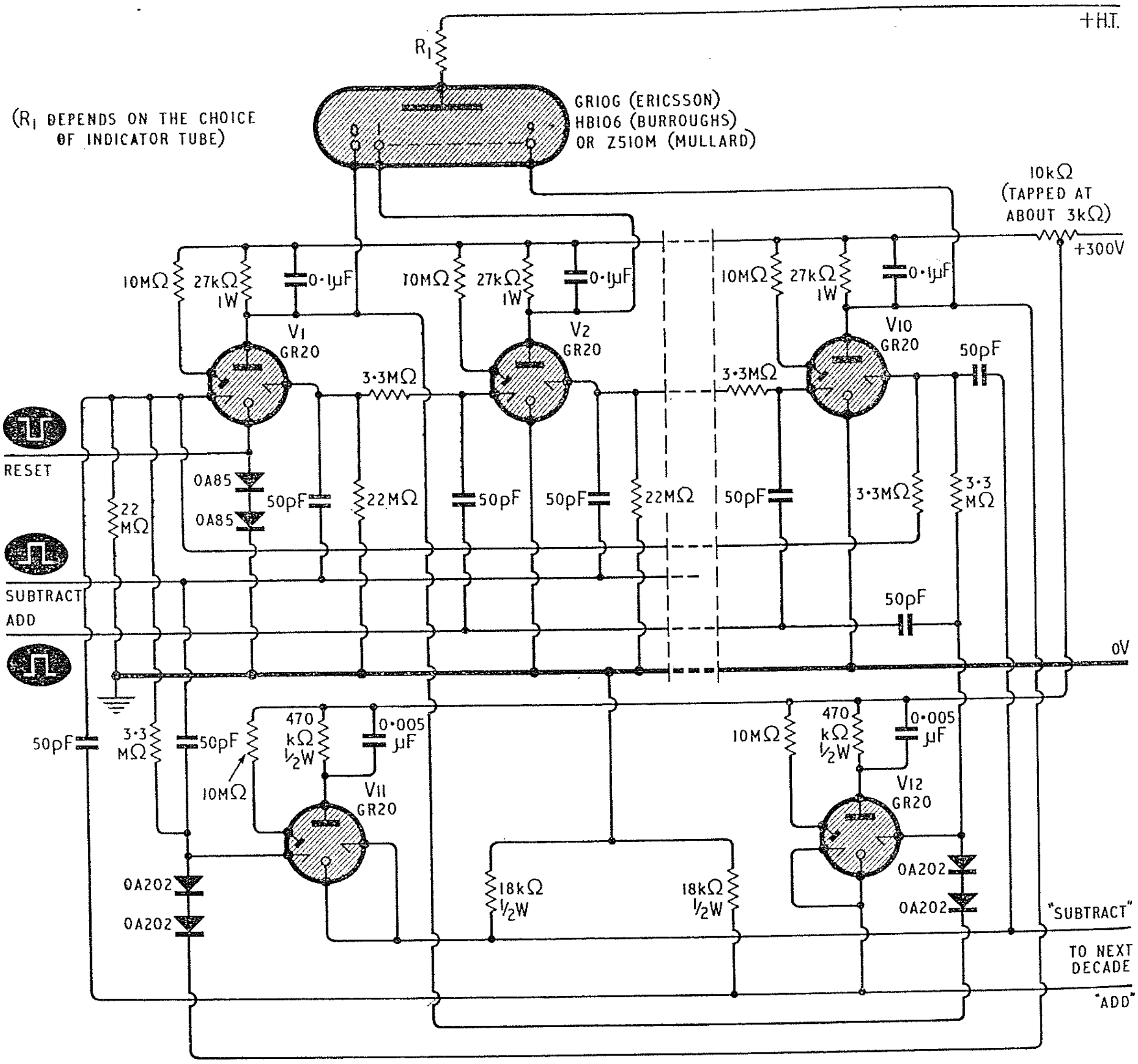


Fig. 3.15 A decade counter using trigger to trigger coupling

When *V*10 is ignited, *V*9 (not shown), *V*12 and *V*1 will receive a bias voltage and this will be conveyed from the trigger of *V*1 to the trigger of *V*11. Thus, if a 'subtract' input pulse is received, not only *V*9 but also *V*11 would be ignited if it were not for the presence of the OA202 diodes in the trigger circuit of *V*11. These diodes prevent *V*11 from being ignited unless *V*10 is in its non-conducting state. The diodes ensure that the trigger of *V*11 is never more positive than the anode potential of *V*10; this potential is low when *V*10 conducts. Similarly *V*12 does not ignite if *V*1 is conducting.

Owing to the high impedance of the trigger circuits, it is easier to reset the circuit by means of a negative going pulse of about 150 V in amplitude and 20 μsec in duration applied to the cathode of the first tube than to apply a pulse to the trigger electrode. When a negative going resetting pulse is applied, the OA85 diodes in the cathode circuit of *V*1 prevent the pulse from being shorted to earth, but allow the normal *V*1 anode current, however, to flow.

The positive going input pulses to the circuit of Fig. 3.15 should have an amplitude of 100 to 150 V and a duration of at least 20 μsec. When the trigger electrode of a GR20 tube is connected to earth via a 22 MΩ resistor and the tube anode current is 8 mA, the trigger potential rises to about 80 V with respect to the cathode; this value varies only slightly with changes in anode current caused by supply voltage changes. The H.T. supply to the numerical indicator tube should be equal to 110 V (the maintaining voltage of the GR20) plus the normal working voltage of the indicator tube plus the voltage drop across the indicator tube anode resistor. The absence of a cathode resistor in the trigger tube circuits enables a lower H.T. supply potential to be employed than in many other trigger tube circuits which use a numerical indicator tube. A maximum frequency of 1 kc/s can be obtained if the H.T. supply voltage has a tolerance of ±10%.

3.4.12 The G1/371K Tube

The S.T.C. G1/371K tube is a primed trigger tube of the special construction shown in Fig. 3.16[18]. A discharge passes between a priming anode and a priming cathode in a separate compartment. The light generated by this priming discharge passes through a mica window into the cathode–trigger space of the other compartment. The special construction of this tube enables ionisation times as low as 0.5 μsec to be attained.

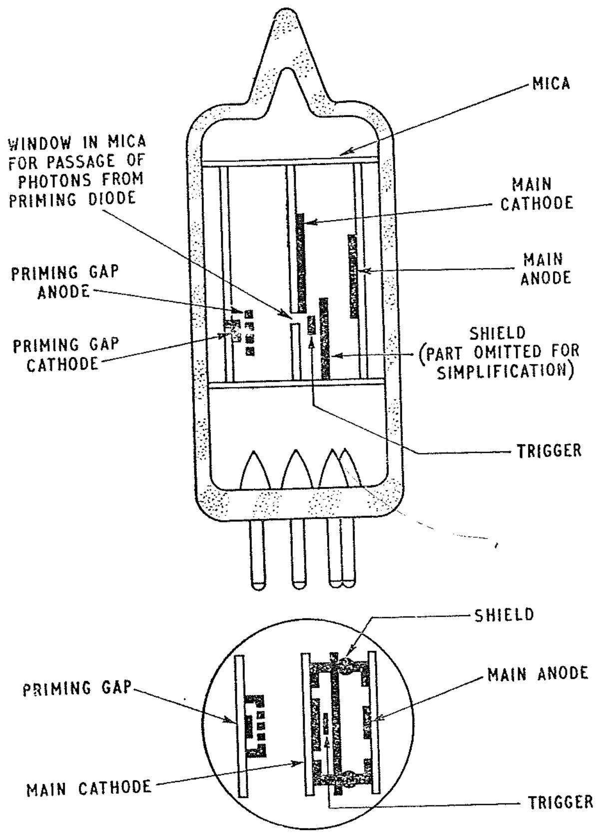


Fig. 3.16 The electrode structure of the G1/371 K trigger tube

The electrodes in the main section of this tube are the anode, cathode, trigger and shield. The shield is biased so as to provide an electric field which will remove ions quickly; it may also be used as an auxiliary triggering electrode in certain circuits. The geometry of the electrode structure is designed to enable ions to be removed very quickly and deionisation times of about 30 μsec can be attained without difficulty; when the cathode current is only a little above the recommended minimum value of 2 mA, deionisation times of about 10 μsec are obtainable. This is much shorter than that obtained with conventional trigger tubes and enables

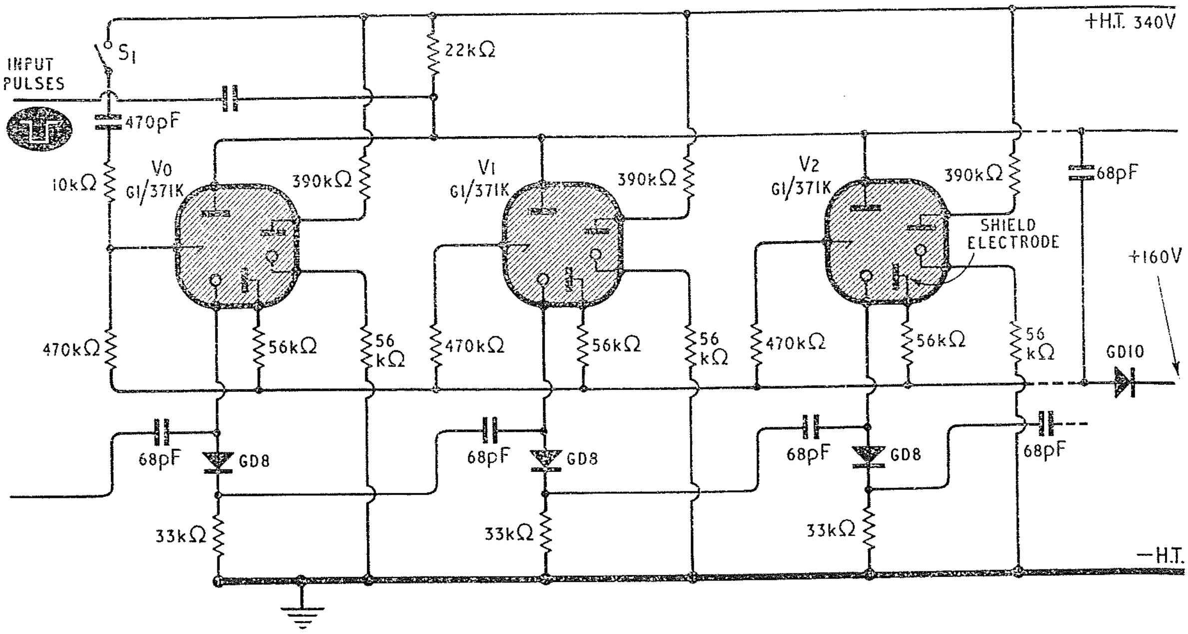


Fig. 3.17 A chain counter using the G1/371K trigger tube. The priming diode is shown on the right-hand side of each tube

the G1/371K to be used in counting circuits at frequencies up to 100,000 pulses per second.

3.4.13 High Speed G1/371K Counters

Fig. 3.17 shows the circuit of a chain counter using G1/371K tubes(18). The basic principle of operation of this circuit is the same as that of the diode counting circuit of Fig. 3.3, but much greater counting speeds are possible.

When S_1, the reset and starting switch, is momentarily closed, *V*0 conducts. If a negative pulse is now applied to the input, *V*0 is extinguished and its cathode becomes more negative. This negative pulse is applied to the cathode of *V*1 via the 68 pF coupling capacitor. The diode in the cathode circuit of *V*1 prevents the negative pulse from leaking rapidly away. At the end of the input pulse the trigger to cathode discharge in *V*1 is transferred to the main gap.

The negative input pulses are also coupled to the trigger and shield electrodes via a 68 pF capacitor. This is necessary in order that premature triggering and loss of triggering energy before the end of the pulse shall be prevented. On the other hand the

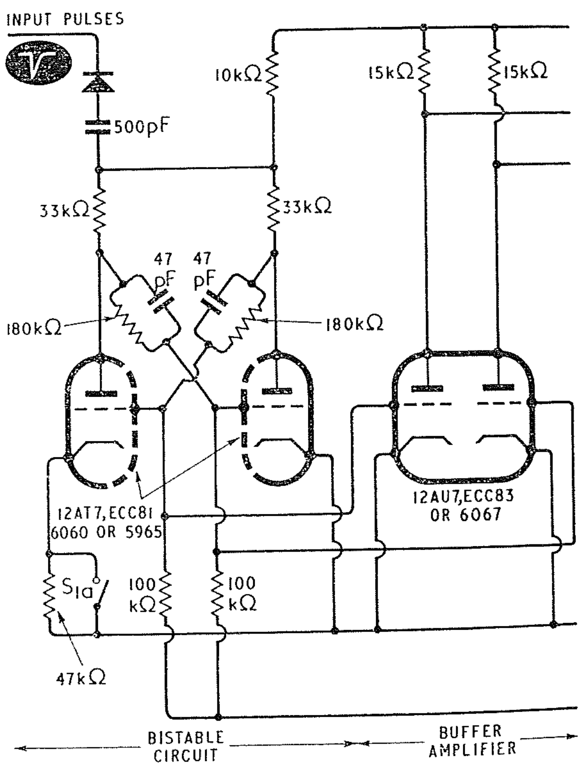


Fig. 3.18 A high speed ring counter.

reduction in the shield potential lowers its deionising efficiency and this (together with the common anode capacity) limits the maximum counting speed.

These limitations can be largely overcome by the techniques shown in the circuit of Fig. 3.18 which can count at frequencies of up to about 100,000 pulses per second[18]. The input pulses fed into this circuit operate an Eccles-Jordan stage which feeds a 12AU7 buffer amplifier. The anodes of alternate trigger tubes are connected together and the potentials of the two sets of anodes are swung in anti-phase by the buffer amplifier. A tube can be triggered within about a microsecond of the previous tube being extinguished.

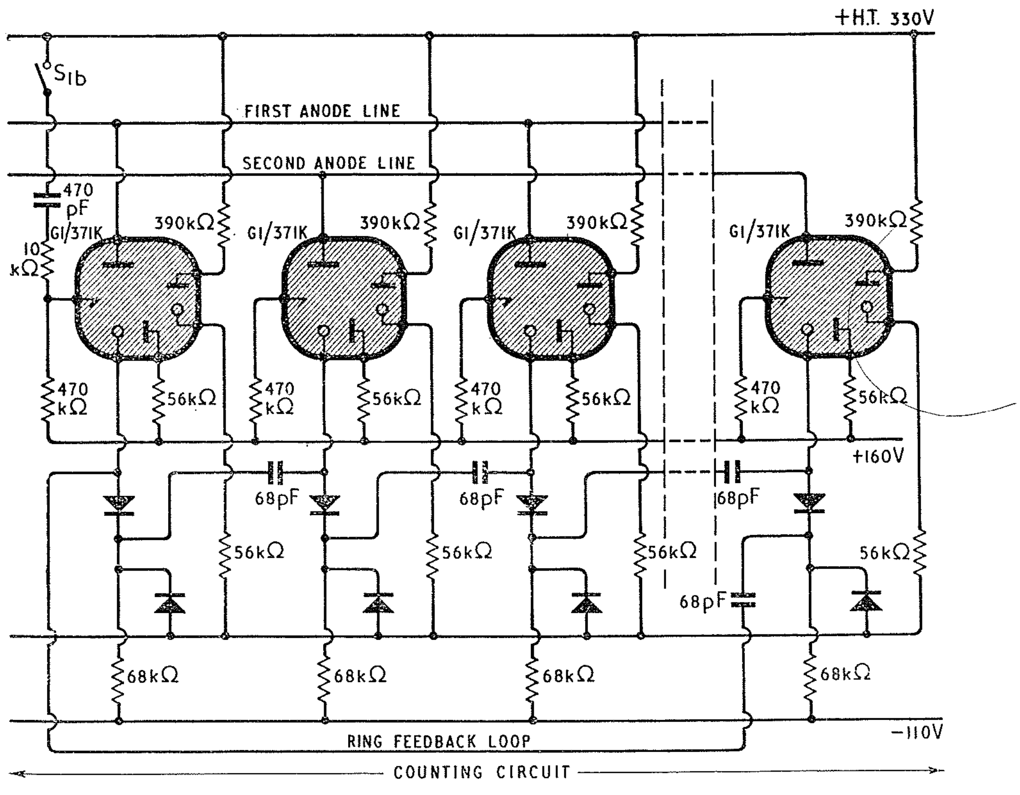
The switches S_{1a} and S_{1b} are used for starting and resetting the circuit. They are ganged so that the state of the Eccles-Jordan circuit is always matched to that of the trigger tube circuit. The use of the negative line shown in Fig. 3.18 is essential if the sharp cathode wave forms required at high counting speeds are to be obtained.

3.5 DESIGN OF TRIGGER TUBE RING CIRCUITS

In order to illustrate the general methods by which ring circuits may be designed, let us assume that a trigger tube circuit of the type shown in Fig. 3.19 is to be designed using GR21 tubes[19]. The following information may be obtained from the tube data sheets:

	Symbol	*Min.*	*Max.*
Maintaining voltage	V_m	106 V	116 V
Trigger ignition voltage	V_t	130 V	155 V
Cathode current	I_k	2.5 mA	8 mA
Anode supply voltage	V_b	180 V	270 V
Control capacity		40 pF	5,000 pF

In order that a tube shall ignite only when both the pulse and bias voltages are fed to it, the following three conditions must be satisfied:



All diodes are S.T.C. types GD8 or GD10

$$V_{1\,max} < V_{t\,min} \quad (1)$$

$$V_{i\,max} < V_{t\,min} \quad (2)$$

$$V_{1\,min} + V_{i\,min} > V_{t\,max} \quad (3)$$

The following equations may be derived from the circuit:

$$V_{1\,min} = (V_{b\,min} - V_{m\,max}) \frac{R_{3\,min}}{(R_{3\,min}+R_{1\,max})} \quad (4)$$

$$V_{1\,max} = (V_{b\,max} - V_{m\,min}) \frac{R_{3\,max}}{(R_{3\,max}+R_{1\,min})} \quad (5)$$

$$I_{K\,min} = \frac{V_{b\,min} - V_{m\,max}}{R_{3\,max}+R_{1\,max}} \; (>2.5 \text{ mA}) \quad (6)$$

$$I_{K\,max} = \frac{V_{b\,max} - V_{m\,min}}{R_{3\,min}+R_{1\,min}} \; (<8 \text{ mA}) \quad (7)$$

The resistor tolerances will be assumed to be $\pm 10\%$ and at first the design will be attempted using an unstabilised H.T. supply with a tolerance of $+14\%$ to -18% of the nominal value. If the highest value of the H.T. supply is set at the maximum permissible value for tube, the nominal value will be

$$V_b = 270 \times \frac{100}{114} = 237 \text{ V}$$

and the minimum value:

$$V_{b\,min} = 237 \times \frac{100-18}{100} = 194 \text{ V}$$

Putting values in equation (6):

$$I_{K\,min} = \frac{194-116}{(R_{3\,max}+R_{1\,max})} = 0.0025 \text{ A}$$

from which

$$R_{3\,max}+R_{1\,max} = 31.2 \text{ k}\Omega$$

Allowing for resistor tolerances, the mean value of (R_3+R_1) is 28.4 kΩ.

The maximum value of V_1 which may be employed without any tube firing is 130 V. A safety margin of 10 V may be allowed so that $V_{1\,max} = 120$ V. This value may be substituted in equation (5):

$$120 = (270-106)\left(\frac{R_{3\,max}}{R_{3\,max}+R_{1\,min}}\right)$$

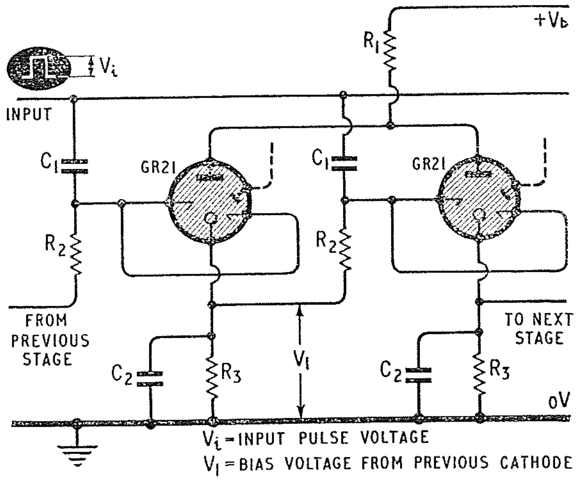


Fig. 3.19 A GR21 chain counter

from which

$$\frac{R_{1\,min}}{R_{3\,max}} = 0.367$$

and, allowing for the 10% resistor tolerances, $R_1/R_3 = 0.449$. Combining this with the relationship found above that $(R_3+R_1) = 28.4$ kΩ, it is found that $R_3 = 19.6$ kΩ and $R_1 = 8.8$ kΩ.

If these values are substituted in equation (4), it is found that $V_{1\,min} = 50.7$ V. Using condition (3) and the fact that $V_{t\,max} = 155$ V, $V_{i\,min} = 119$ V (allowing a 15 V safety margin). If this has the same tolerance as the H.T. supply voltage, $V_{i\,max} = 166$ V. This obviously violates condition (2) and the design is unsatisfactory.

There are three possible ways in which the circuit may be altered to enable it to operate satisfactorily. Close tolerance resistors may be used, the supply voltage V_b may be stabilised or the variation in the values of V_i may be reduced. If the supply voltage is stabilised this will also reduce the variations of V_i. Three SR2 Cerberus stabiliser tubes may be placed in series to provide a nominal stabilised voltage of 264 V. The maintaining voltage of each stabiliser tube may vary by ± 3 V and, therefore, $V_{b\,min} = 255$ V and $V_{b\,max} = 273$ V. This maximum voltage actually exceeds the maximum recommended for the GR21 tube by 3 V, but this is permissible, since the minimum breakdown voltage for the anode to cathode gap is 290 V.

If these values are used in the equations as before, it is found that $R_1 = 16.3$ kΩ and $R_3 = 34.2$ kΩ. The nearest preferred values of 15 kΩ and 33 kΩ respectively have been used in the calculation of the following values. Using equations (6) and (7), it is found that $I_{k\,min} = 2.6$ mA and $I_{k\,max} = 3.9$ mA.

for counting frequencies of up to 2 kc/s is 47 pF, but it may be increased with decreasing frequency. The minimum value of R_2 (4.7 MΩ) is determined by the maximum quiescent trigger current.

The importance of supply voltage and component tolerances in the design of cold cathode tube

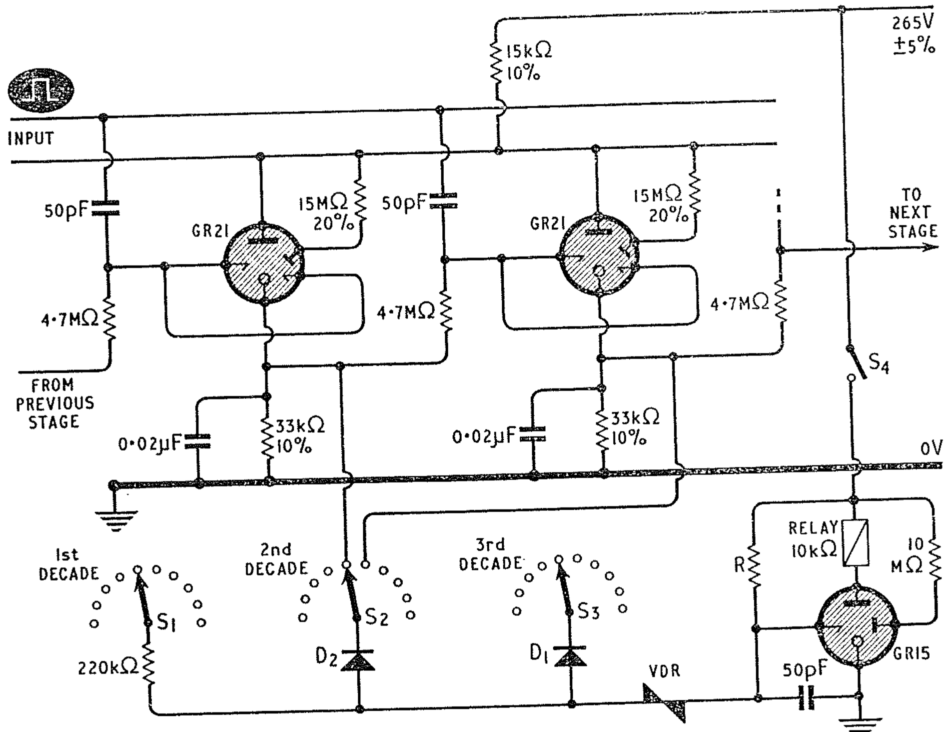


Fig. 3.20 A trigger tube predetermined counter. Only the fifth and sixth stages of the second decade are shown; other stages are identical with them

Using equations (4) and (5), it is found that $V_{1\,min} = 89.4$ V and $V_{1\,max} = 121.7$ V. All GR21 trigger tubes strike when their trigger to cathode potential reaches +155 V. If another 20 V in excess of this is allowed to ensure rapid ignition, it can be seen from condition (3) that $V_{i\,min} = 86$ V. This voltage can increase by over 40% before condition (2) is violated. In actual practice there is always stray capacitance in the trigger circuit and this forms a potential divider with C_1. V_i can therefore exceed the maximum calculated value by a small amount.

The value of C_2 is set at about 0.02 μF by the deionisation time of the GR21 tube. A lower limit for the value of C_1 is set by the recommended minimum control capacity of 40 pF. A suitable value

circuits can be clearly seen in the above example. A small percentage variation in the H.T. supply voltage (especially if it is fairly low in value) can result in a larger percentage variation in the current taken by the tube, since the maintaining voltage is almost independent of this current.

3.5.1 Predetermined Counting

Output potentials may be obtained from any selected cathodes of a trigger tube ring counter and can be used for the operation of a relay when the state of the count reaches a certain predetermined number. The basic circuit of such a predetermined counter is shown in Fig. 3.20[20]; the design of the ring

Table 3.1

TABLE OF BASIC TRIGGER TUBE DATA

The data given below is only approximate and may apply only under certain conditions. Further details are given in manufacturers' data sheets.

Type and Manufacturer	*Maximum H.T. Supply Voltage*	*Approx. Maintaining Voltage*	*Trigger Striking Voltage*	*Continuous Current (mA)*	*Base*	*Remarks*
CERBERUS:						
GR15	270	107	120–140	10–40	B9A	Priming anode.
GR16	350	111	120–140	20–40	B9A	Priming anode; internal shield.
GR20	270	109	120–140	4–30	B9A	Twin triggers; priming anode.
GR21	270	110	130–155	$2^1/_2$–8	submin.	Twin triggers; priming anode.
GR31	350	111	125–140	10–40	B9A	Priming anode.
GR32	205	{105, 110}	121–126	5–25	B9A	2 main anodes + priming anode.
GR33	290	105	128–137	25 max.	B9A	Priming anode.
GR41	350	110	120–140	4–10	submin.	Twin triggers; priming anode.
GR43	250	107	115–122	1–5	submin.	Priming anode.
ELESTA:						
ER1	250	107	125–140	10–40	B9A	
ER2	340	111	125–140	15–40	B9A	Priming anode
ER3	250	107	125–140	10–40	B9A	Twin triggers; priming anode.
ER32	340	115	120–140	7–15	submin.	Twin triggers; priming anode.
ER33	260	107	120–140	5–15	submin.	Twin triggers; priming anode.
ENGLISH ELECTRIC:						
*5823	200	62	73–105	25 max.	B7G	
*QT1250	210	62	72–80	25 max.	B7G	Close tolerance versions of the 5823.
*QT1251	210	62	72–80	25 max.	submin.	
ERICSSON†:						
GDT120M	340	112	105–155	3–9	B7G	Priming diode.
GDT120T	400	112	100–155	5–25	B9A	Priming diode.
GPE120T	250	{105, 110}	120–125	25 max.	B9A	2 main anodes; priming anode.
GPE175M	310	150	173–183	$3^1/_2$ max.	B7G	Twin triggers; priming cathode.
GTE120Y	275	106	114–122	1–5	submin.	Priming anode.
GTE130T	290	105	128–137	25 max.	B9A	Two anodes.
GTE175M	310	150	173–183	$3^1/_2$max.	B7G	Priming cathode.
*GTR80M	200	62	70–90	25 max.	B7G	
GTR120W	310	118	110–170	3–9	submin.	
FERRANTI:						
*GK10	150	75	80	$7^1/_2$max.	B7G	
*GK32	140	80	85–98	2 max.	3 caps	
*GK33	140	80	85–98	2 max.	3 wires	
*GK40	140	75	79–85	5 max.	3 caps	
*GK42	140	75	79–85	5 max.	3 wires	
G.E.C.:						
*CCT6	250	60–80	70–90	1–5	submin.	

Table 3.1 *(cont.)*

Type and Manufacturer	*Maximum H.T. Supply Voltage*	*Approx. Maintaining Voltage*	*Trigger Striking Voltage*	*Continuous Current (mA)*	*Base*	*Remarks*
HIVAC:						
*XC13	200	70	75	7.5 max.	submin.	
*XC18	210	73	68	1 max.	submin.	
*XC22	210	70	69	1/2 max.	submin.	
*XC23	200	67	70	7.5 max.	submin.	
*XC24	210	73	68	1 max.	submin.	
MULLARD/ PHILIPS:						
Z70U/Z700U	310	116	137–153	2–4	submin.	Priming cathode.
Z70W/Z700W	310	116	137–153	2–4	submin.	Twin triggers; priming cathode.
*Z71U/Z701U	165	60	73–90	3–9	submin.	Twin triggers.
Z803U	290	105	128–137	8–25	B9A	Priming anode.
Z806W	390	110	118–121	12–25	B9A	Priming anode; screening anode.
*Z900T	200	62	73–95	35 max.	B7G	Tritium primed.
R.C.A.:						
*OA4G	225	70	70–90	25 max.	Octal	
*1C21	180	70	66–80	25 max.	Octal	
*5823	200	61	80	25 max.	B7G	
S.T.C.:						
*G1/237G, *G1/238G	200	70	75	$1^1/_2$ max.	submin.	
*G1/371K	360	175	190	10 max.	B7G	Priming diode+shield.
*G150/2D	150	68	70	30 max.	Octal	
*G240/2D	230	90	75	30 max.	Octal	
TELEFUNKEN:						
*OA4G	225	70	70–90	5–25	Octal	
*5823	200	65	70–90	5–25	B7G	
*5823A	350	65	70–90	5–25	B7G	
ZC1010	335	121	157–167	8 max.	submin.	Priming anode.

* Signifies that the cathode is coated with a material of low work function.
† Now obtainable through Hivac Ltd.

circuit employed has been discussed in the previous section. Two stages of the second decade ring circuit are shown together with the coincidence circuit. Any number of similar decades can be added. The GR21 has two trigger electrodes and may, therefore, be used in reversible ring counters using the principles discussed previously.

The desired predetermined number is set by means of the selector switches S_1, S_2 and S_3. If each cathode selected by these switches is conducting, the potential of the junction of the diodes D_1 and D_2 in the coincidence circuit will be raised to a value which will result in the GR15 tube striking and the 10 kΩ relay in the anode circuit of this tube closing. Some means must be provided for opening the contacts of S_4 after the relay has closed so that the GR15 tube is extinguished ready for the next operation. The contacts S_4 normally form part of a circuit (such as a batching unit) which is operated by the relay in the GR15 anode circuit.

Siemens E50C2 diodes are suitable for D_1 and D_2. The voltage dependent resistor marked *VDR* should pass about 100 μA when the potential difference across it is 100 V; a Philips type VD 1000 P/680 B is suitable. The resistor *R* should be chosen so that the potential difference across the voltage dependent resistor is 80 to 100 V. The input pulses may have an amplitude of about 120 V and a duration of about 20 μsec.

3.5.2 Relay Operation

If it is required to operate a relay or an electromagnetic counter from a trigger tube circuit, a valve circuit similar to that of Fig. 4.37 will be suitable. The trigger tube replaces the Dekatron, *V*1, the output voltage from the cathode of the trigger tube being fed through the 4,700 pF capacitor into the circuit of *V*2. If no heater supplies for valves are available, however, the circuit of Fig. 4.38 which employs only cold cathode tubes may be more convenient.

3.6 THYRATRON COUNTING CIRCUITS

Thyratron tubes contain a gas filling, but unlike the tubes used in the circuits discussed in this chapter, they have thermionic cathodes and require a heater supply. They can be used in binary and ring counting circuits which operate in very similar ways to the cold cathode tube circuits discussed in this chapter. Circuits showing how the 2D21 (EN91) thyratron can be used for counting have been published[21]. Thyratrons are not normally used as self indicating devices, although they do glow somewhat in operation. They have been used for counting in the past, but are now seldom employed for this purpose, since other devices have been developed which are much more convenient and consume less power. The maximum frequency at which thyratron circuits can operate is, like all gas filled tubes, limited by ionisation and deionisation times.

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