9

Ratemeter Circuits

9.1 INTRODUCTION

Various types of ratemeter or frequency meter have been used as alternatives to scalers in radioactivity measurements for many years. They can also be used for the measurement of the frequency of a source of pulses or other waveforms. Ratemeters are rather different from the other types of counting circuits, since instead of indicating the number of pulses, they show the mean rate of arrival of the input pulses. Each individual pulse makes a small contribution to the final indication. The main advantages and disadvantages of the ratemeter may be summarised as follows[1].

ADVANTAGES:

1. A direct and continuous indication of the count rate is given without the necessity for any separate timing operations.
2. Any appreciable change in the count rate quickly becomes obvious unless a long time constant is employed.
3. Most commercial ratemeters provide an output which will operate a pen recorder. This is especially useful when the energy spectrum of ionising radiation is to be plotted.
4. Special types of ratemeters can be designed which have a logarithmic response, which provide automatic compensation for counts lost due to the finite resolving time or which indicate the difference or the ratio between two pulse rates. Such instruments are very useful for some special applications.

DISADVANTAGES:

1. Ratemeters are not so accurate as scalers.
2. Ratemeters must be calibrated against scalers and the accuracy of the ratemeter is dependent on the accuracy of calibration.
3. A ratemeter does not indicate the total number of counts received in a certain time.
4. When a linear ratemeter is employed, a suitable range and time constant must be chosen.
5. In random pulse counting the statistical errors of a linear ratemeter are dependent on the counting rate.

Scalers are normally used in radio-isotope work where high accuracy is required or where the count rate does not greatly exceed the background rate. Ratemeters can be used in most other cases and are particularly useful when a direct reading or a chart indication is required and for general laboratory monitoring. In other fields ratemeters are used for frequency measurements where direct reading facilities are more important than very high accuracy.

Extremely simple ratemeters of limited accuracy can be constructed. In the simplest possible case the input pulses may be merely fed into a meter, the movement of which is damped so that the arrival of each individual pulse does not cause an appreciable fluctuation in the meter reading. Such a simple system will obviously be of very limited accuracy, since if the pulse amplitude or duration alters, the reading will be affected. Ratemeters designed to give reasonably accurate indications of the count rate, therefore, employ a pulse amplitude limiting circuit and a pulse shaping circuit which ensure that all pulses reaching the count rate measuring circuit are uniform in amplitude and duration. The count rate measuring circuit itself may be divided into an integrating circuit and a voltage measuring circuit. The integrating circuit converts the incoming pulses into a steady output voltage, the amplitude of which is dependent on the incoming pulse frequency. The output from the integrating circuit is measured by a voltmeter circuit which indicates the pulse rate directly. The general design of ratemeter circuits has been discussed in a paper by G. D. Smith[(2)].

A number of pulse shaping circuits have been used in ratemeters in the past in which a thyratron[(3)] has been employed. Trigger tubes have also been employed in portable ratemeters[(4–5)], but have now been almost entirely displaced by transistor circuits. Monostable pulse shaping circuits are sometimes used[(6–7)], but it is necessary to adjust the length of the output pulse from the monostable circuit for each counting range provided on the instrument. If the pulses are too long, some counts will be lost at high frequencies, whilst if the pulses are too short, they will not fully charge the larger capacitors used in the low frequency rate measuring circuits. Most versatile accurate modern ratemeters normally employ a bistable pulse shaping circuit and the mean length of the square wave output then varies as the reciprocal of the pulse rate. In such a circuit, however, the rate measuring circuit receives only one pulse for each two input pulses and, therefore, a longer time constant is required at low pulse rates in order to obtain a reasonably steady meter reading, but this is not a disadvantage in random pulse measurements, since a long time constant is in any case required at low input pulse rates to smooth out the statistical variations in the count rate.

Almost all ratemeter integrating circuits consist of a 'tank' capacitor, C_t, in parallel with a leak resistor, R_t. When this circuit is fed with unidirectional current pulses, the capacitor stores charge which leaks away through the resistor. If n pulses are applied to the integrating circuit per second and each supplies a charge of q coulombs, the total charge supplied to C_t is nq coulombs per second. The potential difference across C_t increases until at equilibrium the amount of charge leaking away through R_t is equal to nq coulombs per second. At equilibrium the potential, V_e, across C_t and R_t is therefore given by

$$V_e = iR_t = nqR_t \tag{1}$$

from which it can be seen that V_e is proportional to n if q is constant for all pulses. In practice V_e is measured by a microammeter placed in series with R_t or, if greater accuracy or greater meter robustness is required, a valve voltmeter (VTVM) is connected across C_t and R_t. One of the main problems encountered is that of keeping q constant as the value of V_e alters with the pulse input rate.

It should be noted that n is the frequency of the input pulses applied to the integrating circuit itself. If a bistable pulse shaping circuit is employed, this will divide the incoming pulse frequency by a factor of two and the input frequency to the bistable circuit must be $2n$.

One possible circuit for feeding the integrating capacitor, C_t, is shown in Fig. 9.1[(8)]. A pentode which is biased to cut off in the quiescent state is employed. When positive going input pulses of controlled duration are applied to the circuit, the pentode conducts for a moment and passes a charge to C_t. The use of a pentode renders the charge passed to C_t per pulse more or less independent of the voltage across C_t, since the anode current of a pentode operated above the knee of the characteristic is almost independent of the anode voltage. This type of circuit is not used in ratemeters of the highest accuracy, since the charge passed to C_t per pulse depends on the valve characteristics, the various grid potentials and the H.T. supply voltage. In fact the ratemeter range can be changed by altering the screen grid potential.

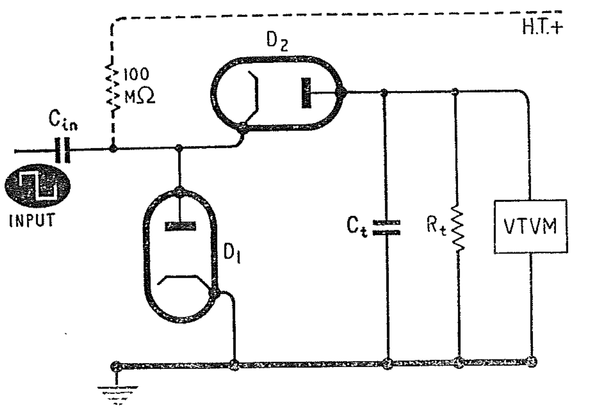


Fig. 9.1. A pentode fed integrating circuit

Almost all ratemeters of high accuracy employ the so-called 'diode pump' circuit to feed the integrating capacitor. A circuit of this type is shown in Fig. 9.2. The input capacitor, C_{in}, charges through D_1 during the positive part of the square wave input cycle. During the negative part of the input cycle C_{in} discharges through D_2 into C_t. The charge

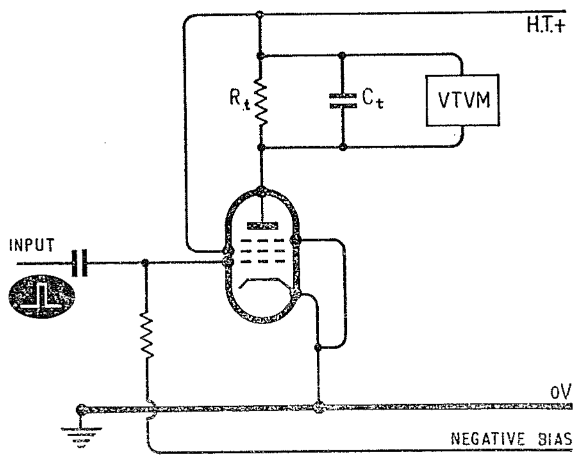


Fig. 9.2 A diode pump circuit

passed to C_t is therefore independent of the input pulse duration and of the internal resistance of the pulse source provided that the pulse duration is great enough for the capacitor C_{in} to become fully charged during the positive part of the input pulse.

As C_t charges and the potential across it increases, C_{in} will no longer pass all of its charge to C_t. The value of q will therefore vary with the input frequency and a linear scale will not be obtained. If V_{in} is the peak to peak amplitude of the input square wave and if C_{in} is fully charged to this voltage by each pulse, the charge fed to C_t per pulse is given by the equation

$$q = (V_{in} - V)C_{in} \tag{2}$$

where V is the potential across C_t. At equilibrium $V = V_e$ and equation (2) may be substituted in equation (1), hence

$$V_e = nR_t(V_{in} - V_e)C^{in} \tag{3}$$

and

$$V_e = \frac{nR_tC_{in}V_{in}}{1+nR_tC_{in}} \tag{4}$$

It can be seen from equation (3) that if a ratemeter with a linear scale is required, V_e must be negligible compared with V_{in}. This can be arranged if the current passing through R_t is measured by a sensitive meter, but in this case it is necessary to choose a relatively small value of R_t and hence C_t must be very large if a suitable time constant is to be obtained at low count rates. This is inconvenient because electrolytic capacitors cannot be used for C_t, since their leakage current would effectively reduce the value of R_t.

If a valve voltmeter is used to measure V_t, it is desirable that this voltage should not be less than about 10 V or appreciable errors will be introduced by the drifting of the zero of the valve voltmeter. A feedback circuit has been designed to overcome this difficulty in which a constant charge per pulse is fed to C_t, although V_e may be quite large.[9]

The 100 MΩ resistor shown dotted in Fig. 9.2 is often included in the circuit, since it allows a few microamps of current to flow through D_1 in the quiescent state and stablises the anode potential of this diode. If the resistor is omitted, the anode of D_1 returns to a potential which varies somewhat with input pulse spacing at high frequencies.

When a source of pulses is initially connected to the ratemeter input, the indicated count rate will gradually rise as the charge on C_t increases until it differs from the equilibrium value, V_e, by a negligible amount. The reading of a ratemeter should not therefore be taken until the meter needle shows no further rise. The time taken for the meter indication to reach 90% of its equilibrium value from zero is 2.3 R_tC_t sec. In order to limit the error to 1%, the reading should not be taken until it has reached 99% of its equilibrium value which will occur after 4.6 R_tC_t seconds. Thus if a ratemeter time constant is 80 sec, one should wait for over 6 min before taking a reading if 1% accuracy is required.

The time constant of the tank circuit may be made quite small if the incoming pulses are evenly spaced and if their frequency is not very small, since the integrating circuit must then merely smooth out the pulses so that the needle of the indicating meter does not fluctuate appreciably as each pulse arrives. When random pulses are being counted in radio-isotope work, however, the time constant must be chosen so that it is large enough not merely to smooth out the incoming pulses but also to smooth out the statistical variations of the pulse rate. If the input frequency is low, this demands a long time constant and there will be an appreciable delay before the meter reading alters after the input pulse rate has been changed. At higher input frequencies the statistical variations are smoothed out satisfactorily if a shorter time constant is used and advantage can then be taken of the rapid response. Many ratemeters therefore have a range of time constants.

The time constant is normally selected by trial and error so that the smallest value which gives a steady reading can be used. Most good ratemeters have circuits in which all of the tank capacitors (which determine the time constant in conjunction with the leak resistor) are charged simultaneously; a small time constant can then be selected at first to enable an approximate reading to be obtained very quickly, but after a short time a longer time constant may be used so that an accurate reading can be obtained. If all of the tank capacitors are not charged simultaneously, it is necessary to wait an appreciable time whenever the time constant is altered before another reading can be taken.

It can be shown [10][11] that the fractional standard deviation of a single ratemeter reading at equilibrium is $1/\sqrt{2nR_tC_t}$. A single reading from ratemeter of time constant R_tC_t thus has the same expected statistical error as a single counting operation carried out using the same pulse source and a scaler for a time of $2R_tC_t$ sec. If a ratemeter is connected to a pen recorder or, if a series of readings are obtained, the statistical errors can be reduced.

9.2 PRACTICAL RATEMETER CIRCUITS

The techniques used in modern ratemeter circuitry will be illustrated by the rate measuring circuits of some well known ratemeters. With one exception all of the circuits to be discussed have been designed for radio-isotope work, but they can be used for other purposes also. The circuits show some of the wide variety of refinements which are possible in ratemeters. It should be remembered that most instruments for radio-isotope work have other circuits built into them such as pulse height discriminators or high voltage supplies for Geiger or scintillation probe units.

9.2.1 The 1021C Monitor[7]

The 1021C radiation monitor consists of a simple ratemeter with power supplies for Geiger and alpha scintillation probes which is intended mainly for monitoring laboratories, clothing, glassware, etc. for radio-active contamination. The accuracy of the 0–200 and 0–2,000 pulses per second ranges is $\pm 2.5\%$, but when the 0–2 and 0–20 ranges are in use, the nominal accuracy is only $\pm 10\%$. This is adequate for simple monitoring.

The basic rate measuring circuit of this instrument is shown in Fig. 9.3, but the switching of the meter to indicate the H.T. voltage or the voltage supplied to the probe has been omitted for simplicity. The input capacitor, C_7, is used to block the d.c. voltage supplied to operate the probe and in conjunction with the resistor R_{28} it differentiates the input so that sharp pulses are obtained. $V7$ is a cathode coupled amplifier which has positive feedback from the anode of $V7$a to the grid of $V7$b. If S_7 is in position 1 (for Geiger counting), the gain of $V7$ may be varied from 10 to 40 by VR_2, whereas if S_7 is in position 2, the gain is fixed at 50 for scintillation counting.

The output from $V7$ is fed into the monostable circuit of $V8$ and V9. In the quiescent state $V9$ is biased beyond cut off and $V8$ is conducting. A negative going pulse of about 1 V or more in amplitude will trigger the monostable circuit which will return to its quiescent state after a pre-set time, t. During this time the circuit is insensitive to any input pulses which may be applied to it. The duration of the time t is varied from 50 μsec to 50 msec by factors of ten as the range switch S_{5b} is moved from position 1 to position 4. $V9$ conducts for a time t and charges the tank capacitor C_{20}. Thus, as t is increased by the range switch S_{5b}, the charge fed to C_{20} per input pulse increases and the count rate for full scale deflection is reduced. The full scale deflection on three ranges may be adjusted by means of VR_3, VR_4 and VR_5. The meter is protected from overloading by means of a diode. The H.T. supply is stabilised by $V5$ and $V4$, but it was found that the meter readings were dependent of the heater supply voltage. Compensation for variations in the heater supply voltage is therefore provided by R_{22}, R_{32} and R_{33}. If the mains voltage alters, the potential at the junction of R_{21} and R_{22} will change and this can be used to alter the pulse amplitude at the grid of $V8$.

The time constant is fixed at 1 sec (determined by C_{20} and R_{45}), but a socket is provided so that an external capacitor of about 25 to 100 μF can be placed in parallel with C_{20} to increase the time constant to 6.25 or 25 sec respectively. The external capacitor should not be an electrolytic or its leakage resistance may reduce the reading by up to 10%.

This simple type of circuit has the advantage that there is no zero drift, since a valve voltmeter is not employed. A sensitive and therefore fairly delicate meter must, however, be used.

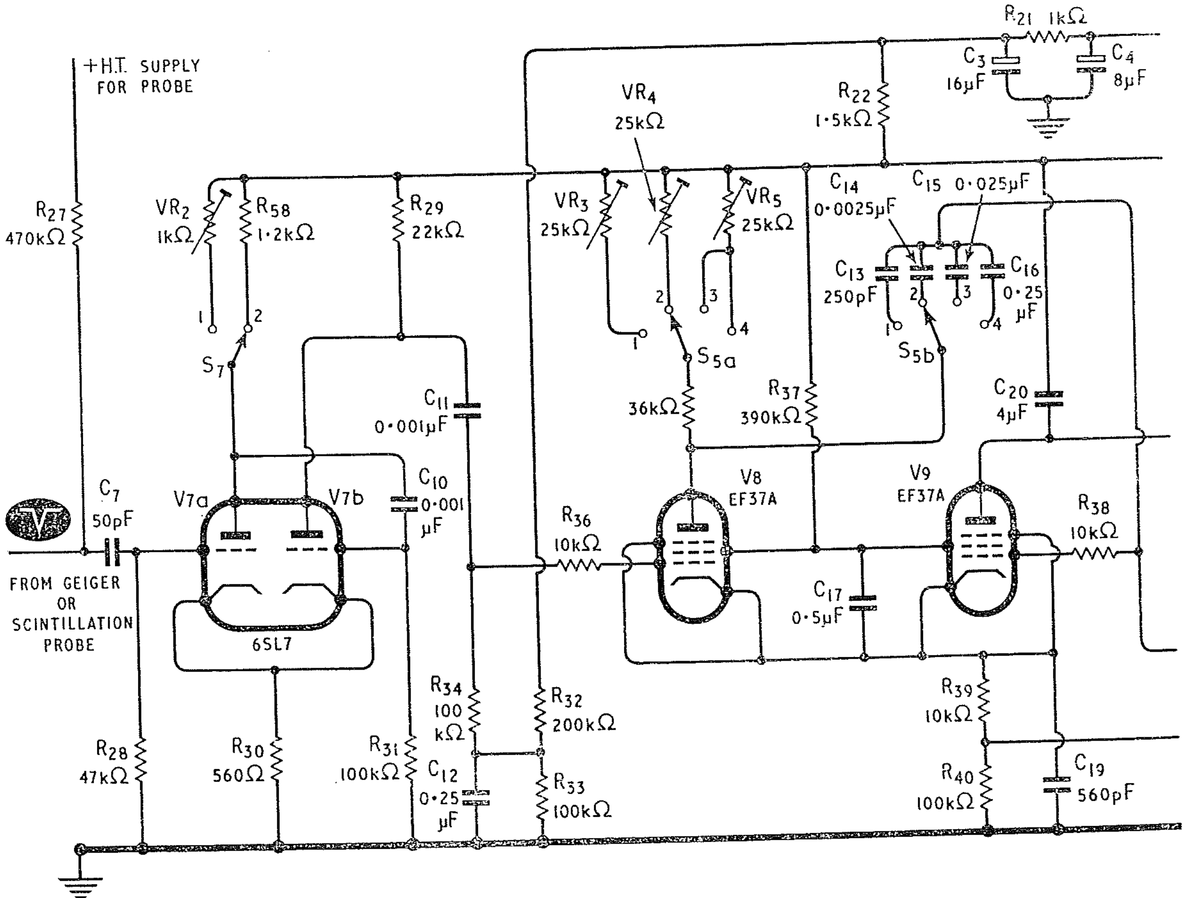


Fig. 9.3 The rate measuring circuit of

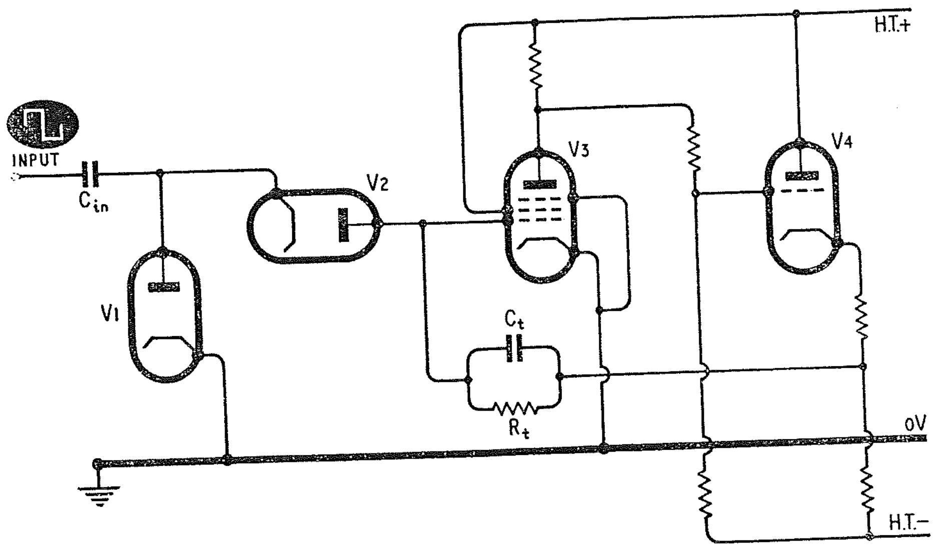
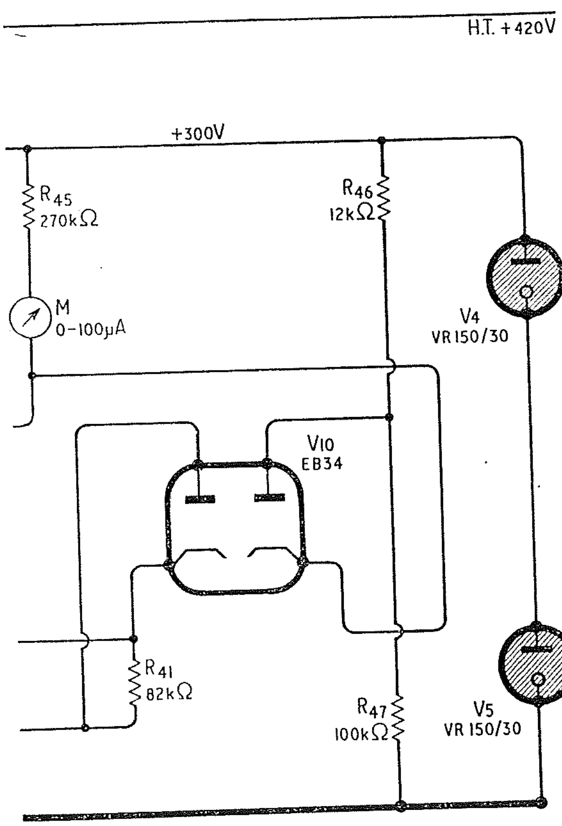


Fig. 9.4 A basic ratemeter circuit with feedback



the 1021C monitor (somewhat simplified).

9.2.2 Accurate Ratemeter

The circuit of a linear ratemeter which can provide an accuracy of better than ±1% of the full scale deflection was published in 1951[9]. This uses a diode pump circuit, but as shown in the basic circuit of Fig. 9.4, the tank capacitor, C_t, is connected across a direct coupled amplifier. The pulses charge C_t as in the simple diode pump circuit of Fig. 9.2, but the feedback ensures that almost all of the resulting change in potential across C_t appears at the side remote from $V2$, since the feedback amplifier circuit of $V3$ and $V4$ maintains the potential of the grid of $V3$ almost constant. The grid of $V3$ is a 'virtual earth'. The change in potential across C_t divided by the change in potential of the grid of $V3$ is equal to the gain of the amplifier circuit; this gain is normally over 100. Thus the voltage across C_t has little effect on the charge per input pulse fed to C_t. Equation (3) for the diode pump circuit becomes

$$V_e = nR_t\left(V_{\text{in}} - \frac{V_e}{G}\right)C_{\text{in}} \qquad (5)$$

where G is the gain of the amplifier. V_e/G can be made considerably less than 1% of V_{in} and therefore can be neglected. This basic feedback principle is used in many modern ratemeter circuits.

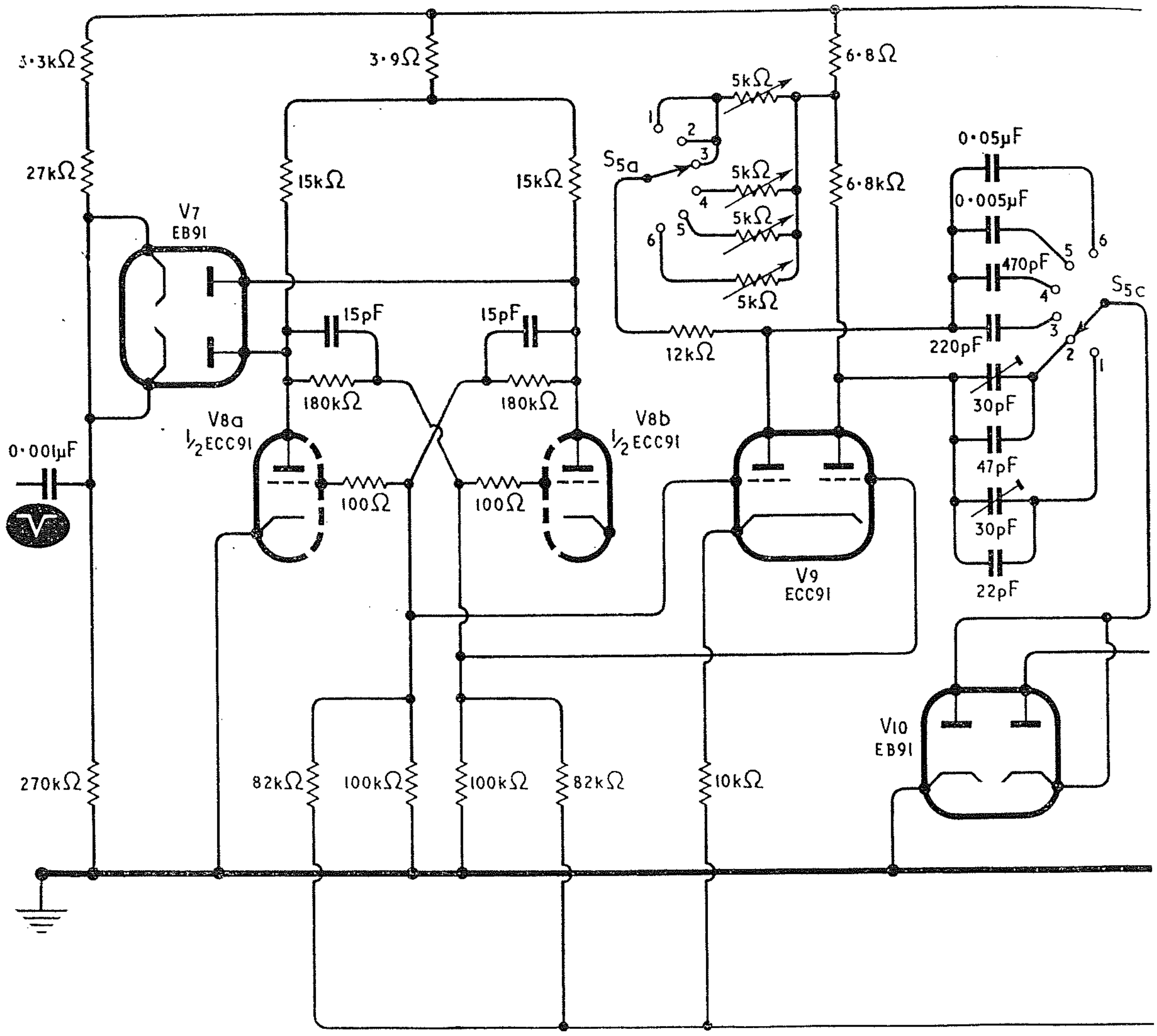
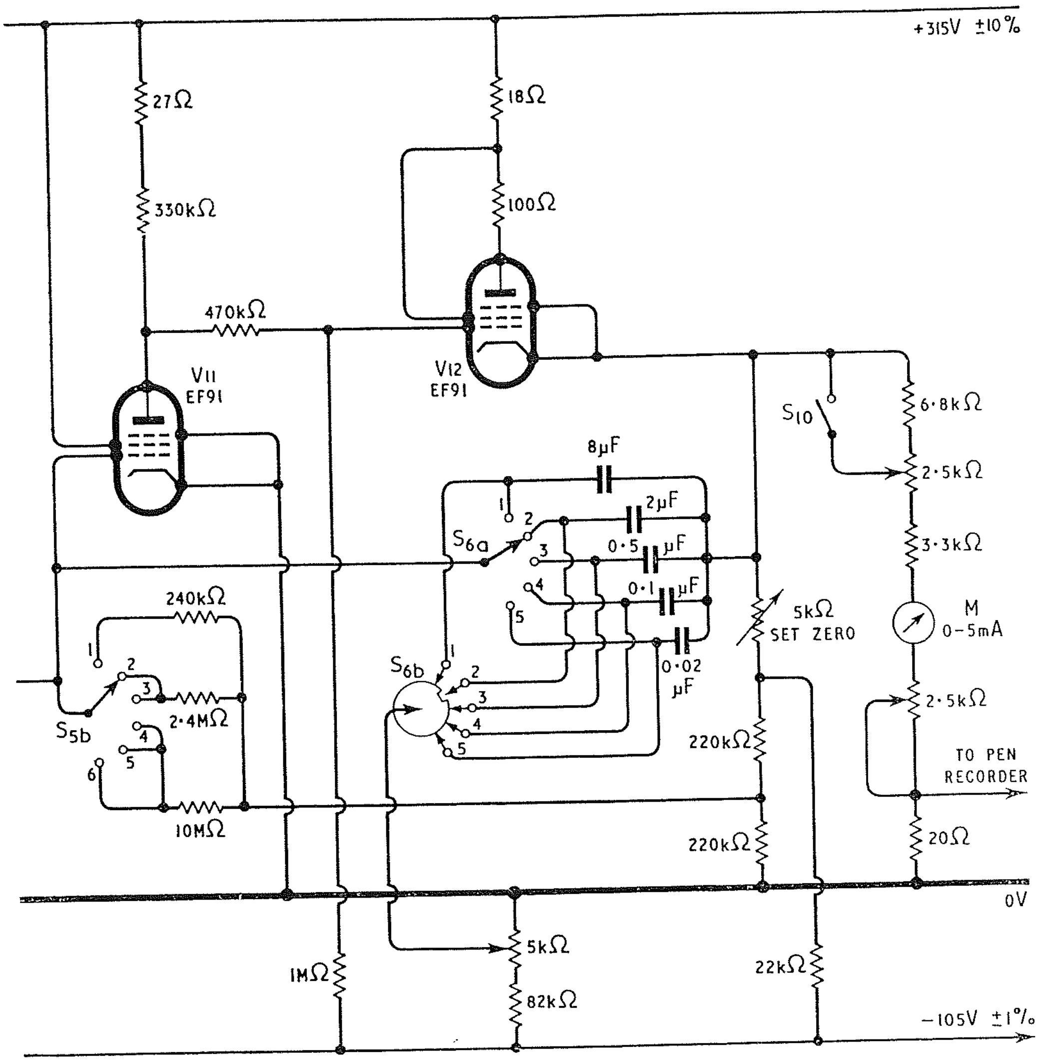


Fig. 9.5 An accurate

A practical circuit of a ratemeter employing the principles of Fig. 9.4 is shown in Fig. 9.5[9]. S_5 is the range switch and S_6 can be used to adjust the time constant. The tank circuit capacitors which are not in use at any time are connected via S_{6b} to a 5 kΩ potentiometer, the sliding contact of which is adjusted to the mean potential of the grid of *V*11 (which is almost constant for the reasons discussed above). When S_6 is operated to bring another capacitor into circuit, this capacitor already has almost the correct charge and therefore one does not have to wait very long for the desired equilibrium reading to be obtained.

The diodes *V*7 gate the incoming pulses alternately to the anodes of the bistable circuit of *V*8. The square wave from *V*8 is fed to *V*9, the two halves of which conduct alternately and limit the amplitude of the square wave to a value determined by the anode load resistors and the cathode resistor. The current passing through the conducting section of *V*9 is accurately determined, since the grid of the conducting section of *V*9 is held at earth potential by the conducting section of *V*8. The output pulses from *V*9 are fed to the input capacitor of the diode pump selected by S_{5c}, the range switch. If the input capacitor is small, the charge fed to the diode pump



ratemeter circuit

per input pulse will be small and a high frequency input will be required for a full scale deflection. The value of the integrating circuit resistor is reduced on the high frequency ranges or the input capacitor would have to be extremely small and changes in the stray wiring capacitance could produce errors; the integrating circuit resistors are selected by S_{5b}. The full scale readings of each range can be set by adjusting the preset potentiometers selected by S_{5a} except for the two upper frequency ranges which are adjusted for the correct full scale deflection by the preset trimmers in the diode pump input capacitance. If the values shown in Fig. 9.5 are employed, full scale readings from 1 to 100,000 pulses per second are obtained increasing from range to range by factors of ten. Intermediate ranges are also very desirable.

It is most important that the diode input capacitors in the S_{5c} circuit should be of high stability, since any change in their value will affect the meter deflection. The wiring associated with these capacitors should be kept short and rigid so that no changes of stray capacity are likely to occur. The tank capacitors selected by S_{6a} must have a very high leakage resistance, although their stability is not so important. The voltage built up across them at full scale deflection is about 70 V on ranges 1 and 2 and about 150 V on the other ranges. Variations in the potential of the grid of $V11$ are normally less than 1 V.

9.2.3 Ratemeter with Auto-correction for Lost Counts

A ratemeter has been constructed which will automatically compensate for counts that are lost due to the finite resolving time of the system[(12)]. It incorporates the feedback principle used in the circuit of Fig. 9.4 together with another feedback loop. The use of such a ratemeter enables the time normally taken in correcting for resolving time losses to be saved. It has been shown in Chapter 1 that if n pulses per second are recorded by a system of resolving time t, then the number of pulses, N, which would have been recorded if the resolving time of the system had been zero is given by the equation

$$N = \frac{n}{(1-nt)}$$

In the ratemeter circuit to be described, feedback is used so that a rising non-linear characteristic is obtained which provides an output of $1/(1-nt)$ times the output which would be obtained without feedback. The feedback must make the system more sensitive as the input pulse rate increases. This system can be used to compensate for counts lost in the ratemeter circuit itself or in another part of the apparatus preceeding the ratemeter provided that the resolving time of the system is known.

In the case of the linear ratemeter of Fig. 9.5 it has been shown from equation (5) that

$$V_e = nR_t V_{in} C_{in}$$

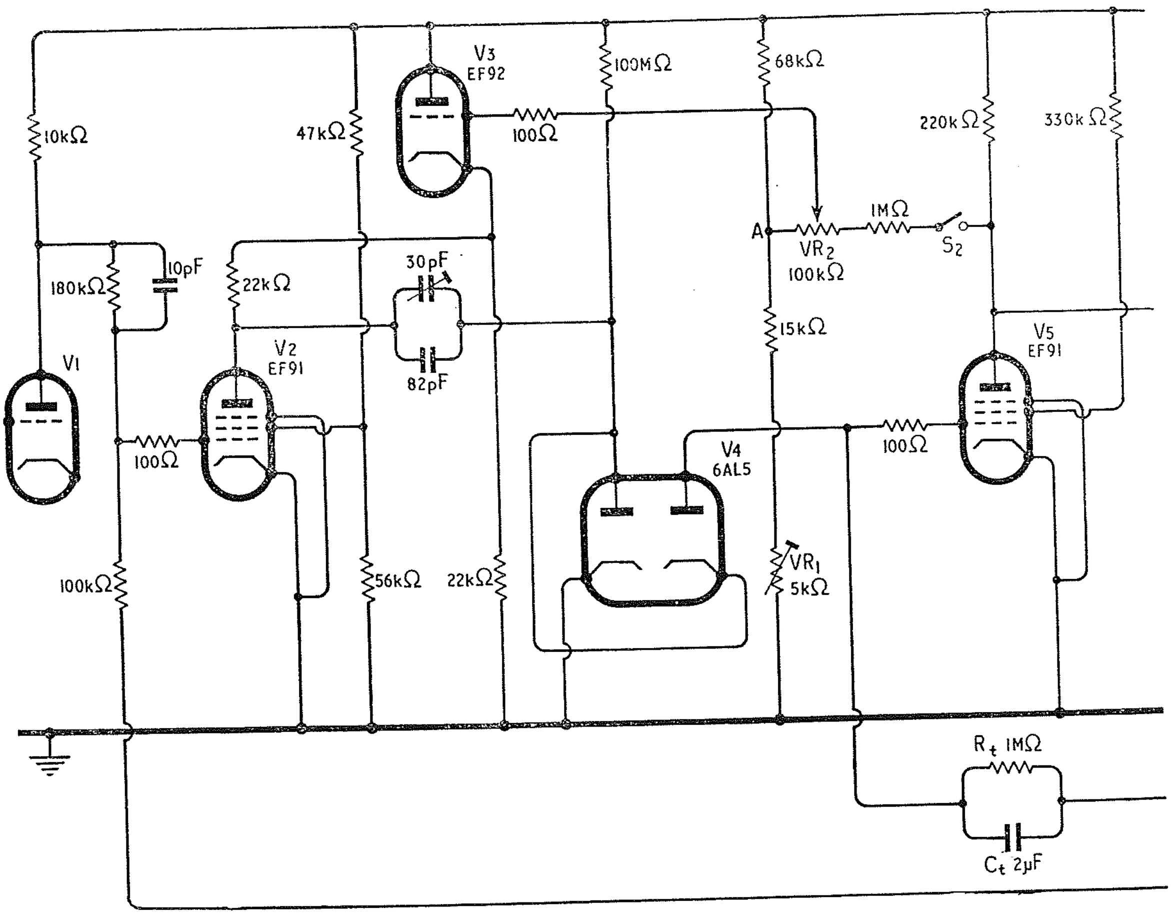


Fig. 9.6 A counting rate meter with automatic compensa-

if G is large. If a fraction p of the voltage V_e is fed back so that it adds to the input, the following equation applies

$$V_e = (V_{in}+pV_e)C_{in}R_t n$$

or

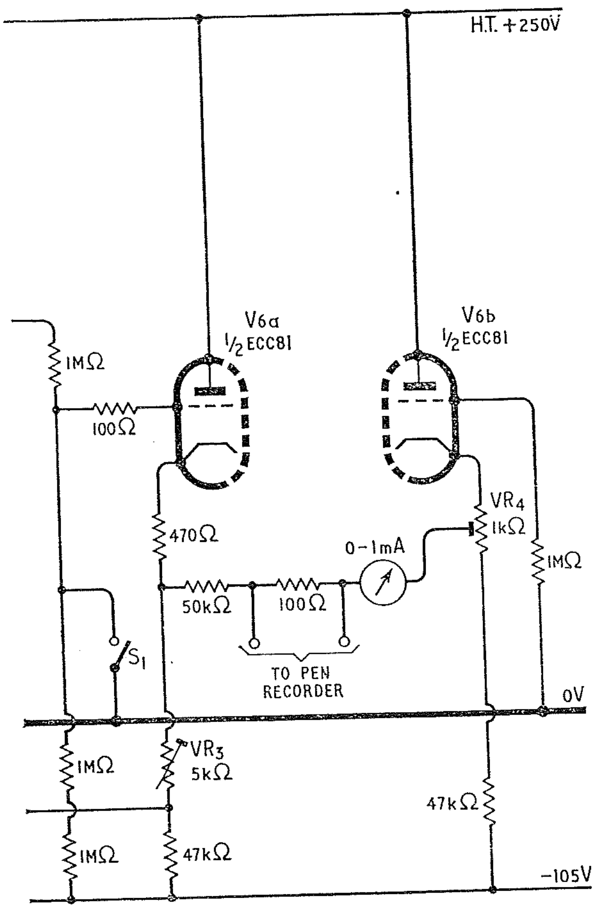
$$V_e = V_{in}C_{in}R_t \frac{n}{(1-npC_{in}R_t)}$$

Hence if p is chosen so that $pC_{in}R_t$ is equal to the resolving time t of the equipment,

$$V_e = V_{in}C_{n}R_t \frac{n}{(1-nt)} = V_{in}C_{in}R_t N$$

Thus the output voltage is directly proportional to the corrected counting rate, N.

A circuit of this type with a full scale deflection of 10,000 pulses per second for use when the system



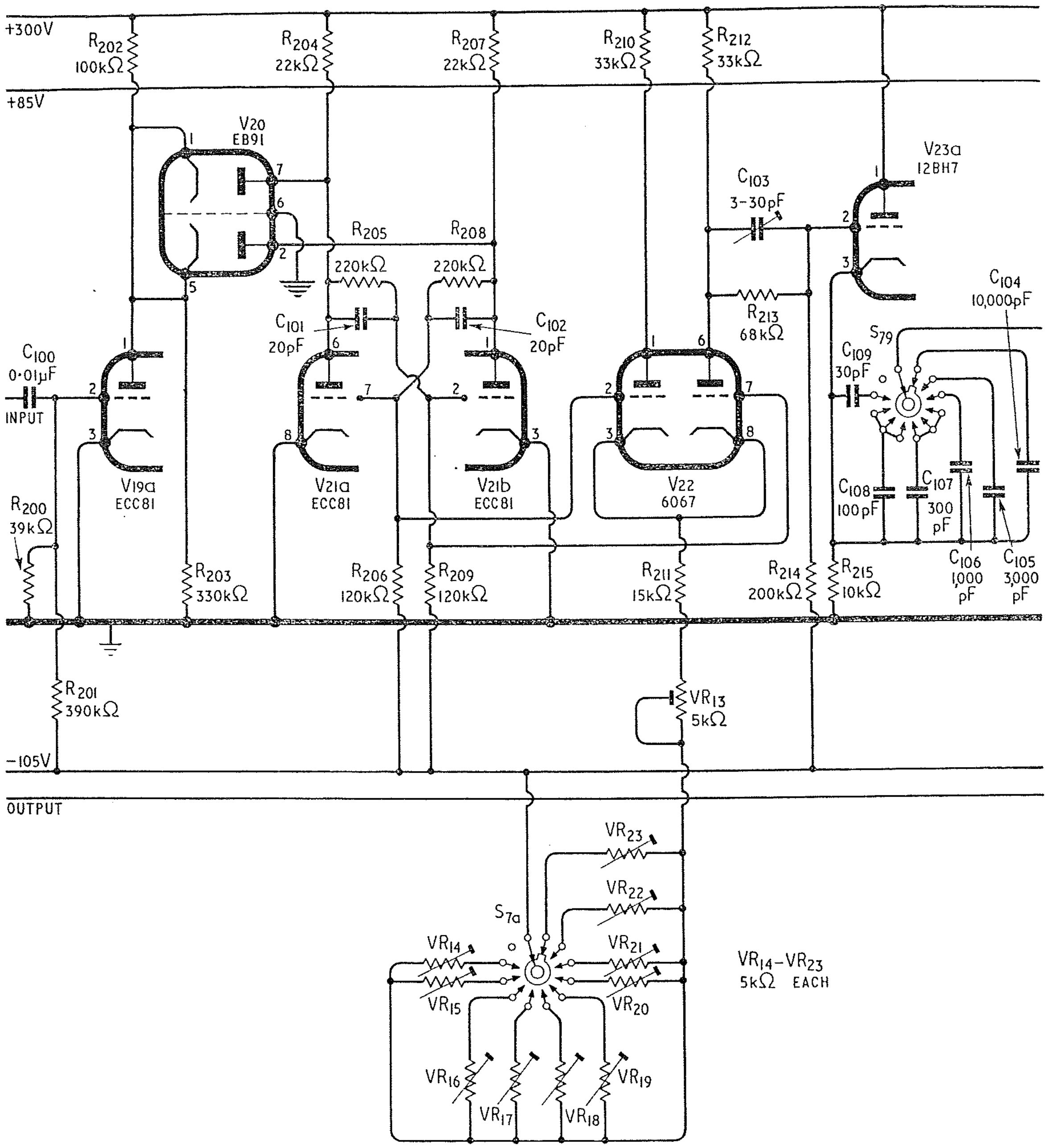
tion for counts lost due to the finite resolving time.

has a resolving time of about 10 μsec is shown in Fig. 9.6[12]. It is very suitable for use with scintillation or proportional counters. If S_2 is opened, the extra feedback loop from the anode of $V5$ to the grid of $V3$ is broken and there will no longer be any compensation for lost counts.

The rectangular input pulses from $V1$ alternately cut off and saturate $V2$. When saturated the anode potential of $V2$ is only a few volts above earth potential. The anode voltage of $V2$ thus swings between this lower limit and an upper limit determined by the cathode potential of $V3$ which is a few volts above the grid potential of $V3$. The peak to peak anode voltage swing of $V2$ is thus approximately equal to the potential of the grid of $V3$ above earth.

The anode potential of $V5$ increases with increasing input frequency and the grid of $V3$ receives a portion of this increase when S_2 is closed. The anode voltage swing of $V2$ therefore becomes larger with the result that the charge per input pulse fed to the diode pump circuit, $V4$, is increased, thus giving the desired rising characteristic with increasing frequency.

A few adjustments must be made before the instrument is used. S_1 is closed and VR_4 adjusted for a zero reading of the meter. S_1 is then opened and VR_3 is adjusted for a zero reading. The grid of $V6a$ is then at earth potential and, owing to the values of the coupling resistors and the negative supply line voltage, the anode of $V5$ will be at +52.5 V. A sensitive high resistance voltmeter should then be connected from the anode of $V5$ to the point marked A, and VR_1 adjusted for a zero reading on this meter. Both of these points and the grid of $V3$ are now at +52.5 V and the peak to peak amplitude of the pulses fed to the diode pump will also be 52.5 V. This adjustment is made so that the pulse amplitude is unaffected by the setting of VR_2 at low input pulse frequencies. Evenly spaced pulses are now fed to the circuit with S_2 open and the input trimmer capacitor in the anode circuit of $V2$ is adjusted so that the meter indicates the input frequency. S_2 is then closed and VR_2 of is adjusted until the desired amount of compensation is obtained. For example, if the resolving time of the system is 10 μsec, the pulse generator may be set to provide



+300V
+85V
-105V
OUTPUT
INPUT
R202 100kΩ
R204 22kΩ
R207 22kΩ
R210 33kΩ
R212 33kΩ
V20 EB91
V23a 12BH7
C103 3-30pF
R205
R208
220kΩ
220kΩ
C101 20pF
C102 20pF
R213 68kΩ
C104 10,000pF
S79
C109 30pF
C100 0·01μF
V19a ECC81
V21a ECC81
V21b ECC81
V22 6067
C108 100pF
C107 300 pF
C106 1,000 pF
C105 3,000 pF
R200 39kΩ
R203 330kΩ
R206 120kΩ
R209 120kΩ
R211 15kΩ
R214 200kΩ
R215 10kΩ
R201 390kΩ
VR13 5kΩ
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VR19
VR14–VR23 5kΩ EACH

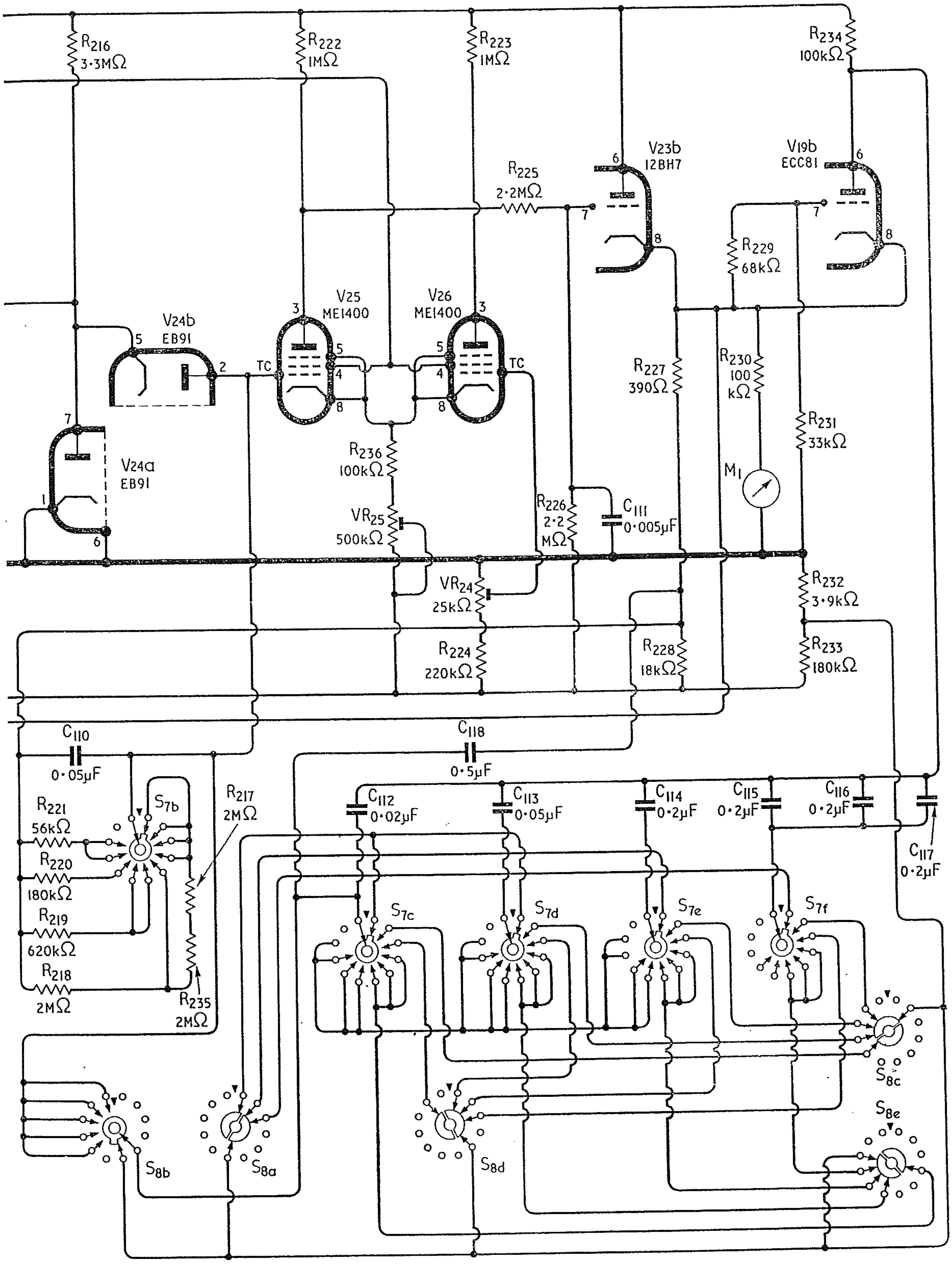


Fig. 9.7 A ratemeter with automatic control of the time constant (part of the Ecko N600 ratemeter).

$n = 9{,}100$ evenly spaced pulses per second and VR_2 should be adjusted until the meter reads $N = 10{,}000$ pulses per second. The meter should now indicate the compensated count rate at all points on the scale. If at any time the instrument is to be used to count evenly spaced pulses, no compensation will be required and S_2 should therefore be opened. The instrument is accurate to about 1% of the full scale deflection.

9.2.4 Ratemeter with Automatic Control of Time Constant

The Ecko type N600 ratemeter [13] employs a circuit in which the time constant is automatically adjusted to provide an almost constant pre-selected mean probable statistical error. On the six lowest frequency ranges with full scale deflections of 3 to 1,000 pulses per second, the mean probable error may be set at 1%, 2%, 3%, 5% or 10%. A sixth position of the mean probable error switch enables a short time constant to be obtained during the manual scanning of energy peaks, etc. On the ranges with full scale deflections of 3,000 and 10,000 pulses per second the mean probable error is fixed at 1%, whilst the two highest frequency ranges with full scale deflections of 30,000 and 100,000 pulses per second are intended mainly for the measurement of evenly spaced pulses, since the minimum resolving time of three microseconds will lead to mean counting losses of 10% and 30% at full scale deflection in these respective ranges if the input pulses are randomly distributed in time. In addition to the mean probable error control, a number of other refinements are incorporated into this ratemeter and will be described below.

The circuit of the rate measuring section of the N600 ratemeter is shown in Fig. 9.7[13]. The positive going pulses from the preceding pulse height analyser circuit are fed into the amplifier $V19$a. The negative going output pulses from this stage are alternately gated by $V20$ to the two valves $V21$a and $V21$b which form a bistable circuit. The outputs from this stage are fed into the $V22$ limiter stage. Each section of $V22$ is alternately cut off. The conducting section passes a current which is determined by the anode load resistor, the cathode resistors and the negative supply line potential. The full scale deflection of each range can be adjusted by the appropriate preset resistor which is switched into circuit by the range switch S_{7a}. VR_{13} is a master sensitivity control which is effective on all ranges. These sensitivity controls alter the amplitude of the square wave which is fed from $V22$ to the cathode follower stage of $V23$a. This cathode follower is included because it can provide the large current pulses which are necessary to fully charge the diode pump input capacitor (selected by S_{7g}) in the shortest possible time.

The two diodes $V24$ form the diode pump circuit. $V24$a is normally in the conducting state owing to the current passing through it from the H.T. line via R_{216}, whilst $V24$b is normally in the non-conducting state owing to the slightly negative potential applied to its anode from the cathode circuit of $V23$b.

$V25$ and $V26$ are used in a high gain differential amplifier which compensates for any changes in the heater supply voltage. The output from $V25$ is fed via a potential divider to the grid of the cathode follower $V23$b which is at about earth potential. The output from this valve is fed back to the grid of $V25$ via the integrating resistors associated with S_{7b}. This feedback circuit is very similar in principle to that of Fig. 9.4 and therefore the grid of $V25$ remains at an almost constant potential. VR_{24} controls the grid voltage of $V26$ and hence the common cathode potential; it therefore affects the anode potential of $V25$ and can be used as the set zero control.

A small capacitor, C_{110}, is permanently in circuit and acts as the integrating capacitor when the shortest time constant is being used (that is, when S_{8b} is open circuited). The remaining integrating capacitors, C_{112} to C_{117}, are selected singly or in groups by the range switch S_7 and the mean probable error switch, S_8. Except for C_{110}, the integrating capacitors are effectively connected across the resistor(s) selected by S_{7b} via the Miller integrating valve $V19$b. The value of the capacitor(s) selected by the switches is effectively multiplied by the gain of the valve $V19$b, but the leakage current passed by the capacitors is effectively multiplied by the same factor also. Capacitors of a reasonably small value can, therefore, be used, but they must have a very high insulation resistance.

The input voltage applied to $V19$b from the cathode of $V23$b develops a large potential across the anode resistor of $V19$b. This charges the integrating capacitor(s) selected by the switches, the other side of the capacitor(s) being held at the almost constant potential of the grid of $V25$. The charge held by a capacitor is equal to the voltage across it multiplied by its capacitance value. Increasing the voltage applied to the integrating capacitor(s) by the use of the amplifier stage of $V19$b therefore has the same effect on the charge stored as an increase in the capacitance value. The capacitors not in use are kept charged to about the same potential as the capacitor(s) being used by the same method as that employed in the circuit of Fig. 9.5. No large change in the meter deflection will, therefore, occur in this case if the mean probable error switch is altered.

It has been mentioned earlier in this chapter that the fractional standard deviation of a single ratemeter reading is $1/\sqrt{2nR_tC_t}$ and the fractional mean probable error is this quantity multiplied by 0.675. The percentage mean probable error will thus remain constant as n varies if the product nR_tC_t remains constant. That is, the time constant must vary inversely as the count rate. The grid resistors of $V19$b provide a bias to the Miller integrator valve which renders the gain of the stage non-linear. The gain decreases by a factor of three as the count rate increases from about 1/3 of the full scale deflection to full scale. The mean probable error is thus kept fairly constant over this part of each range.

The temperature coefficient of the diode pump input capacitors selected by S_{7g} is opposite in sign to the temperature coefficient of the integrating resistors selected by S_{7b} and this, therefore, assists in maintaining stability with changes of temperature.

9.2.5 Logarithmic Ratemeter

A logarithmic ratemeter is one which provides an output or a meter reading which is proportional to the logarithm of the input frequency. This type of ratemeter can measure a very wide range of pulse frequencies without range switching. This is obviously very convenient if automatic equipment or a pen recorder is to be operated from the output of the ratemeter. There are many applications of logarithmic ratemeters both in radio-isotope work and in other fields. For example, if a radio-isotope of short half life is placed near a probe unit which feeds a logarithmic ratemeter and the output from the latter is passed to a pen recorder, a straight line graph will be obtained. Similarly, if a logarithmic ratemeter is used in the measurement of the thickness of a material by the absorption of beta or gamma radiation, the reading obtained will be linearly related to the thickness of the material if the absorption is exponential. Logarithmic ratemeters are also useful when the ratio of two counting rates is required, since the difference in the output currents or voltages of two logarithmic ratemeters is proportional to the logarithm of the ratio of the input pulse rates.

The percentage accuracy of logarithmic ratemeters is normally fairly constant over a very wide range of input frequencies. The percentage accuracy of a linear ratemeter at full scale deflection is considerably greater than that of a logarithmic ratemeter of similar quality, but in the case of a linear ratemeter, however, the percentage accuracy decreases on any range as the input frequency decreases.

It has been shown[14] that the output of a number of diode pump circuits of differing time constants may be added to give a response which is almost logarithmic over a very wide frequency range. Each of the diode pump circuits is non-linear, the output from each pump circuit being determined by equation (4), since the voltage across the tank circuit is not kept small. If the time constant of a diode pump circuit is T, the output voltage from a single pump circuit is

$$V_e = V_{in}\frac{nT}{(1+nT)}$$

If nT is much smaller than unity, V_e is approximately zero, whilst if nT is much larger than unity, V_e will be approximately equal to V_{in}. When m diode pump circuits of time constants T_1, T_2, T_3, etc. are employed, the sum of the output voltages,

V_e, will be given by

$$V_e = V_{\text{in}}\left(\frac{nT_1}{1+nT_1} + \frac{nT_2}{1+nT_2} + \frac{nT_3}{1+nT_3} + \right.$$
$$\left. + \cdots\cdots \frac{nT_m}{1+nT_m}\right) \qquad (6)$$

If $T_2 = 0.1\ T_1$ and $T_3 = 0.1\ T_2$, etc., at any given frequency between $1/T_2$ and $1/T_{m-1}$ a number of terms in the bracket of equation (6) will be approximately zero, some will be between zero and unity and the remainder will be approximately unity. If n is increased by a factor of ten, there will be an additional term of unity and one less zero term, whilst the values of the intermediate terms will be unchanged, although they will have moved one position to the right. Each factor of ten increase in

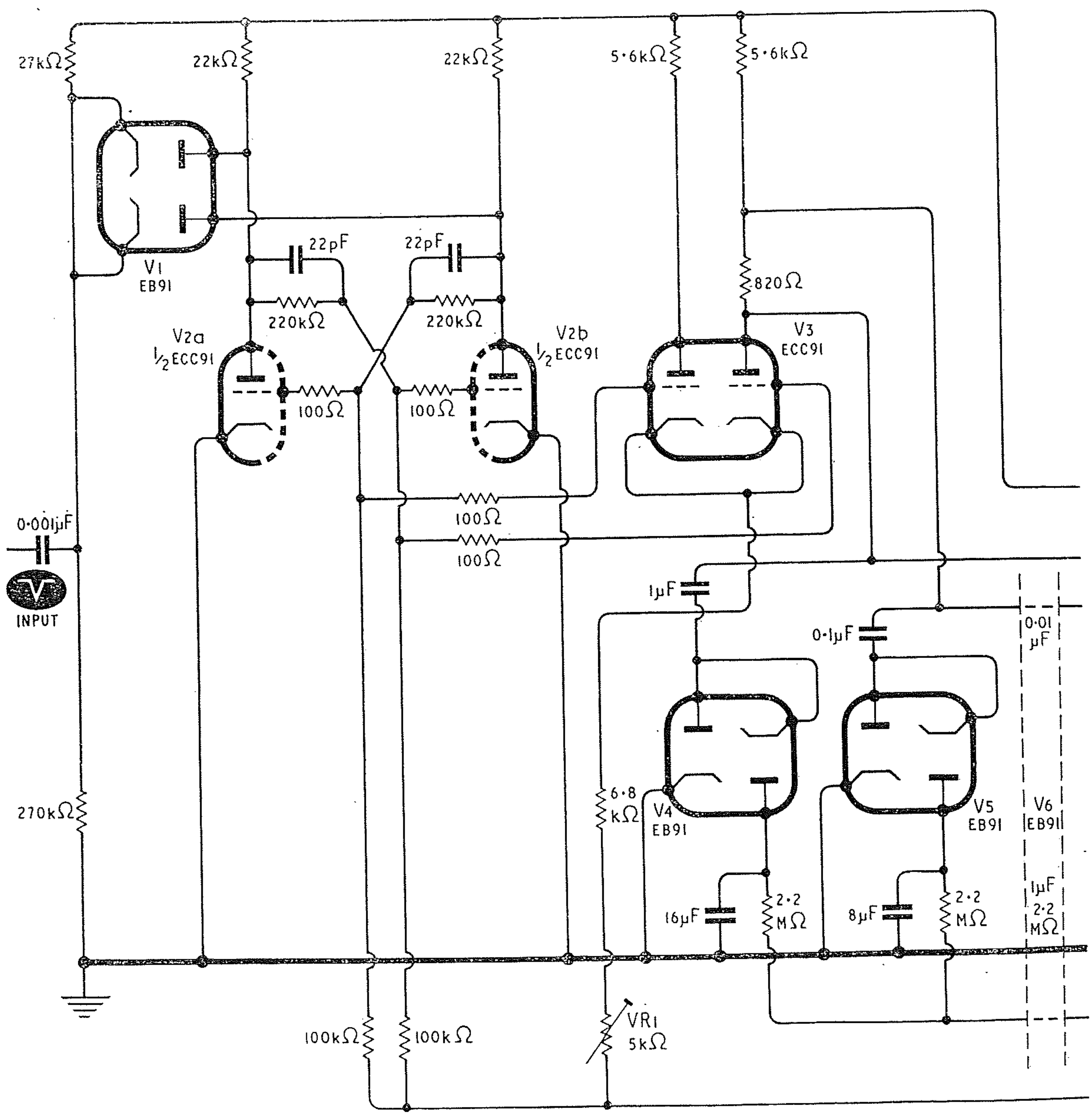


Fig. 9.8 A wide range

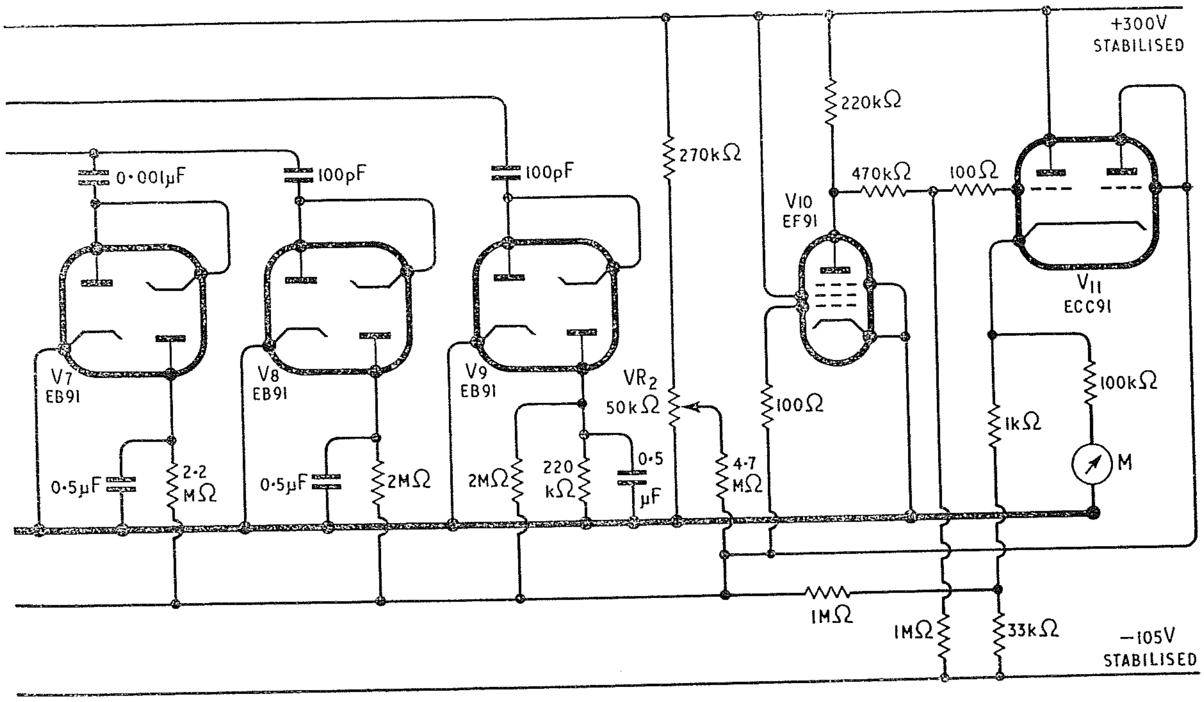
the input frequency, therefore, causes the same increase in the output voltage and the response from decade to decade is logarithmic. It has been shown empirically that the response is also closely logarithmic over a fraction of a decade[14]. It can be shown mathematically that the output voltage is approximately proportional to the logarithm of the input pulse frequency[15].

If a ratemeter is to cover N decades and not deviate from a logarithmic response by more than $\pm3\%$, $(N+3)$ diode pump circuits are needed[14]. This requirement may be reduced somewhat if the input pulse amplitude to the two end diode pump circuits which have the largest and smallest time constants is increased somewhat, since this reduces the errors caused by the fact that the number of decades is limited. If the amplitude of the pulses fed to these two end pump circuits is increased by 18%, the deviation from a logarithmic response is less than 3% for input frequencies between $1/T_{max}$ and $1/T_{min}$. The factor by which the time constants increase from one pump circuit to the next is normally ten; other factors may be used, but the capacitors required will not then all be of the preferred values.

A logarithmic ratemeter circuit designed to cover a range of 1 to 100,000 pulses per second with an accuracy of $\pm10\%$ is shown in Fig. 9.8[14]. This circuit is in many ways similar to that of Fig. 9.5. The input pulses to be counted are applied to the bistable circuit of $V2$ via the gating diodes $V1$. $V3$ is a limiter valve, each section of which conducts alternately.

The diode pumps $V5$, $V6$, $V7$ and $V8$ are fed with a 50 V square wave, but $V4$ and $V9$ receive a square wave of 15% larger amplitude from the anode of $V3b$. It is more convenient to add the currents passing through the leakage resistors than to add the output voltages. The output currents from the diode pump circuits operate the circuit of $V10$ and $V11$ which feed the meter M. This meter must show a zero deflection at a small but finite input pulse rate corresponding to the bottom of the range of the instrument. The current from the diode pumps is therefore returned to VR_2 which can be used to adjust the zero. The full scale deflection of the instrument can be adjusted by means of VR_1 which controls the amplitude of the square waves fed to the diode pump.

The leakage resistors of $V8$ and $V9$ (2.0 MΩ) are 10% smaller than the leakage resistors of the other



logarithmic ratemeter

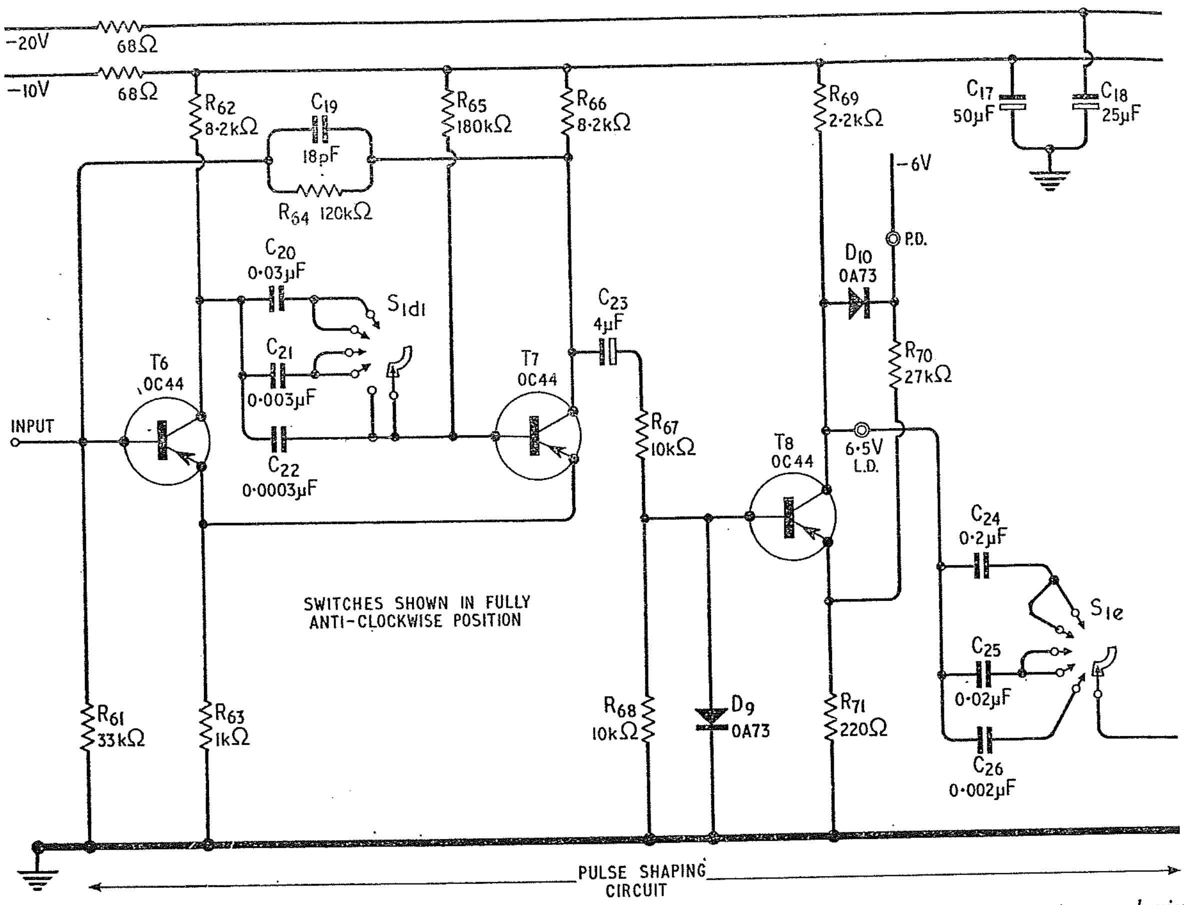


Fig. 9.9 A transistor ratemeter employing

diode pump circuits to compensate for the estimated 10 pF stray capacitance in the input circuits of these two diodes, since this forms an appreciable fraction of the 100 pF input capacitors to the two diode pump circuits. In the other diode circuits the input capacitance is larger and any additional stray capacitance can be neglected. The leakage resistor of *V9* is bypassed to earth by a resistor of 1/10 of its value in order that the diode pump input capacitor may be ten times as large as would otherwise be possible. If the input capacitor to this stage were only 10 pF, considerable error would be likely to arise owing to additional stray capacity.

9.2.6 Transistor Ratemeter

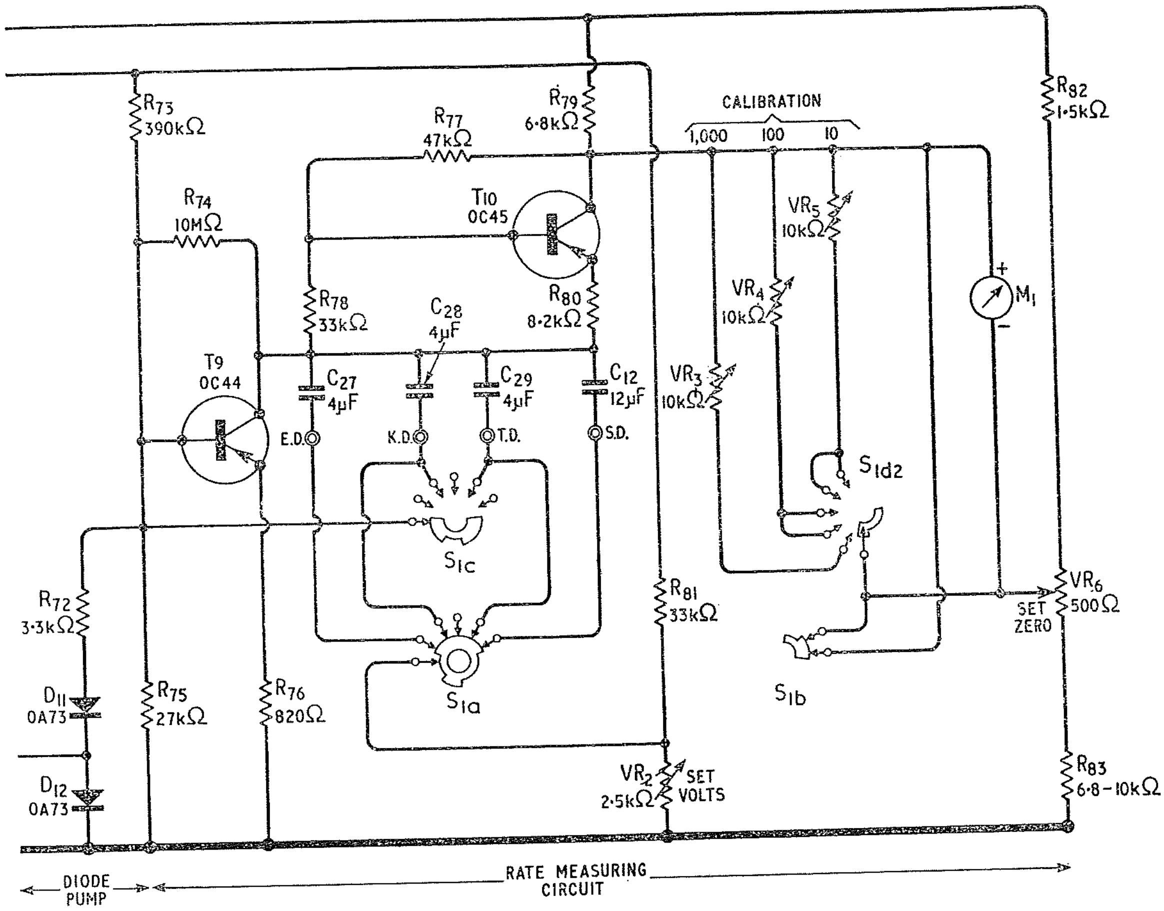
The rate measuring circuit of the Ecko N645A portable transistor ratemeter is shown in Fig.9. 9[16].

The range switch, S_1, also selects the time constant as shown below.

Position of S_1	1	2	3	4	5	6
Full scale deflection (Pulses per second)	OFF	1,000	100	100	10	10
Time constant (sec)	OFF	4	8	4	4	20

The instrument has an accuracy of $\pm 5\%$ of the full scale deflection and can be used with suitable scintillation probes for the detection of alpha or gamma radiation or with a Geiger probe for the detection of beta particles.

The circuit is basically similar to the valve ratemeter circuits which have already been described. After amplification the input pulses from the probe are applied to the base of *T6* which forms a bistable circuit with *T7*. The output pulses from *T7* have a



a diode pump circuit

pre-set amplitude and duration. The catching diode in the collector circuit of $T8$ limits the output pulse amplitude from this stage to 6 V. These pulses are fed to the diode pump input capacitor which is selected by S_{1e}; the capacitor chosen determines the range.

The output current from the diode pump circuit is applied to the d.c amplifier $T9$ and $T10$. The integrating capacitors connected between the collector and base of $T9$ are selected by S_{1c}. The capacitors not being used at any time are charged to approximately the voltage of the used capacitor by means of S_{1a} so that transients are minimised when they are switched into the circuit. The collector of $T10$ feeds the meter M_1, the ranges being adjusted for the correct full scale deflection by means of the three preset resistors in the collector circuit of $T10$. When the instrument is switched off, the meter is short circuited by means of S_{1b} to protect its movement.

9.2.7 Rate of Revolution Indicators

It is often useful to be able to display the rate of revolution of a shaft as the deflection of a meter. This can be done accurately by arranging that a pair of contacts connected in series with a resistor and a battery close once per revolution of the shaft; the voltage pulses across the contacts are fed into a linear or logarithmic ratemeter such as those described previously. A suitable photocell pick up could also be used if suitable arrangements are made to allow a beam of light to fall on the photocell once per revolution of the shaft.

The simple revolution counter of Fig. 9.10[17] is included as a complete contrast to the more

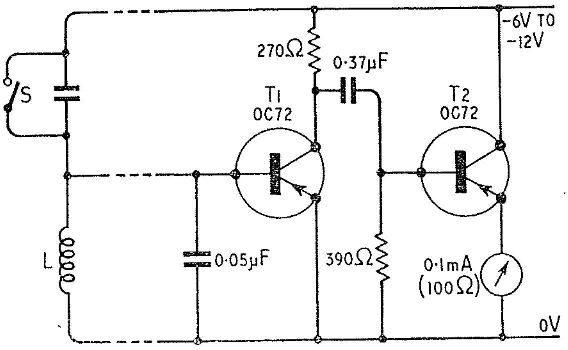


Fig. 9.10 A simple rate of revolution indicator

complicated ratemeter circuits. It is especially suitable for use as an engine speed indicator for petrol engines, but can be used to measure the rate of rotation of any shaft if a pair of contacts operated by the shaft are fitted. The coil L may be the ignition coil of a petrol engine and S the contacts of the contact breaker. The contacts of a petrol engine do not open once per revolution, but the meter can be calibrated accordingly.

Each time the contacts are opened, a voltage pulse is produced across the coil L. This is applied to the base of $T1$ and produces a current of rectangular waveform in the collector circuit of this transistor. The coupling circuit between the two transistors differentiates the pulses and the negative going part of the differentiated waveform causes $T2$ to conduct. If the time constant of the differentiating circuit is low enough, the meter reading will be almost proportional to the input pulse rate and therefore to the rate of revolution of the shaft. It is desirable, however, that the revolution indicator shall be calibrated at various points on the curve, since the meter reading is not usually quite linear with respect to counting rate.

9.2.8 Other Types of Ratemeter

Many other type of ratemeter for use at relatively low frequencies (less than 1 Mc/s) have been designed. For example, a logic circuit may be included in a ratemeter in order to provide a means of changing the range automatically[18]. The accurate measurement of high frequencies may be rapidly carried out by high speed counting circuits as described in Chapter 12. Another type of instrument for the measurement of high frequencies employs a stable beat frequency oscillator; beats which occur between this oscillator frequency and the input signal are amplified and fed into a normal type of ratemeter[19]. Frequency meters of this type are much simpler than those instruments which employ high speed counting circuits, but they are not usually so convenient to use.

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10

Readout

10.1 INTRODUCTION

A counting circuit may provide information as to the state of the count by means of either a visual indication or by an electrical output. Any counting circuit which is not self indicating must provide electrical readout to the components which are used to convert this form of readout into visual readout, or information on the state of the count will not be available. In predetermined counting circuits the electrical readout can be used to operate any other circuit after a preset number of counts.

Although self indicating counting circuits are relatively simple, digital methods of readout are obviously much more satisfactory than analogue methods. It is very easy for a tired operator to make a mistake when adding the counts indicated by a binary neon or tungsten filament lamp display. A system employing ten separate lamps renders errors less likely, since the count in any decade is indicated by a single lamp and the operator does not have to carry out any addition. Even if ten lamps are employed in each decade and the number of counts indicated by each lamp is marked on the glass in front of the lamp, the display is still not ideal, since the position of the displayed digit varies with the count. Ideally a display should be of the 'In-line Digital' type in which the various digits are displayed in the same position and a multi-decade number appears as a line of digits. This type of readout not only occupies the minimum of space on the front panel of the instrument, but also reduces operating errors to a minimum. Other systems are used only for circuit simplicity.

Different types of counting circuit provide different forms of electrical readout. In one form the output voltage or current increases step by step as the input pulses are applied; it is known as a staircase waveform. The E1T can provide this form of readout from the deflector plate which is not connected to the input. If the count in a decade is to be indicated by means of a meter, the electrical output must be in the form of a staircase waveform. Transistor binary decades can be arranged to provide this form of readout by one of the methods discussed in Chapter 8.

Other types of counting circuit (such as ring circuits, cold cathode decade selector tubes and trochotrons) provide electrical readout in the form of an output pulse at any one of ten different electrodes (decade readout). This form of readout is obviously very suitable for the operation of digital indicator tubes. It is normally much easier to convert decade readout into a staircase waveform than vice-versa.

The third type of electrical readout is the binary coded decimal system in which the count in each decade is given by a combination of the outputs from several binary stages. Variations of this coding occur when the 1st, 2nd, 3rd and 4th binary stages do not correspond to counts of 1, 2, 4 and 8 pulses respectively. It is relatively easy to convert these types of readout into either decade or staircase readout by the methods discussed in Chapter 8. Various other methods of information conversion are also available using beam switching tubes(1) or other devices.

Many methods by which readout can be effected from various types of counting circuit have already been fully discussed in previous chapters. The most

Table 10.1 FORMS OF READOUT COMMONLY EMPLOYED WITH VARIOUS TYPES OF COUNTING CIRCUIT

Type of counter	*Visual readout*	*Electrical readout*
Electro-magnetic	Normally self indicating digital. Relay switched electroluminescent digital etc.	Special contacts may provide electrical readout.
Trigger tube decade ring Trigger tube binary	Self indicating. Indicator tube. Self indicating.	Decade readout. Binary readout.
Polycathode gas filled decade tubes	Self indicating. Indicator tube.	Decade readout from selector tubes only.
The E1T	Self indicating. (Meter readout possible).	Staircase waveform only available.
Beam switching Tubes	Indicator tubes. Ten filament or neon tubes. (Meter readout possible).	Decade readout.
Cascaded binary valve Cascaded binary valve with feed-back to form decade system	One neon tube per binary. Meter readout. Indicator tube. 4 or 10 neon tubes per decade. Meter.	Binary readout. Binary coded decade. (Various other codes are possible).
Transistor binary with feedback to form decade	Indicator tube (incl. Z550M). Meter. 4 or 10 filament or neon bulbs per decade.	Binary coded decade. (Various other codes possible).
PNPN four layer diode in a decade ring	Indicator tube. Ten neon or filament bulbs per decade. Meter possible.	Decade readout.
Tunnel diode	Meter. Other types after amplification of output.	Binary or staircase (depending on type of circuit).
Binary magnetic core	Magnetic is the simplest.	Decade possible.
Magnetic flux counters Ferro-electric counters	Any form of readout disturbs the counting process. (see Chapter 8)	
Ratemeter	Meter. Pen recorder.	Output voltage or current proportional to the input pulse rate or to some function of the input pulse rate.

common forms of readout are summarised in Table 10.1. In this chapter the detailed operation of gas filled cold cathode indicator tubes will be discussed and various other methods by which digital readout can be obtained will be mentioned. The principles employed in digital readout are often useful when other information than a pure number is to be displayed.

10.2 GAS FILLED COLD CATHODE INDICATOR TUBES

One of the most economical and popular forms of digital readout involves the use of one cold cathode numerical indicator tube per decade which displays an actual digit in the form of a red or orange glow. The Z550M is a special type of tube and will be discussed separately. Some manufacturers have registered trade names by which their numerical indicator tubes are known. These are:

Manufacturer	*Trade Name*
Burroughs	'Nixie'
Ericsson	'Digitron'
Hivac	'Numicator'
S.T.C.	'Nodistron'

Another type of indicator tube is available which indicates a digit by means of the position of a point of light. The tube is mounted in an escutcheon on which the ten digits are marked. The digit to be indicated is the one which is adjacent to the point of light. The type of display and the construction of the tube are similar to that of the multi-electrode gas filled counting tubes described in Chapter 4 in which a point of light rotates during counting. This type of indicator tube will be referred to as a point indicator tube to distinguish it from numerical indicator tubes. Point indicator tubes are used mainly in high speed decades which are followed by gas filled decade tubes, since a similar form of readout is then available from all decades. They take a much smaller current than numerical indicator tubes owing to their smaller cathode area.

Some tubes for indicating characters other than digits are also available. The Ericsson GR2G (side viewing) and GR2H (end viewing) and a number of Burroughs tubes can indicate either a plus or a minus sign at any one time. The GR4G indicates $^1/_4$, $^1/_2$, $^3/_4$ or 1. The GR12G indicates one of the letters A to L inclusive, whilst the GR12H indicates one of the letters L to X excluding P and Q but with the addition of E. The Burroughs B5018 tube indicates A to K except I, whilst the B50113 indicates L to X excluding O, Q and U. It is not possible to place all 26 letters in one envelope and obtain satisfactory readout. The Mullard Z521M (ZM1021) indicates $+$, $-$, V, A, Ω, % or $\sim$. The C.S.F. tube type F9007 indicates monetary signs of various countries including the £ sign, whilst the F9008 indicates some electrical symbols and the F9009 some mathematical symbols. The Burroughs B6037 tube indicates any number from 0 to 19. The B5094 indicates N, M or μ on the left hand side of the tube and S, V or A on the right hand side; this tube can therefore be employed to indicate the symbols for nanosecond (NS), millivolt (MV), microvolt (μV), etc.

The Burroughs cold cathode alpha numeric indicator tubes contain 13 or 15 cathodes and a common anode. Each cathode is in the form of a straight line. If a current passes to a number of suitably selected cathodes, the glow of these cathodes can be used to display any chosen digit or any letter of the alphabet. The alpha numeric display principle is used in electroluminescent display devices and is described in detail later in this chapter (Section 10.4).

The Burroughs Company also manufacture special cold cathode indicator tubes which may be used to obtain digital readout from circuits operating on biquinary principle. These tubes are similar to the normal cold cathode digital indicator tubes, but the odd numbered cathodes are placed in one section of the tube and the even numbered cathodes in another section. Each section has its own anode and the two sections are screened from each other. The cathodes 0 and 1, 2 and 3, 4 and 5, etc. are joined internally in pairs. The voltage applied to the anodes is controlled by the binary circuit and that applied to the cathodes by the ring of five of

Table 10.2 BASIC DETAILS OF NUMERICAL INDICATOR TUBES

	Numeral height (in.)	Cathode Current (mA)	Min. anode voltage	Nom. maintaining voltage	Typical operating conditions V_b	Typical operating conditions R_a (kΩ)	Base	Remarks	End or side viewing
Burroughs:									
'Miniature'									
7009	0.3	0.7–1.2	170	100	300	200	11 pin or flying lead		End
B4081 (wide angle)	0.3	0.7–1.4	170	100	250	150	11 pin or flying lead		End
7977 (B4032)*	0.3	0.7–1.4	170	140	250	91	11 pin or flying lead		End
B4021	0.3	0.7–1.4	120	100	120	20	11 pin or flying lead	Low voltage tube	End
'Standard'									
6844A	0.6	1.5–3.0	170	140	300	82	B13B		End
8037 (B5031)*	0.6	1.5–3.0	170	140	250	56	B13B		End
B5092* (wide angle)	0.6	1.5–3.0	170	140	300	62	B13B		End
'Super'									
7153	0.8	2.0–3.0	250	140	250	43	B13B		End
B6033*	0.8	1.5–4.0	170	140	300	56	B13B		End
B6091* (wide angle)	0.8	1.5–4.0	170	140	250	39	B13B		End
'Large'									
B8091* (wide angle)	1.375	3.0–6.0	170	140	300 250 170	33 22 5.6	B17A		End
'Jumbo'									
B7094* (wide angle)	2.0	4.0–7.0	300	140	300	27	B17A		End
'Rectangular'									
B5991*	0.61	1.5–3.0	170	140	300 250 170	68 47 8.2	SK136 special		End
C.S.F.:									
TA542 (F9004)	0.81	2.2–3.6	170	140	250	40	B13A		End
TA543 (F9002)	2.25	10–14	170	140	250	10	DB25S special		Side
Ericsson:									
GR10G	1.181	9 max.	220	180	250	10	B26A	See text	Side
GR10H	0.748	2.5 max.	150	140	250	82	B17A		End
GR10J*	1.181	4 max.	150	145	250	33	B26A		Side
GR10K*	0.748	1.8 max.	150	140	250	82	B17A		End
GR10M*	0.61	1.0–2.5	170	140	250	82	B13B	Red filter	End
GR10N	2.35	5	170	135	300	33	B17A		Side
GR10W	0.59	4 max.	220	160	220	18	Flying lead.		Side
Hivac:									
XN1	0.55	1.5–2.0	180	130	180 250 300	33 82 120	Flying lead		Side
Mullard/Philips:									
Z510M	0.61	1.5–3.0	160	127	250	68	B13B		End
Z520M (ZM1020)*	0.61	1.0–2.5	170	140	250	56	B13B	Red filter	End
Z522M (ZM1040)*	1.2	3.0–6.0	170	140	250	27	B13B	Red filter	Side
Z550M (ZM1050)	0.12	3		84	A.C. supply only		B13B	See text	End
ZM1080*	0.51	1.5–2.5	170	140	250	56	Flying lead	Red filter	Side
S.T.C.:									
GN4	0.6	1.5–3.0	170	140	250	56	B13B	Red filter	End
GN5, GN5A	1.0	2.5–5.0	200	140	250	33	B12A	Red filter in GN5 only	End
GN6	0.6	1.5–2.5	170	140	300	100	Flying lead	Red filter	Side

* Long life tube.

The Mullard ZM1022 is equivalent to the Z520M without the red filter.
Burroughs tubes with a suffix 'A' (e.g. 7009A) contain radio-active material to ensure prompt striking; they are useful when the tubes are to be photographed for data recording.

the biquinary. The appropriate digit is thus indicated.

The Burroughs 'Pixie' tube provides digital readout, but the ten small digits appear in different places near the circumference of the tube. It may be considered as a point indicator tube in which the discharge shines through a hole in the shape of the digit to be indicated. As in the case of point indicator tubes, the power consumed is very small. The display is similar to that of the Z550M tube which is described in Section 10.3.

any adjacent surfaces. The cathodes are surrounded by a wire mesh anode onto which most of the sputtered material will be deposited. If this type of anode were not used, the visibility of the glow would be reduced by the sputtered material which would be deposited on the glass envelope. Undesirable reflections would also occur from the back of the tube on which the sputtered material had been deposited.

Numerical indicator tubes provide an extremely clear form of readout which is much more satisfactory than that given by self indicating counting tubes. When switching occurs the digits indicated appear almost exactly in the same position as the digits indicated previously. The tubes can be viewed from a wide angle and the brightness of the display is independent of the angle of view. Most types can be viewed from angles up to $\pm 50°$ from the central axis, but wide angle types are also available which can be viewed from angles of up to $\pm 80°$ from the axis[4]. The cathodes of these wide angle tubes are placed near to the tube face. Although numerical indicator tubes may extinguish completely at high counting speeds (above 200 kc/s), they impose no limitation on the counting speed, since they will indicate the correct count as soon as the counting speed falls or the counting ceases. The high speed counter must, however, be able to function satisfactorily with the variations in load imposed by a conducting or non-conducting indicator tube. Indicator tubes do require a high voltage supply, but the current passed is quite small.

Table 10.3 BASIC DETAILS OF POINT INDICATOR TUBES

Type	*Cathode Current (mA)*	*Minimum supply voltage*	*Nominal maintaining voltage*	*Base*	*Escutcheon*
GR10A (Ericsson)	0.05–0.25	129	108	B12A	N.80977
Z503M (Mullard/Philips)	0.05–0.25	129	108	B12A	101064

Cold cathode numerical indicator tubes consist of a number of cathodes (often made of nickel) mounted closely one behind the other inside an anode which consists of fine wire mesh. Each cathode is in the shape of one of the digits (or other symbols) which are to be indicated. At any one time a current is passed to only one of the cathodes which is covered in a red or orange glow. The cathode glow has a width which is considerably greater than that of the cathode itself and therefore the glow is not obscured by any other cathodes which may be in front of it. The cross section of the cathode wire may be about 0.4 mm in width by 0.25 mm in thickness, whereas the glow is about 3 mm in diameter[2].

In a simple gas discharge tube there is a Crookes dark space between the negative glow and the cathode, but if an indicator tube is filled with a suitable gas at a suitable pressure, the Crookes dark space will not be visible. The anode is placed in the Faraday dark space so that the positive column striations are not present. A gas pressure is chosen which is low enough to give complete cathode coverage at a current of a few milliamps, but large enough to ensure a clear edge to each digit[3].

During the operation of the tube a small amount of material will be sputtered from the cathode onto

The reliability of numerical indicator tubes is extremely good. Special long life versions of some tubes are available which contain a small amount of mercury vapour[2]. These tubes emit a faint bluish glow in addition to the cathode glow, but if used with a red filter they provide a display similar to that of the ordinary tubes. The mercury vapour reduces the current required to cover the cathode and also reduces sputtering. This gives an overall improvement of about twice the normal life. Some tubes are believed to have a life exceeding 200,000 hours[4] and will therefore outlast the equipment in which they are used. The amount of sputtered material on the glass envelope gives an indication as to when the tube should be replaced.

A large variety of digital indicator tubes is available for displaying digits of various sizes. Tubes which display large digits are often constructed for side viewing, but for some applications tubes which are viewed through the domed end are more suitable. The side viewing tubes require less front to rear space, whereas the end viewing tubes take up a smaller height on the front panel and are very useful when several lines of indicator tubes must be stacked above one another.

Small numerical indicator tubes are quite suitable for most apparatus, since the operator is usually near to the equipment. If the state of the count must be visible from a distance, larger indicator tubes may be used and are ideal for use in industrial control panels. The approximate distances at which numerical indicator tubes can be read are as follows:

Height of numeral (in.)	0.3	0.6	1.5	2.25
Max. viewing distance (ft)	12	30	60	90

The tubes with large characters require more current than small tubes, but the striking and maintaining voltages are virtually independent of the size of the displayed digit.

10.2.1 Characteristics

The characteristic of a GR10G numerical indicator tube is shown in Fig. 10.1[5]. The shaded area shows the variation in maintaining voltage at various cathode currents owing to manufacturing tolerances

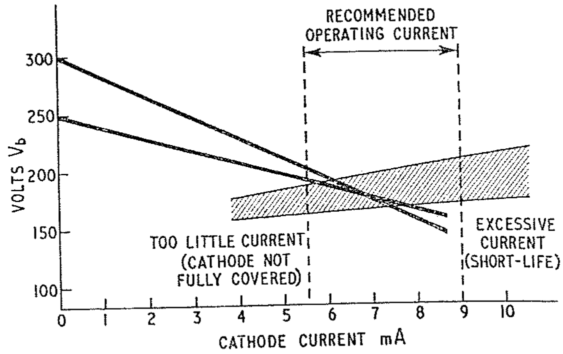


Fig. 10.1 The characteristic of a numerical indicator tube type GR10G

and tube ageing. It can be seen from the characteristic that the potential across the tube is not strongly dependent on the current passing through it. If the current is too small, the surface of the largest cathode will not be covered by the discharge, whilst if the current is too large, the life of the tube will be reduced. Owing to the sputtering of material from the cathodes during life, a used tube requires a higher current to completely cover the cathode than the minimum current required by a new tube. This is allowed for in the tube data sheets.

The basic circuit for the operation of numerical indicator tube is shown in Fig. 10.2. The current passing through the tube, i, is given by the equation

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

where V_b is the supply voltage.

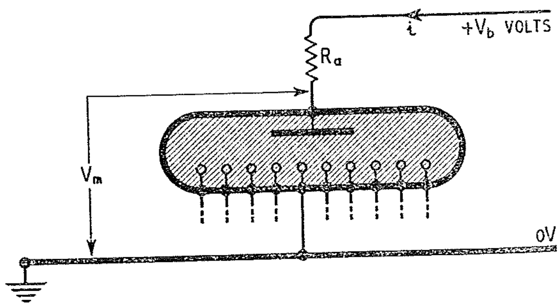


Fig. 10.2 The basic circuit for a numerical indicator tube showing only one cathode in circuit

V_m is the tube maintaining voltage which varies very slightly with i. Load lines for various values of R_a and V_b can be drawn on the characteristic of Fig. 10.1 in order to determine suitable values for these quantities. The load line should always intersect the characteristics of the tube within the recommended cathode current range as R_a and V_b vary within the expected tolerances. Two suitable load lines for different supply voltages are shown in Fig. 10.1. An additional requirement is that V_b must exceed the striking voltage of the tube. Generally it is good practice to employ a high value of V_b and a high value of R_a so that variations in V_b cause a relatively small change in the current passed by the tube.

In some cases it is advisable to include compensating resistors in the leads of those cathodes which have a smaller surface area than the other cathodes in the tube. For example, it is recommended that an 8.2 kΩ resistor is inserted into the cathode 1 lead of a GR10G tube and a 4.7 kΩ resistor in the cathode 7 lead. In some tubes, however, the design has been modified so that the use of additional compensating cathode resistors is unnecessary. In most plus and minus sign indicator tubes the series resistors are placed in the cathode leads. If the supply voltage is 250 V, the GR2G requires a 15 kΩ resistor in its +cathode lead and a 27 kΩ resistor in its −cathode lead, whilst the GR2H end viewing tube requires 82 kΩ and 120 kΩ resistors in these positions. The +sign has a larger cathode area and thus requires a smaller series resistor so that a larger current can flow.

The cathodes of a numerical indicator tube which are not being used at any time must either be unconnected or alternatively may be biased positively with respect to the conducting cathode. If the bias potential is not great enough, the unused cathodes will glow somewhat and the display will not be clear. The positive bias applied to the non-conducting cathodes is known as 'pre-bias'. The variation of the current passed by the non-conducting cathodes of a GR10H tube with the pre-bias voltages applied to them is shown in Fig. 10.3[6]. The current passed by an unused cathode decreases as its distance from the glowing cathode increases (owing to ionisation coupling). In the area A the unused

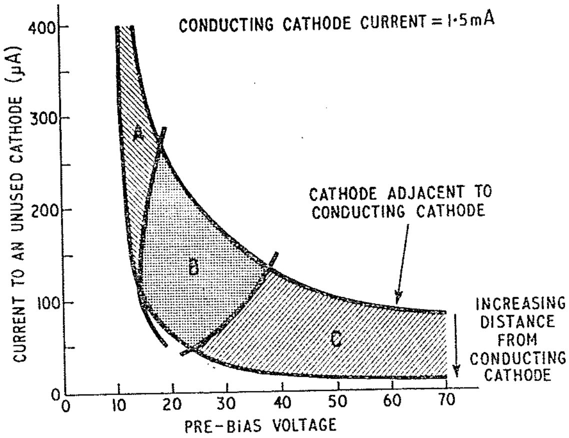


Fig. 10.3 Legibility of the numerical indicator tube type GR10H

cathodes are passing such a high current that the glow emitted by them completely obscures the desired glow from the conducting cathode. In the area B some confusion can arise, since it is only possible to distinguish the glowing cathode from the background haze with some difficulty. The operating point of all unused cathodes should normally be situated within the area C in which the glowing cathode is clearly visible against a slight background haze which decreases in intensity as the pre-bias voltage increases.

The voltage required to switch a numerical indicator tube is equal to the pre-bias to place the operating point of the unused cathodes in the area C. The pre-bias voltage is of particular significance if the tube is to be operated from low voltage semiconductor scaling circuits. The required value of pre-bias voltage varies from tube to tube, however, being dependent on the cathode spacing. Typical values for satisfactory operation range from 40 to 120 V.

10.2.2 Operation from Unsmoothed Supply Voltages

The life of an indicator tube may be approximately doubled if it is operated from an unsmoothed half wave rectified supply provided that the peak current does not exceed the maximum recommended for the tube. Some loss of brightness will result, but this is not important unless the tube is used in bright sunlight.

Some tubes (such as the GR10H) may be operated from an unrectified alternating supply. An additional electrode, called the a.c. anode, is placed so that the glow from it cannot be seen from the viewing position. The main anode is connected to the additional anode through a high resistance to facilitate the striking of the tube.

Numerical indicator tubes cannot be operated from either an unsmoothed rectified or an unrectified supply unless isolating buffer amplifying stages are employed between the counting circuit and the indicator tube, since counting circuits cannot be operated from unsmoothed supplies.

A number of methods have been published by which the amount of light evolved from an indicator tube can be reduced for operation in subdued light[4]. These circuits employ valve or transistor astable circuits so that the voltage supply is applied to the indicator tube for a fraction of the operating time. In conditions of high ambient lighting it is recommended that a red filter or a polaroid filter be placed in front of the tube to reduce reflections from the glass envelope and hence to increase the contrast of the display[4].

10.3 THE Z550M INDICATOR TUBE[7, 8]

The Mullard/Philips Z550M is a unique tube which has been developed to satisfy the need for a decade indicator tube which can be operated directly from the low voltage electrical readout provided by transistor scalers. It requires an input signal of about 5 V at a current of about 50 μA. The form of the display is different from that of other indicator tubes. Ten figures are cut in the anode in the shape of the digits to be indicated; they are arranged in a circle, each digit being 3 mm in height. A gas discharge takes place behind one of the digits so that red light from the discharge shines through the cut away portion of the anode in the form of the digit to be indicated. The display can be quite bright, since the control circuit does not supply power to the main discharge.

The tube employs common anodes and common cathodes with ten separate trigger electrodes. The cathodes are in the form of a ring of molybdenum as shown in Fig. 10.4(a). The shaded parts of the ring are coated with a material of high work function so that they do not emit electrons under ionic bombardment. The ring thus acts as ten separate cathodes. Two other rings are mounted 3 mm above and below the cathode ring and are connected together to act as the anodes. The digits are cut out of the upper anode ring. A wire trigger passes through the lower anode ring into the hole in the cathode ring as shown in Fig. 10.4(b). A trigger electrode can be used to initiate the discharge at the

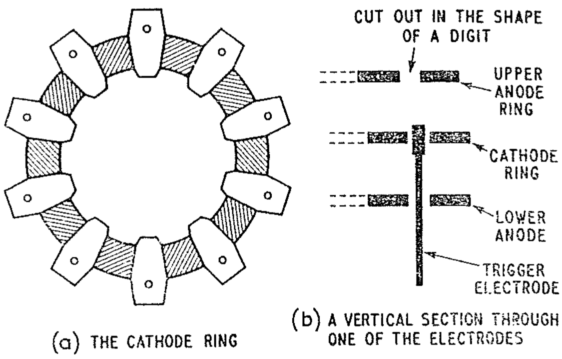


Fig. 10.4 The electrodes structure of the Z550M tube

desired position in the tube between the main anode and one section of the cathode. The tube is filled with neon containing a small percentage of argon, the total pressure being about 10 cm of mercury. Some material is sputtered from the cathode during manufacture so that the cathode surface is purified and the sputtered film which is deposited on the walls of the tube assists in the removal of contaminating gases.

The basic circuit in which this type of indicator tube can be used is shown in Fig. 10.5; for simplicity only two trigger circuits are shown. The power supply should be half wave or full wave rectified, but must not be smoothed. The trigger electrodes have a potential which is not very different from that of the common anodes provided that no discharge is taking place. A discharge between a trigger and the cathode can be initiated by a lower applied potential than is required to initiate a discharge between the anode and cathode. As the unsmoothed power supply voltage rises during a

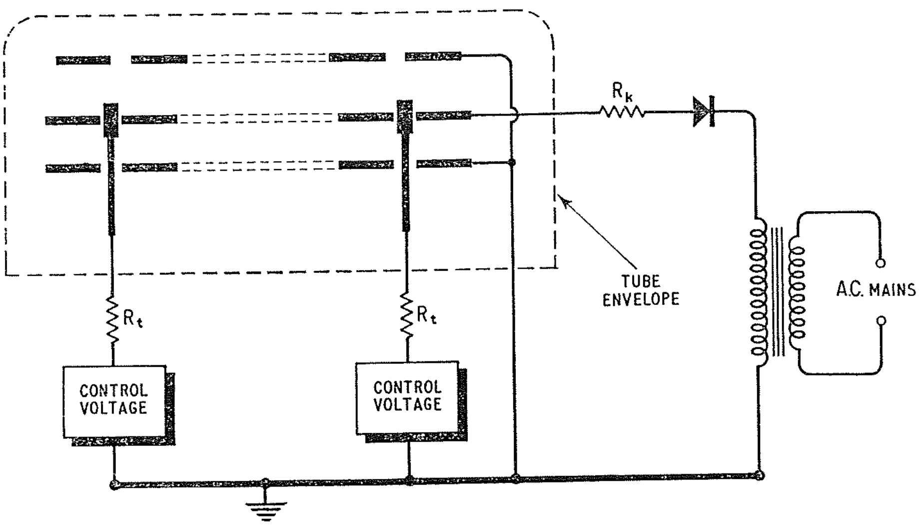


Fig. 10.5 The basic Z550M circuit

half cycle of the mains supply, a discharge will occur between the cathode and one of the trigger electrodes. If the current passing across this gap is large enough, the ions formed in this discharge will initiate a discharge between the main anode and cathode at the point at which the triggering discharge took place. The potential difference between the anode and the cathode then falls to the maintaining voltage for the tube and none of the other gaps can therefore reach their breakdown potential. The discharge ceases when the power supply voltage falls at the end of the half cycle. The process is repeated during a succeeding half cycle. Once a discharge has commenced at any point, a discharge cannot take place at any other point during the same half cycle of the power supply.

The position at which the triggering discharge occurs is controlled by the application of a small positive potential from the counting circuit to the desired trigger electrode so that the potential of this electrode is slightly higher than that of the other trigger electrodes. Its potential therefore rises to a value which is large enough to initiate a discharge before any of the other trigger gaps have reached their breakdown potential. At the next half cycle of the mains supply, the same trigger will initiate the discharge unless the counting circuit has switched the small additional potential to another trigger.

If the trigger voltage required for the initiation of an auxiliary discharge could be made exactly the same at all points in the tube, the tube could be operated by a very small control voltage. In practice, the trigger potentials required for ignition may vary by not more than 5 V and therefore the positive control voltage applied to the selected trigger electrode should not be less than this value. The differences between the ignition potentials of the various trigger to cathode gaps are minimised by the careful purification of the cathode surfaces. In addition the gas mixture is carefully chosen so that the trigger to cathode ignition potential is not strongly dependent on the electrode spacing.

The power supply frequency to the tube is quite important. It should not be so low that there is a noticable flicker. On the other hand it should not be so high that there is not enough time for a gap to deionise between cycles of the power frequency or the glow will remain at one cathode indefinitely. The control voltage, which must be applied to the selected trigger electrode, increases at power input frequencies above 500 c/s and in excess of 3 kc/s it is not possible to alter the position of the discharge.

There is some statistical delay in the ignition of a trigger to cathode gap, since each discharge must be started by the presence of an electron in a suitable position. If there is a large statistical delay in the firing of one trigger to cathode gap, another gap

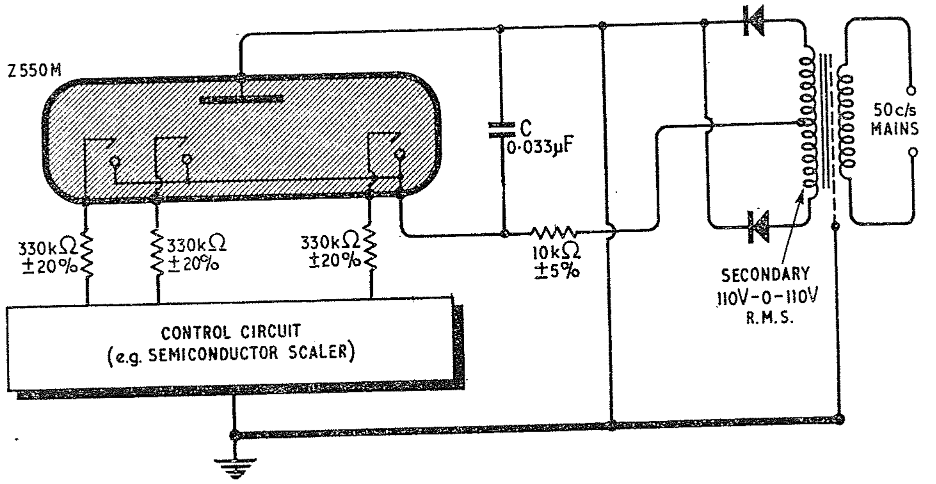


Fig. 10.6 A practical circuit for the Z550M.

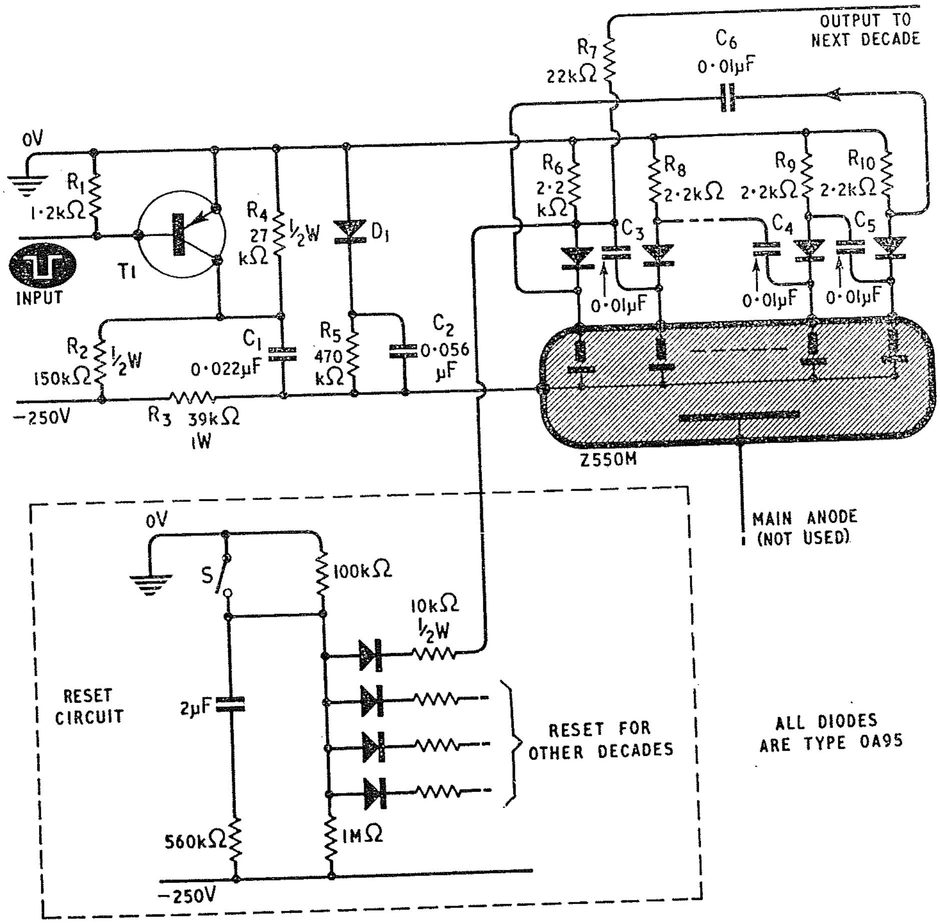


Fig. 10.7 A circuit for the operation of the Z550M as a scaler

may ignite during the delay time. This effect is minimised by the addition of a trace of radio-active gas to the tube; this gas provides electrons which can initiate the discharge. Nevertheless the power input frequency should not be too low or the gas will become almost completely deionised during the non-conducting period and this may cause a greater statistical delay in the striking of the tube.

A practical circuit for the operation of the Z550M indicator tube from a decade scaler is shown in Fig. 10.6. The scaler may employ PNPN devices in a ring circuit to provide decade electrical readout which can drive the indicator tube. If a cascaded transistor binary circuit is employed in the scaler with feedback to convert the scale of 16 to a scale of 10, some means must be provided to convert the binary readout into decade readout to drive the indicator tube. Full wave rectification is normally preferred to half wave circuits. The capacitor, C, is used to prevent any voltage spikes from affecting the operation of the tube. The cathode current should be about 3 mA and the control circuit resistance in the trigger circuits should be between 100 and 470 kΩ. A power supply of between 90 and 130 V R.M.S. (nominally 110 V) at 40 to 100 c/s is suitable. The maximum potential between any trigger and the anode should be limited to 30 V and that between the anode and the other nine triggers not being used should be limited to ± 5 V.

10.3.1 The Operation of the Z550M as a Scaler

The Z550M was primarily developed for use as an indicator tube, but it can itself be used as a counting tube for frequencies up to 1 kc/s, only one driving transistor per decade being required. The tube may be used as an indicator in high speed transistor decades and as a counter in the succeeding slower but much more economical decades; a uniform type of readout is thus obtained from all decades.

A ring circuit in which the Z550M tube is used as a scaler is shown in Fig. 10.7[9]. In this circuit the trigger electrodes are used as anodes, the normal common main anode of the tube being left unconnected. The trigger electrodes should be regarded as the anodes of ten neon diodes which have a common cathode. Although an alternating power supply is used with the tube when it is an indicator, a smoothed power supply must be employed to operate it when it is used as a scaler.

A negative going input pulse of 0.5 V in amplitude and 0.2 msec in duration applied to the base of the transistor $T1$ causes it to saturate. The amplified positive going pulse at its collector is fed via C_1 to the common cathodes of the tube. The collector of $T1$ is connected to the tapping of the voltage divider $R_2 - R_4$ in order to reduce the collector to emitter voltage applied to $T1$ to a value within the ratings of this transistor. If the input pulse has a steep trailing edge, $T1$ is cut off so rapidly that a sudden large negative change in the common cathode voltage will occur and this could result in faulty counting. This difficulty can, however, be avoided by the use of D_1, C_2 and R_5. Any sudden negative going pulse in the common cathode line merely charges C_2 via D_1. The values of C_2 and R_5 are chosen so as to ensure reliable operation of the circuit even if square wave input pulses are used. In addition, C_2 protects $T1$ against excessive transient voltages.

The tube counts on the same principle as the neon diode circuits of Chapter 3. When a positive going pulse from $T1$ is applied to the common cathodes, the trigger electrode which was passing current will be extinguished. A positive pulse of about 9 V in amplitude will occur in this trigger circuit and is capacitively coupled to the succeeding trigger electrode. This latter electrode will therefore conduct when the cathodes resume their normal potential at the end of the input pulse. The coupling in the reverse direction is not appreciable, since the coupling capacitor concerned is discharged via the two trigger resistors and a forward biased diode.

When the zero trigger gap strikes, a negative going pulse is produced at the output which is suitable for the operation of a succeeding identical decade. It is not essential to employ components corresponding to D_1, C_2 and R_5 in any decade after the first, since pulses derived from a preceding decade have a suitable shape for the operation of a Z550M tube. When S is closed momentarily, a positive going resetting pulse is fed to the zero trigger electrode of all decades. The amplitude of this pulse is great enough to cause a current to flow in the zero trigger and cathode circuit which will increase the common cathode voltage to a value at which a discharge at any other trigger electrode will be extinguished. The diodes in the reset circuit prevent undesired coupling between the various decades.

The Z550M tube can also be used for reverse counting in the type of circuit shown in Fig. 10.8[9]; the input circuit should be similar to that of Fig. 10.7. For forward counting the line marked '*F*'

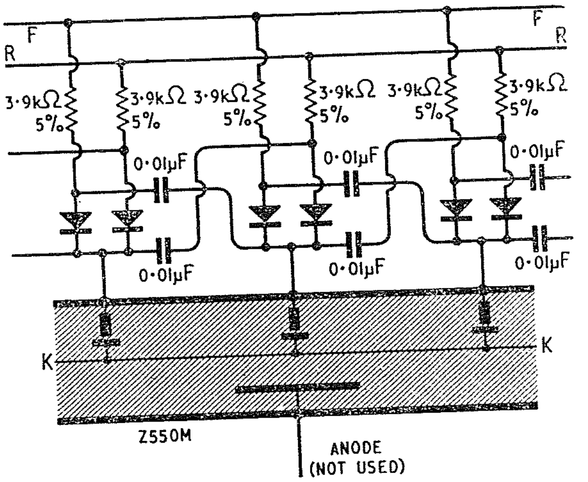


Fig. 10.8 The Z550M used in a reversible counting circuit

should be at least 15 V positive with respect to the line marked '*R*', but for reverse counting the polarities of these lines should be reversed. In either case the input pulses should be positive going and are applied to the common cathode line, *K*. If the line '*F*' is more positive than the line '*R*', the conducting trigger electrode will take its current from the '*F*' line and the diode connecting that trigger with the '*R*' line will be reverse biased. The additional components therefore have little effect on the counting which proceeds in the forward direction as in the circuit of Fig. 10.7. If, however, the '*R*' line is positive with respect to the '*F*' line, the trigger electrode current will be taken from the '*R*' line and counting will occur in the reverse direction.

In the reversible counting circuit of Fig. 10.8 the trigger electrodes are loaded by an extra capacitor and resistor; the pulses coupled from a preceding stage are therefore attenuated somewhat. For this reason the resistance values chosen should be rather higher than those used in the circuit of Fig. 10.7 and should be of close tolerance. The common cathode resistor (not shown in Fig. 10.8) should have a value of 47 kΩ, ±2% (compare with R_3 of Fig. 10.7). The value of the voltage supply to this cathode resistor should be −210 V ±2% with respect to the line '*F*' for forward counting or with respect to line '*R*' for reverse counting.

10.4 ELECTROLUMINESCENT READOUT

Electroluminescence occurs when a suitable phosphor is excited by a changing electric field so that it emits light. A thin layer of the phosphor in a suitable dielectric (e.g. polystyrene) is placed between two conducting films (one of which is transparent) and the three layers are attached to a suitable base such as a sheet of glass or metal for mechanical support.

When an alternating potential is applied between, the two conducting layers of the 'photo-capacitor's the phosphor emits light which passes through the transparent conducting film. The brightness and colour of the emitted light depend on the composition and thickness of the phosphor, the amplitudo and frequency of the applied voltage and the temperature[10]. Such electroluminescent panels can be used for lighting purposes. The maximum amount of light which can be obtained from a given area of the phosphor is limited by the dielectric breakdown which occurs at high applied potentials.

The frequency of the applied voltage is important, since its affects the colour and the amount of light. The frequency of the emitted light is twice the frequency of the applied potential, but at higher frequencies the light output does not fall to zero between half cycles of the applied voltage. An increase in the frequency of the power input increases the number of times per second the charge of the capacitor is reversed. Hence an increase of power frequency increases the light output, but if the frequency is raised above about 1 kc/s the life of the phosphors being produced at present is reduced[11].

In order to display digits, the back electrode of an electroluminescent panel may consist of ten strips

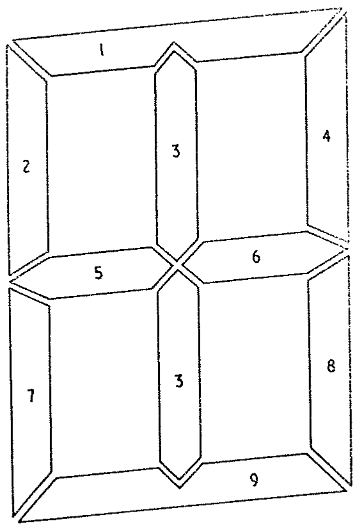


Fig. 10.9 The elements of a numeric panel

as shown in Fig. 10.9[11]. This is known as a numeric display, since it is mainly intended for indicating numbers. The two strips marked 3 are connected together. The transparent conducting film acts as a common electrode for all ten strips. If selected combinations of the back electrodes are employed at any one time, any chosen digit can be indicated. For example, if the electrodes 1, 4, 6, 5, 7 and 9 are used, the digit two is indicated. If all the electrodes except those marked 3 are employed, the digit indicated is eight. Some letters can be formed using this type of display. For example, if the power supply is connected between the common transparent front electrode and the electrodes 7, 2, 1, 4, 8, 5 and 6, the letter *A* is indicated. Some letters, such as *K*, *R*, *V*, etc. cannot be formed by the use of this simple pattern of electrode strips.

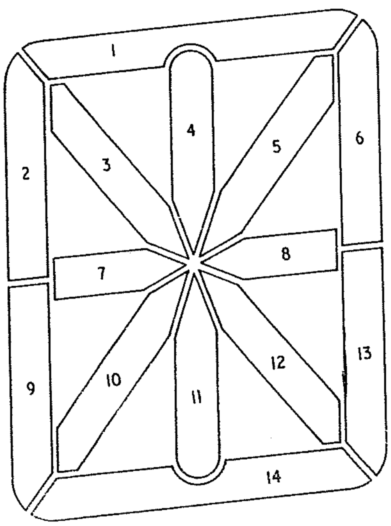


Fig. 10.10 The elements of a typical alpha numeric panel

The Ericsson Telephones 'Phosphotron' indicators types P22 and P23 employ the electrode pattern of Fig. 10.9 and indicate digits 1 in. high. These indicators require a 240 V R.M.S. supply at a frequency between 50 and 800 c/s. The current taken per electrode increases from 10 to 80 μA and the surface brightness from 1 to 8 ft-lamberts as the frequency increases from 50 to 400 c/s. These display elements can be made virtually as large as desired; the Sylvania Company produce numeric indicators varying in size from $\frac{3}{8}$ to 10 in.

A slightly more complicated indicator employing more electrodes can be used to indicate any digit or any letter of the alphabet in addition to various other signs. The pattern of electrodes which may be used is shown in Fig. 10.10[12]. This type of pattern is known as an alpha numeric display. The letter W, for example, can be formed by using the strips 2, 9, 14, 11, 4, 13 and 6. Such indicators are available from the Sylvania company for displaying digits up to 10 in. high. A 'Phosphotron' of a similar pattern (type P40) is available from Ericsson Telephones Ltd. and indicates any digits or letters 4 in. high[11]. This indicator employs two more electrodes than those shown in Fig. 10.10; they are placed at the upper and lower left-hand corners of the display. The P40 alpha numeric panel is used in the Ericsson Telephones relay decade counter unit type LJEQ 11/40 for readout.

Electroluminescent digital indicators have the advantages that they can be viewed from a very wide angle, occupy a very small volume, generate a negligible amount of heat and can be obtained in forms which display various colours and symbols of many types. Their main disadvantage is the complexity of the switching which is required to operate them. A transistor inverter is normally employed to provide the power supply for the operation of electroluminescent indicators, as the surface brightness of an indicator supplied with power directly from the 50 c/s mains is not normally adequate for use in an undarkened laboratory.

The difficulty of switching the elements of the luminescent digital indicators may be overcome in the following way. The input signal is used to light one of ten luminescent strips in a separate unit. The light developed passes through certain holes in a mask and falls on parts of a photoconductive matrix. The parts of this matrix which conduct determine which elements of the separate numeric display will glow and hence which digits will be indicated. Similar combinations of electroluminescent panels, a dark mask and a photoconductive matrix can be used for converting binary information to the decimal form and vice-versa[12]. Combinations of electroluminescent and photoconductive devices can also be used in various types of logic and information storage circuits.

It appears that electroluminescent devices will find considerable application in counting equipment in the future, especially if a large clear display is required.

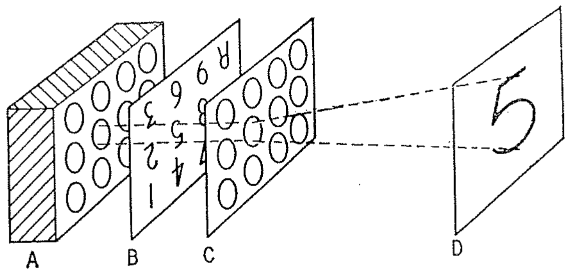
10.5 LOW POWER DIGITAL READOUT

Meter readout has the advantage that very little power or potential difference is required to operate it. This type of readout is therefore very suitable for use with transistor scaling circuits, no readout amplifiers being required. Errors can, however, easily be made in reading the state of the count from this type of analogue display. If, however, the meter needle is replaced by a film strip containing the ten digits and a suitable optical projection system is employed, digital readout can be obtained. When the current passing through the moving coil of the instrument changes, the film moves and the digit projected onto the screen is altered. This type of readout can provide a large and brilliant display. It has the advantage that it is operated from staircase waveforms and can therefore be used with almost any type of counting circuit.

A typical example of an indicator of this type is the Weston S462 digital indicator. The full scale deflection is 500 μA $\pm 10\%$, but indicators with higher sensitivities can be designed. The digit nine should be adjusted so that it is in the centre of the screen when the full scale current is passing through the coil; the other digits will then be in their correct positions when the appropriate proportion of the full scale current is being passed through the coil. A 6.3 V, 2 W lamp is used in the Weston system which projects a digit 1·25 in. high and can be viewed from about 30 ft. If a number of the indicators are placed side by side for a multidecade display, a single front screen may be used. Provision is made for a lamp to be fitted to each indicator to show the position of the decimal point. Indicators for various symbols are also available to show the units of the quantity being indicated.

10.5.1 Multi-Lamp Projection Systems

A method which can be used to obtain in-line digital readout from a number of lamps is shown in Fig. 10.11. One of the filament lamps at *A* illuminates the corresponding digit at *B*. The light passes to



10.11 A digital projection system

the appropriate projecting lens at *C* which forms an image of the digit on the screen at *D*. The whole unit is placed in a suitable enclosure. This method of readout can produce large clear digits on a flat screen. It is, however, normally necessary to employ a relay to switch on each of the lamps which normally have a rating of about 2 W. Projection instruments occupy a larger volume than most other readout devices.

Multi-lamp projection indicators are available from Counting Instruments Ltd. for digits $\frac{5}{8}$, 1 or $3\frac{3}{4}$ in. high in any chosen colour. Other symbols and words may also be indicated. Similar units are available from the Burroughs Corporation.

10.5.2 Numeric Pattern with Indicator Bulbs

Another form of digital in-line display involves the use of a numeric pattern indicator such as that of

Fig. 10. 9 in which each strip is cut out from a mask and is illuminated by a filament or neon bulb placed behind it. The pattern may be simplified somewhat by the omission of the strips marked 3 and by replacing the strips marked 5 and 6 by a single strip. This reduces the number of bulbs required to seven. If neon bulbs are employed, a matrix of resistors may be used to cause the appropriate neons to ignite when the matrix is fed with a suitable decade electrical readout of 150–250 V amplitude(13). A slightly different form of readout may be used to operate the neons from a binary counting circuit(14).

Recently gallium phosphide lamps have been used in numeric indicators(15). Each line of the display consists of a number of the gallium phosphide diodes connected in parallel. The emitted light is red in colour. Although the diodes are ideal for use in solid state circuitry, since they are small, reliable and operate at small voltages and currents, they are not yet cheap enough for arrays of them to be employed in commercial instruments. The forward voltage drop across these diodes is only about 1.9 V.

10.5.3 Plate Type Indicators

Another type of digital indicator employs ten transparent plates mounted closely behind one another. The plates are normally made of plastic material, one digit being engraved on each plate. Ten filament lamps are placed so that any plate can be floodlit from the side by one of the lamps. The digit engraved on this plate will then be visible from the front through the other plates as a large number of small points of light. Such indicators provide a good clear display on a flat screen without the use of any projecting lenses. They can be viewed from a fairly wide angle and have the advantage that they occupy a smaller depth than systems which employ projection methods. A variety of plate type indicators are available from K.G.M. Electronics Ltd. for displaying digits and other symbols.

The Burroughs Corporation have published a report(16) giving details of an investigation they have carried out to determine the legibility of various types of digital readout display from a distance and from an angle.

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