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A STUDY ON THE TRIGGERING OF A PLATE-COUPLED MULTIVIBRATOR BY NEGATIVE PULSES*

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(*Received for publication, July 5, 1952*)

Plates XXII A-B

ABSTRACT. A study has been made on the triggering of the plate-coupled multivibrator by negative pulses. It has been observed that the voltage forms of different electrodes of such a multivibrator are markedly influenced by the form of the input pulses. In general, the triggering of such a multivibrator depends largely on the amplitude of the input pulse. It has been observed that triggering is more perfect by small amplitude pulses than by those of larger amplitudes, which is contrary to the general concept of triggering such a plate-coupled multivibrator. These are inherent characteristics of such a circuit, and the coupling valve is mainly responsible for it. Oscillograms of the voltage forms of different electordes of the multivibrator have been presented.

A mathematical analysis of the transient characteristics of the multivibrator for different types of input pulses has been given The theoretical curves have been plotted and it has been shown that these curves fit well with the oscillograms.

INTRODUCTION

Multivibrator circuits now a days are used widely and mostly in timing circuits. There are different types of multivibrator circuits in use. The authors had the opportunity of closely studying the driven plate-coupled multivibrator which was utilised in producing delays between two signals from G-M counters to study the short-lived metastable states in titanium (46) (Nag, Sen and Chatterjee, 1949)

EXPERIMENTS AND THE OBSERVATIONS

A detailed investigation has been made on the triggering of a plate-coupled multivibrator by negative pulses and the following observations were made therefrom.

(1) The different electrode voltage forms of the multivibrator are markedly influenced by the form of the input pulses.

(2) In general, the triggering of the multivibrator depends largely on the amplitude of the input pulse.

*Communicated by Prof. M. N. Saha, F.R.S.

(3) The value of the coupling condenser C_2 in figure 1 has much to alter the performance of the multivibrator.

(4) These are inherent characteristics of such a multivibrator circuit and the coupling valve is mainly responsible for it.

The experimental arrangement is shown in figure 1. A negative pulse from a pulse generator, (Banerjee, 1945) at the input of 6 AK 5 (coupling valve) is one stage amplified and applied to the grid of T_2 through the

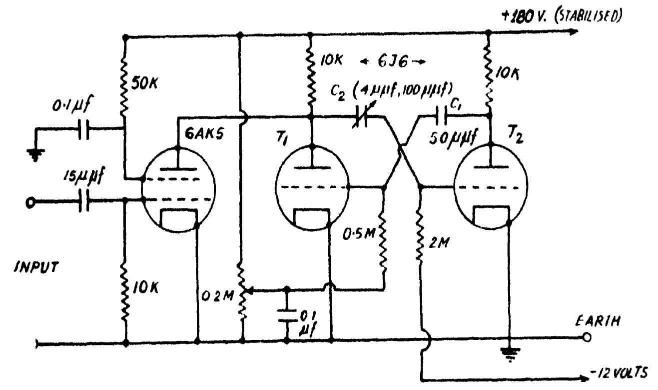


FIG. 1

Circuit dirgram of the driven plate-coupled multivibrator.

condenser C_2. The grid of T_2 is returned to a negative voltage (−12 volts) so that initially T_1 is non-conducting. With the arrival of a positive pulse at the grid of T_2, T_2 becomes conducting and its plate-point voltage decreases. This decrease of anode potential of T_2 is transmitted through C_1 to the grid of T_1 (returned to positive voltage), whose anode potential then rises. The rise of T_1 anode potential is again transmitted to the grid of T_2 and the action is cumulative with the result that T_1 becomes non-conducting and T_2 fully conducting.

This cumulative or regenerative switching action, which ends with the plate current of T_1 reduced to zero and that of T_2 increased to a maximum, takes place extremely rapidly, in a small fraction of a microsecond in a well-designed multivibrator and in our theoretical discussion we shall assume this switching action to be instantaneous.

The positive pulse at the grid of T_2 cannot cause the switching action to start if it is not large enough to raise the grid potential of T_2 above cut-off and cause current to flow in the plate of T_2.

At the end of the switching action C_1 will begin to discharge so that the grid voltage of T_1 will begin to rise exponentially so much so that the cut-off bias voltage of T_1 is reached, T_1 begins to conduct and reverse regenerative switching process takes place by which T_1 again becomes conducting and T_2 non-conducting. This switching process is also extremely rapid so that the process may also be assumed to be instantaneous for theoretical discussions.

Now, when T_1 has again become conducting instantaneously, a high negative voltage is transferred to T_2-grid. Since the grid of T_2 is returned to 12 volts negative, it cannot remain permanently at the high negative voltage and hence the condenser C_2 will discharge to —12 volts exponentially. Thereafter the multivibrator tubes come to their original states and these states will continue to persist unless another negative pulse arrives at the input of 6 AK 5.

The grid of 6 AK 5 is normally at zero potential. The plate voltage of 6 AK 5, when both 6 AK 5 and T_1 are conducting initially, is 75 volts. Now, as a negative pulse is applied to the grid of 6 AK 5, generally both 6 AK 5 and T_1 are simultaneously made non-conducting and condenser C_2 begins to charge. While the condenser is charging, the grid of 6 AK 5 falls to zero as the input pulse terminates. This makes 6 AK 5 conducting and the plate voltage of 6 AK 5 consequently comes down. Since T_1 is still non-conducting, the plate voltage of 6 AK 5 which is also the plate voltage of T_1, finally comes down to a voltage higher than it was when both the tubes were conducting. Under this condition the condenser C_2 will be experiencing simultaneously two changes of voltages, a growth of voltage due to charging as T_1-plate current is cut-off and a decay of voltage as 6 AK 5 is made conducting. Consequently, the actual voltage across the condenser will be the resultant of these two.

The plate current of 6 AK 5 may not always become zero when a negative pulse is applied at the grid of 6 AK 5. If the amplitude of the input pulse is big enough, then only 6 AK 5 will be non-conducting and the plate voltage of T_1 may rise to its highest voltage. In all other cases, when the amplitude is small, there remains always in the plate of 6 AK 5 a current although T_1 is non-conducting.

Oscillograms have been taken of the voltage forms of the different electrodes of the multivibrator with input pulses of various amplitudes and are represented in figures (*i*)-(*iv*) in Plates XXII A-B.

The photographs have been taken on a Cossor double beam oscilloscope (Model No. 1035). Input pulses have been applied to one beam and the electrode voltages of the multivibrator to the other. The multivibrator electrode voltages were not directly applied to the vertical plates of the oscilloscope but through a cathode follower circuit so that actual voltage forms are not changed during recording.

Small Amplitude :

Figures *i* (*a*), (*b*) and (*c*) [Plate XXII A] show the anode voltage of T_1, anode voltage of T_2 and the grid voltage of T_1 respectively with $C_2 = 4\mu\mu F$ and input pulses are hown in each photograph. In this case the input pulse amplitude is not big enough to completely cut-off the plate current of 6 AK 5, though the T_1-plate current is zero. With $C_2 = 4pF$, the charging time is small so that very soon after T_1 is made non-conducting C_2 is fully charged and the anode voltage of T_1 is raised to a high voltage near the supply voltage (not equal to the supply voltage because 6 AK 5 was not completely non-conducting ; it still had a plate current). Generally the anode voltage of T_1 should remain constant at this value as long as T_1 grid is held negative beyond its cut-off value. But although T_1 is still non-conducting, 6 AK 5 is highly conducting because the grid of 6 AK 5 rises at the end of the input pulse, finally becoming zero. Consequently, the anode voltage of T_1 will come down.

Figure *i* (*b*) shows the anode voltage form of T_2 while figure *i* (*c*) that of T_1-grid voltage. It will be seen that the forms of these electrode voltages are similar.

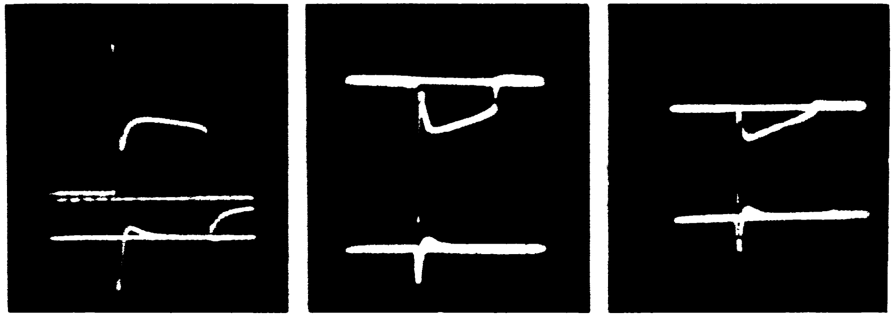
Figures *ii* (*a*), (*b*) and (*c*) [Plate XXII A] show the T_1-anode voltage, T_2-anode voltage and T_1-grid voltage respectively with the same input pulse as before, but now $C_2 = 100pF$. In this case the charging time is very large so that long time after T_1 is made non-conducting, the condenser C_2 is charged to its full voltage. In the meantime since the grid of 6 AK 5 has been driven positive, the plate voltage of T_1 has come down. This time it will be observed that the kink in the plate voltage of T_1 is below the flat portion of the square top pulse and that the kink is less pronounced although the input pulse is the same as before. This can be explained as below.

Since C_2 is large, the charging time is long so that long before the condenser has been charged to its full voltage, the grid of 6 AK 5 is driven positive and therefore the kink appears in the lower portion of the voltage form. Also when 6AK5 has been made less conducting by the negative drive of the grid of 6AK5, the plate voltage of T_1 could not rise much from its initial value because of the large time constant and so the kink is not so pronounced as before. In the previous case, T_1-plate voltage reached the maximum value within a very short time and came down right from there when 6 AK 5 was again made conducting.

Large amplitude :

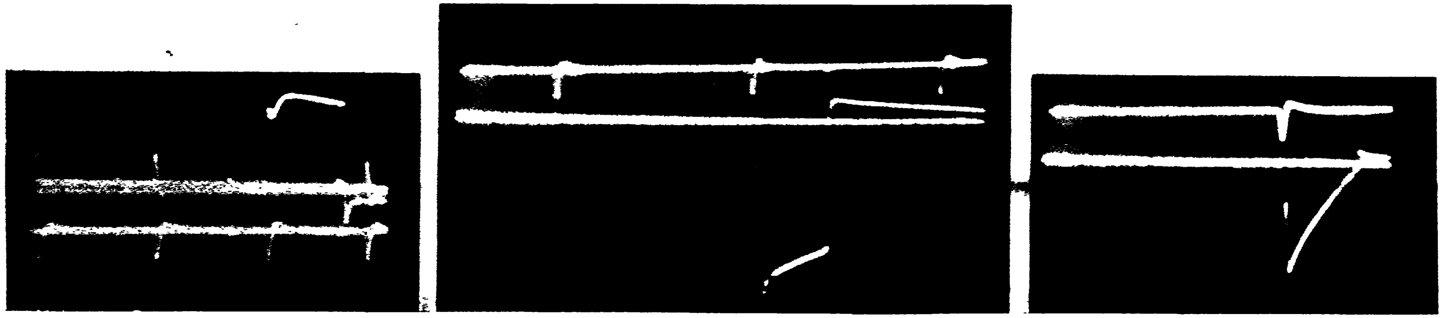
Figures *iii* (*a*), (*b*) and (*c*) [Plate XXII B] represent the anode voltage of T_1, anode voltage of T_2 and the grid voltage of T_1 respectively when the input pulse is very big and $C_2 = 4pF$. From the figures it will be observed that the output pulses are not like those from a multivibrator. Further, it was noted that changing the grid voltage of T_1, there was no appreciable change of the pulse width. At the first sight it will appear that the multivibrator did not trigger. But this is not so because the other electrode voltages have also been photographed under the same condition and shown in figures (*iii*)

Fig *i*



a *b* *c*

Fig. *ii*



a *b* *c*

Voltage forms at different electrodes

Fig. *i*: $C_2 = 4\mu\mu F$

Input pulse—sharp and small amplitude shown at the bottom

(*a*) T_1 - plate voltage ; (*b*) T_2 - plate voltage

(*c*) T_1 - grid voltage

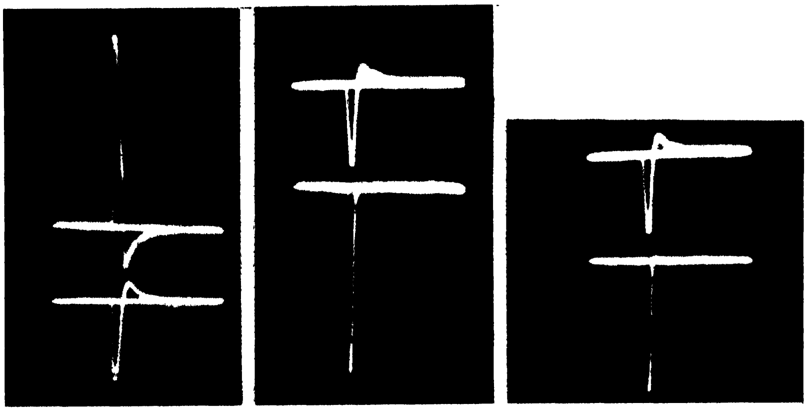
Fig. *ii*: $C_2 = 100\mu\mu$

Input pulse—sharp and small amplitude shown at the bottom in (*a*) and at the top in (*b*) and (*c*).

(*a*) T_1 - plate voltage ; (*b*) T_2 - plate voltage

(*e*) T - grid voltage

Fig. iii



C_2=4μμF

Input pulse—sharp and big amplitude shown at the bottom in (*a*) and at the top in (*b*) and (*c*).

(*a*). T_1 - plate voltage ; (*b*). T_2 - plate voltage ; (*c*). T_1 - grid voltage.

Fig *iv*

C_2=4μμF

Input pulse - wide and big amplitude shown at the bottom.

T_1 - plate voltage.

(*b*) and (*c*) which suggests that with the arrival of a negative pulse at the input of 6 AK 5, both 6 AK 5 and T_1 are made non-conducting as well as T_2 conducting. This behaviour of the multivibrator circuit can be explained with the help of figure 1. As the input pulse amplitude is very big, the rise of anode voltage is also greater than before, because previously, the input pulse amplitude was not big enough to completely cut-off the plate current of 6 AK 5 and as such let T_1 -anode voltage rise further. So the negative voltage transferred to T_2 grid through C_2, when the plate of 6 AK 5 comes down at the end of the input pulse is also greater. The result is that T_2 -anode voltage rises back too high to be transferred to T_1 -grid through C_1 to drive it towards zero voltage. Since this positive drive of T_1 -grid is large enough to take the T_1 -grid on the positive side of its cut-off bias value, this will result in changing from its non-conducting to conducting state and thus switching off the current from T_2 to T_1 rather abruptly. If we now compare figures *ii* (*b*) and (*c*) we find that positive drive of T_1 -grid was not sufficient to take it beyond cut-off bias and that is why the states of T_1 and T_2 were not disturbed. It can also be observed from figure *iii* (*a*) that the output form of T_1 -anode voltage is unlike that of the input pulse and it shows definite sign that the multivibrator becomes unstable abruptly.

Under the same condition (with big input pulse) triggering occurs when the condenser C_2 of $4pF$ is replaced by a large value condenser, $C_2 = 100pF$. This is due to the fact that when 6 AK 5 and T_1 are made non-conducting, the plate voltage of T_1 cannot rise faster, so that in the meantime, the grid of 6 AK 5 is driven positive making it conducting. The resultant negative pulse transmitted to grid of T_2 is, therefore, not big enough to make it much negative.

Figure *iv* shows the anode voltage form of T_1 when the input pulse is much broader and large in amplitude. It will be noticed that the widths of both the input pulse and the multivibrator output pulse are equal. Actually, the width of the multivibrator pulse ought to have been greater than this. But since the amplitude of the input pluse is large, T_1 has been forcibly brought down to its original state by the positive drive of the input pulse proving that the output pulse is not at all independent of the input pulse.

SUMMARY AND DISCUSSION OF EXPERIMENTAL RESULTS

The output voltage forms of the multivibrator are not completely independent of the form of input pulses. As the coupling valve is conducting even when T_1 is non-conducting, the plate voltage of T_1 can never remain constant at the supply voltage. The quiescent voltage of the non-conducting tube (T_1) is then equal to the voltage at which 6AK5 remains conducting. The use of pentode instead of a triode as the coupling valve ensures plate current to be constant inspite of the plate voltage changing when T_1 goes from conducting to non-conducting state.

In general, triggering of the multivibrator depends largely on the amplitude of the input pulse. If the initial plate current of 6 AK 5 is small, then with very small input pulse, it will be easily made non-conducting and very small pulses may not trigger the multivibrator at all. If, however, the screen voltage of 6 AK 5 is such that it initially draws a large plate current, the multivibrator may be easily triggered by very short pulses. But difficulties are being encountered when the input pulses are big. With big input pulses, the change of plate current is greater than that with the small pulses so that when 6 AK 5 grid is driven positive at the end of the input pulse, the output pulse amplitude of 6 AK 5 may be big enough to switch the current from T_2 to T_1, bringing the multivibrator to its original state. These are all inherent characteristics of the plate-coupled multivibrator driven by negative pulses and the coupling valve is mainly responsible for them. The phenomena are pronounced when the coupling valve is sharing a large current although the multivibrator can be triggered by very small input pulses in this condition. When the plate current drawn by 6 AK 5 is very small, the phenomena are not so pronounced but at the same time it cannot be triggered by short amplitude pulses.

Thus, in general, when the input pulses have different amplitudes as those from a photomultiplier, one cannot be sure that the multivibrator is triggered by pulses of all amplitudes. In that case the pulses may have to be equalised before applying them to the input of 6 AK 5.

It has been observed that by making C_2 larger, it may be possible to trigger the multivibrator with large amplitude pulses of very short duration when 6 AK 5 is drawing large plate current. Because, due to large charging time of C_2 the plate voltage of 6 AK 5 may not rise much and in the meantime the grid of 6 AK 5 is already driven positive.

All these effects will not be observed in the case of the plate-coupled multivibrator driven by positive pulse. Since in that case, normally the coupling valve and T_1 are non-conducting while T_2 is conducting. When a positive pulse is applied to 6 AK 5 input, it becomes conducting and by cumulative effect, T_1 becomes conducting and T_2 non-conducting simultaneously. At the first impulse, the grid of T_2 is driven to a large negative voltage after which C_2 begins to discharge. The tube T_2 remains non-conducting so long the grid of T_2 is beyond its cut-off bias voltage. Thus under this condition when 6 AK 5 is again non-conducting at the end of the input pulse (in this case the grid of 6 AK 5 is driven negative to its original voltage when the input pulse vanishes), the grid voltage of T_2 is suddenly driven positive but not beyond its cut-off bias so that T_2-anode voltage is unaffected. As a result, the conditions of T_1-anode voltage, T_2-anode voltage as well as of the grid voltage of T_1 remain unchanged.

THEORETICAL ANALYSIS

It has been shown earlier that the height and width of the negative pulse at the input of 6 AK 5 have considerable effect on the triggering of the plate-coupled multivibrator.

We shall now proceed to consider the effect of the following negative pulses at the input of 6 AK 5 on the triggering of the multivibrator on theoretical basis :

(*i*) Narrow and very short pulses that cannot make 6AK5 non-conducting.

(*ii*) Narrow and short pulses that cannot make 6AK5 non-conducting but trigger the multivibrator.

(*iii*) Narrow pulses of such height as to make 6 AK 5 non-conducting.

(*iv*) Narrow and big pulses.

In group (*i*), pulses of such size come which cannot make the triggering possible. If the input negative pulse is very small, the plate current of 6 AK 5 will not very much diminish so as to increase the plate voltage of 6 AK 5 *i.e.* that of T_1 and thus the grid voltage of T_2 above its cut-off value. So T_2 will not conduct and thus triggering is not possible.

If the pulses are so large as not to make 6 AK 5 non-conducting but to increase the plate valtage of 6 AK 5 to such a magnitude that causes the grid voltage of T_2 to rise above its cut-off value, the triggering is possible. This type of pulse comes in group (*ii*).

In group (*iii*), lie those types of pulses which make 6 AK 5 non-conducting but the non-conducting period is very small compared to the actual time-period over which T_2 remains conducting. We shall first of all, consider this type of pulse for our theoretical analysis.

To make the analysis clear and simple we consider first the effect of a negative pulse (figure 2) at the grid of 6 AK 5. During the time interval $t=0$ and $t=t_1$, the plate current of 6 AK 5 is zero, assuming of course that the grid of 6 AK 5 is driven to maximum negative voltage instantaneously. In general, 6 AK 5 will be again conducting at $t \geq t_1$ reaching the phase of full conduction at $t=t_2$.

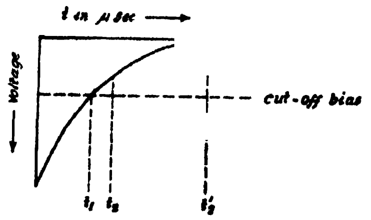


FIG. 2

Between time $t=t_1$, and $t=t_2$, however, the plate current of 6AK5 is very small so that for our theoretical analysis we shall consider the period of actual conduction of 6AK5 to be between $t=t_2$ to $t=t_2'$. Here t_1 denotes the time at which the grid voltage of 6AK5 attains just the cut-off bias voltage while t_2 denotes the time after which the grid attains such a value as to enable 6AK5 to draw appreciable current for its proper functioning.

(a) *Transient plate-point voltage of* T_1: Now when considering the plate voltage of T_1, we shall assume that the plate currents of both 6AK5 and T_1 are cut-off instantaneously, though actually a small fraction of a microsecond elapses during the process. As the plate currents are cut-off for the period $0<t<t_1$, the equivalent circuit when considering the plate-voltage of T_1 is given by figure 3. By applying Thevenin's theorem, figure 3 may be simplified to figure 4,

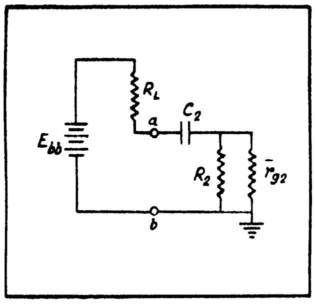


FIG. 3

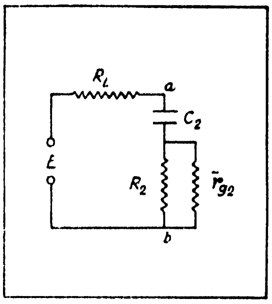


FIG. 4

R_L = plate-load resistance.
C_2 = interstage coupling condenser.
R_2 = grid leak resistance of T_2
$\bar{r}_{g2}$ = conducting resistance between the cathode and grid of T_2 (when T_2-grid is driven positive).

The effect of inter-electrode capacitances and stray wiring capacitances at the output of T_1 has been neglected in the above figures because the conducting resistance ($\bar{r}_{g2}$) between the grid and cathode of T_2 is of very small value.

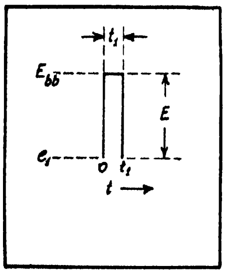


FIG. 5

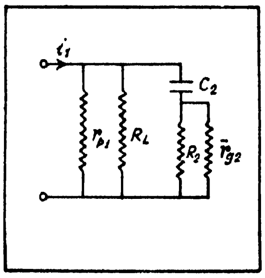


FIG. 6

Figure 5 represents the voltage step at the input of the circuit of figure 4 while the amplitude of the voltage step during $0<t<t_1$ is given by $E=E_{bb}-e_1$ where E_{bb} = supply voltage and e_1 is the plate-point voltage when both 6AK5 and T_1 are conducting.

When 6AK5 begins to conduct between $t=t_1$ to $t=t_2'$ the equivalent circuit is as given in figure 6. The time period between $t=t_1$ to $t=t_2'$ may be again divided into two parts viz. (1) $t=t_1$ to $t=t_2$ when 6AK5 draws negligible current and (2) $t>t_2$ when 6AK5 reaches gradually the phase of full conduction and the current of 6AK5 has reached a steady value.

For the first part *i.e.* during the period $t_1<t<t_2$, the plate current of the pentode 6AK5 is negligible and the plate resistance r_{p1} is very large compared to R_L so that circuit of figure 6 is simplified to that in figure 7 where $i_1=0$ and R_2 has been omitted since the conducting resistance r_{g2} is very small compared to R_2.

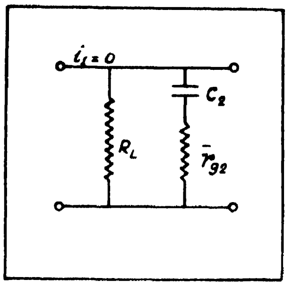


FIG. 7

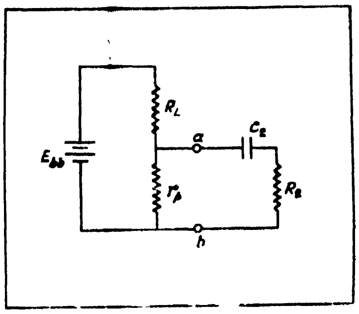


FIG. 8

The plate-voltage of T_1 during the period $t>t_2$ will be dependent on the change of T_1-plate voltage during $t_1<t<t_2$ and two cases may be considered here.

Case (a): *C_2 of small value*: It will be shown later (eqn.2) that for small value of C_2 (say, 4 *pF*), the T_1-plate voltage will diminish considerably in the time $t_1<t<t_2$ and as such the grid of T_2 will be driven towards negative voltage not to draw any grid current. r_{g2} then may be taken open and thus the equivalent circuit for the period $t>t_2$ becomes as shown in figure 8.

When C_2 is big (say, 100 *pF*), the T_1-plate voltage will not change appreciably during time $t_1<t<t_2$ and consequently T_2-grid voltage will not come down to such an extent as to stop the grid current altogether ; the grid current will, however, be decreased so that r_{g2} will be large. But r_{g2} will still be small compared to R_2 and the equivalent circuit in this case for $t<t_2$ will be as shown in figure 9.

The plate resistance r_p of 6AK5 which is a pentode, is very large compared to the load resistance R_L and assuming the internal resistance of the voltage supply to be zero, the impedances of the networks (figures 8 and 9) looking back into the terminals *a-b* are the same which may be taken to be R_L. When 6AK5 begins to conduct steadily during $t>t_2$ the plate voltage of T_1 will come down from the value E_{bb} to a lower value E_1, say, when the output *a-b* is open-circuited and the voltage across *a-b* is as shown in figure 10 where e_1 is the reference voltage equal to the plate-voltage of T_1 when both 6AK5[1] and T_1 are conducting. Norton's theorem is now

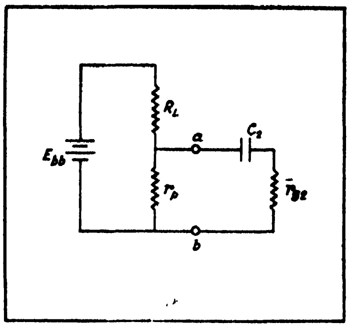


FIG. 9

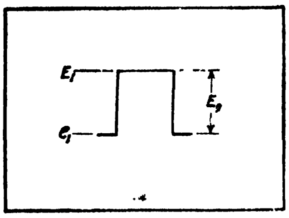


FIG. 10

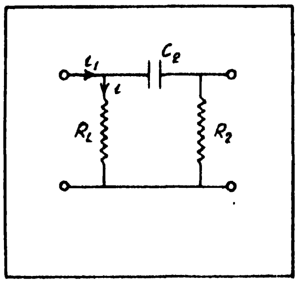


FIG. 11

applied to the circuits shown in figures 8 and 9 to obtain the simplified equivalent circuits as given in figures 11 and 12 respectively where i_1 is the short circuited current at a-b (figure 13).

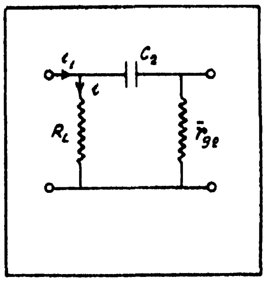


FIG. 12

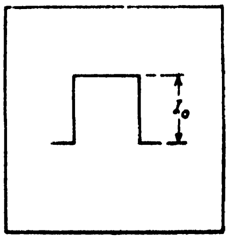


FIG. 13

The equivalent circuits (figures 11 and 12) are valid only for the time interval $t_2 < t < t_3$ where $t = t_3$ reckons the time at which T_1 again begins to conduct, or in other words, the plate current of T_1, remains cut-off from $t = 0$ to $t = t_3$. i_1 can also be analytically represented by

$$i_1 = I_0 U(t)\,;\ [t_2 < t < t_3]$$

The plate point voltage of T_1 is equal to the sum of the voltages across the coupling condenser C_2 and the grid leak resistance R_2. This voltage may now be calculated by four distinct steps :

Step 1 : $(0 < t < t_1)$. The step voltage of figure 5 is applied to the input of figure 4 Taking R_2 to be very large compared to r_{g2}, the output plate point voltage during the interval $0 < t < t_1$ has been found out to be

$$e_0 = E[1 - R_L/(R_L + r_{g2})\epsilon^{-t/(R_L + r_{g2})C_2}] \qquad \dots \quad (1)$$

Step 2 : $(t_1 < t < t_2)$. The step voltage is terminated at $t = t_1$ to form a a rectangular pulse (figure 5) so that the response across $C_2 - R_2$ combination *i.e.* across R_L is found, assuming no current flowing in the input of figure 7, as

$$e_0 = e_0(t_1)\epsilon^{-(t-t_1)/T} \qquad \dots \quad (2)$$

where, $e_0(t_1)$ = plate point voltage at $t = t_1$

and $$T = C_2(R_L + r_{g2}) \qquad \dots \quad (3)$$

Step 3 : $(t_2 < t < t_3$ (*a*) If the coupling condenser is of small magnitude, the response is obtained by assuming the small rectangular pulse (figure 13) at the input of figure 11. The plate point voltage is found out to be

$$e_0 = R_L I_0 + e_0(t_2)\epsilon^{(-t/T)}\,;\ (t_2 < t < t_3) \qquad \dots \quad (4)$$

where

$T = C_2(R_L + R_2)$

I_0 = the amplitude of the current at the input of figure 11

$e_0(t_2)$ = the plate-point voltage at $t = t_2$.

(*b*) If the coupling condenser is of large value the response is obtained by assuming the small rectangular pulse (figure 10) applied to the input of figure 12. Since r_{g2} in this step is different from that in steps 1 and 2, it will be denoted by r'_{g2}. The plate point voltage is calculated to be

$$e_0 = R_L I_0 + e_0(t_2)\epsilon^{(-t/T)} \qquad \dots \quad (5)$$

where

$$T = C_2(R_L + r'_{g2})$$

and the other constants are the same as given in equation (4).

At time $t = t_3$ the small rectangular pulse terminates and T_1 begins to conduct. The equivalent circuit for coupling between the plate of T_1 and the grid of T_2 can now be drawn as given in figure 14 where

$$e_g = \text{grid voltage of } T_1 \text{ for } t \geq t_3$$

Since R_2 is very large compared to R_L, R_2 may be taken as open and reactance of the coupling condenser is so small as to be the practical equivalent of short circuit, figure 14 can be simplified to figure 15 as shown below :

So the plate point voltage which is the voltage across R_L is

$$e_1 = -\frac{\mu R_L}{r_p + R_L}\, e_g \qquad \dots \quad (6)$$

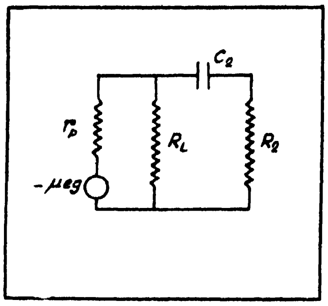


FIG. 14

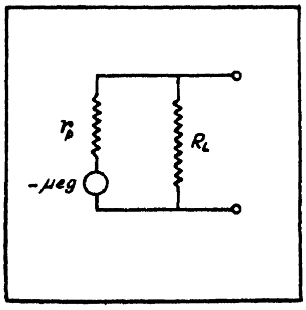


FIG. 15

We shall be able to show later that at $t = t_3$

$$e_g = \frac{R_1 R_2}{R_1 + R_2} I'_0 [\epsilon^{-t_3/T} - 1] \qquad \ldots (7)$$

Thus with the help of equations (7) and (8) we can find out the plate point voltage of T_1 at $t = t_3$ as

$$e_1 = -\frac{\mu R_L}{r_p + R_L} \cdot \frac{R_1 R_2}{R_1 + R_2} I'_0 [\epsilon^{-t_3/T} - 1] \qquad \ldots (8)$$

$$(t > t_3)$$

Step 4 : The voltage e_0 (t_3) will begin to decrease with a time constant T_1 which is equal to that with which the grid of T_1 will begin to rise. The time constant, as will be shown later, is equal to C_1 $(R_L + r_{g1})$. So the output voltage e_0 is calculated to be

$$e_0 = e_0(t_3)\epsilon^{-\frac{t-t_3}{T}} \; (t > t_3) \qquad \ldots (9)$$

The voltage waveform for the plate of the tube T_1 is now drawn with the help of equations 1 to 9 (figure 23).

Transient voltage in the plate of T_2. To analyse the plate voltage of T_2 we must form a clear picture about the current drawn by the plate of T_2 at different times of the period during which T_2 is conducting, Certain simplifying assumptions are to be made to have a not too complex analysis. First of all, R_2 is taken to be grounded and not returned to H.T. Secondly the transition time which is necessary to make the plate current of T_2 maximum is assumed to be instantaneous. Though this is not true, yet the time of switching over is very small compared to the actual time-period over which T_2 remains conducting.

The current in the plate of T_2 will remain maximum for a very short time t_1 after which 6AK5 begins to conduct and the grid-voltage of T_2 comes down.

During the interval $t_1 < t < t_2$ the grid voltage of T_2 will be reduced from its positive value and as a result the plate current of T_2 will begin to diminish sharply and so the plate resistance (r_p) of T_2 will be taken to be very large during this interval.

The coupling condenser C_1 which is moderately large, has little effect during the period between $t=0$ and $t=t_2$ when the rise and fall in the plate current of T_2 are considerably steep. The effect of the inter-electrode and stray wiring capacitances cannot be neglected during this time ; they really determine the times of rise and fall in plate point voltage of T_2.

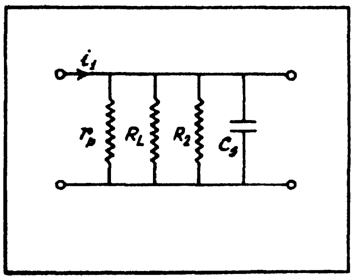


FIG. 16

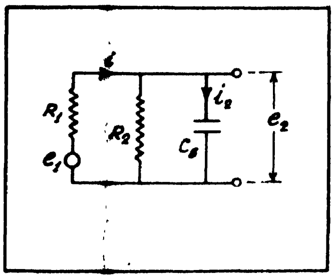


FIG. 17

The equivalent circuit during the time period $0 < t < t_1$ for the tube T_2 is as shown in (figure 16), where C_s takes into account of the stray wiring and inter-electrode capacities. If Thevenin's theorem be applied and R_1 be taken to be equivalent to the parallel combination of r_p and R_L, figure 16 can be simplified to the circuit as shown in figure 17 where $e_1 = i_1 R_1$. Since the coupling condenser has negligible effect on the output voltage e_2 during this period the plate point voltage of T_1 is the voltage across R_2 or C_s. If the voltage e_1 is taken to be a step function

$$e_1(t) = E_1 U(t) \tag{10}$$

the differential equation involving $e_1(t)$ and $e_2(t)$ is

$$e_1 \frac{R_1}{R_2} + C_s R_1 \frac{de_2}{dt} + e_2 = e_1 \tag{11}$$

Solving this equation, we have

$$e_2(t) = \frac{R_2}{R_1 + R_2} E_1(1 - \epsilon^{-\gamma t}) \tag{12}$$

where

$$\gamma = \frac{R_1 R_2}{R_1 + R_2} \cdot \frac{1}{C_s} \quad (0 < t < t_1) \tag{13}$$

The equivalent circuit for the tube T_2 during the period $t = t_1$ and $t = t_2$ is given in figure 18. Since in this interval r_p is very large and R_2 is also very large compared to the reactance of C_2, a simplified equivalent circuit of figure 18 can be drawn (figure 19). The plate point voltage of T_2 which is equal to $e_2(t)$ is now found to be

$$e_2(t) = E_{bb} - [E_{bb} - e_2(t_1)]\epsilon^{-(t-t_1)/C_S R_L} \quad \ldots \tag{14}$$

where E_{bb} = plate-supply voltage
$e_2(t_1)$ = plate point voltage at $t = t_1$.

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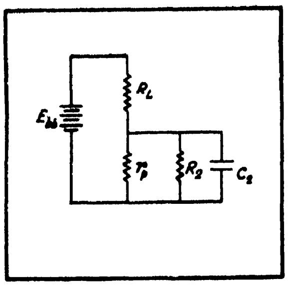


FIG. 18

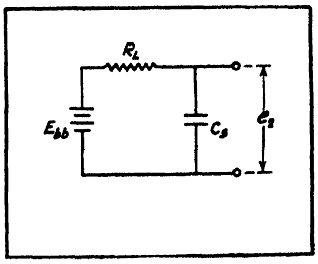


FIG. 19

After the time $t = t_2$, the plate current of T_2 reaches a steady state. Since the plate current of T_2 is then small, r_p is very large. In the reproduction of the flat top of the current pulse, which begins at time $t = t_2$, the coupling condenser C_1 plays a major part while the shunting capacitance C_S is then practically open. So the equivalent circuit for coupling between the plate of T_2 and grid of T_2 becomes as drawn in figure 20 where R_1 denotes the equivalent resistance foi the parallel combination of r_p and R_L and R_2 is the grid leak resistance of T_1.

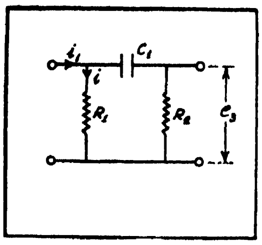


FIG. 20

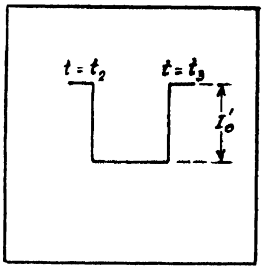


FIG. 21

The current drawn by the plate of the tube T_2 remains steady at the small value in the interval between $t = t_2$ and $t = t_3$ after which the grid of the tube T_1 rises so much as to enable T_1 to conduct and following the cumulative switching action, T_2 sharply regains its non-conducting state. So the current in the plate of T_2 may well be represented by a rectangular pulse (figure 21) beginning at $t = t_2$ and terminating at $t = t_3$, the amplitude of which is given by

$$I'_0 = -g_m e_g \qquad \ldots (15)$$

where g_m = mutual transconductance of tube which, for all purposes, may be assumed to be constant during the above mentioned period.

and $\qquad e_g$ = grid voltage of T_2

Now the current pulse may analytically be written as

$$i = I'_0[U(t-t_2) - U(t-t_3)] \qquad \ldots (16)$$

where $U(t-t_2)$ represents a unit step function beginning at $t = t_2$. If time is reckoned from $t = t_2$, equation (16) can conveniently be written as

$$i = I'_0[U(t) - U(t-t_3)] \qquad \ldots (17)$$

The plate point voltage of T_2 is the voltage across R_1. The differential equation involving the voltage e_2 and current i_1 in figure 20 is

$$\frac{de_2}{dt} + \frac{e_2}{T} = \frac{R_1 R_2}{R_1 + R_2} \frac{di_1}{dt} + \frac{R_1}{T} i_1 \tag{18}$$

where $T = C_1(R_1 + R_2)$

Solving this equation with the help of equation (7) and with the initial condition that at $t = t_2$, $e_2(t) = e'_2(t_2)$, we have

$$e_2(t) = R_1 I'_0 + e'_2(t_2) \epsilon^{-t/T} \quad (t_2 < t < t_3) \qquad \ldots \quad (19)$$

At $t = t_3$ the small current pulse is abruptly terminated. At that time the effect of the interstage coupling condenser is neglected due to the sharp change of current and so the plate voltage of T_2 is equal to the voltage that is developed across R_2 *i.e.* at $t = t_3$, the grid voltage of T_1 and the plate voltage of T_2 are exactly identical. The plate voltage of T_2 is found to be

$$e_2(t_3) = \frac{R_1 R_2}{R_1 + R_2} I_0' [\epsilon^{-t_3/T} - 1] \tag{20}$$

After time $t = t_3$, the tube T_2 is non-conducting, whereas, T_1 begins to conduct and so the eqvivalent circuit for $t > t_3$ is changed to that shown in figure 22. The small conducting resistance r_{g1} between the grid and cathode of T_1 is now put in parallel with R_2. Since R_2 is very large compared to r_{g1}, it can be omitted from figure 22. Since T_2 is non-conducting $i_1 = 0$ and so, analysing the circuit of figure 22 we obtain,

$$\frac{de_2}{dt} + \frac{e_2}{T} = 0 \tag{21}$$

where $T = C_1(R_1 + r_{g1})$

and $R_1 = R_L$

Solving this equation we have

$$e_2(t) = e_2(t_3) \, \epsilon^{-(t-t_3)/T} \qquad \ldots \quad (22)$$

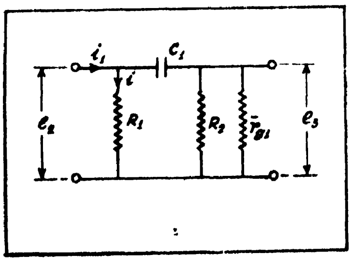


FIG. 22

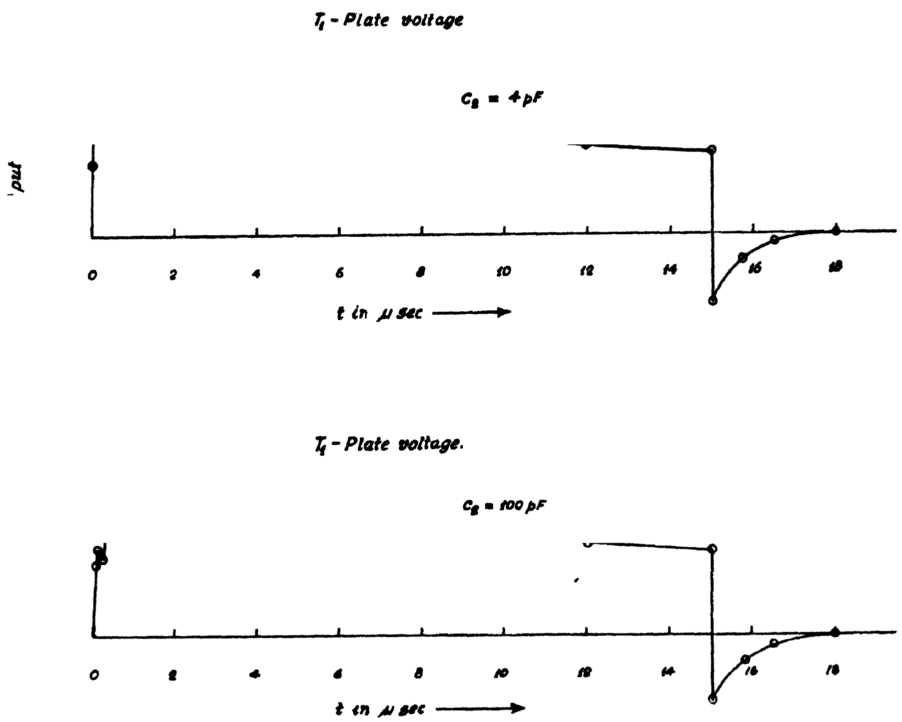


FIG. 23

The voltage waveform in the plate of T_2 is now completely specified by equations (12), (14), (19), (20), (22) and plotted in figure (24).

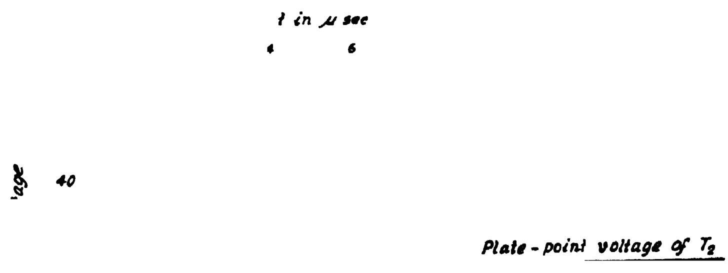


FIG. 24

Transient Voltage in the Grid of T_1. The grid voltage of T_1 will show an almost identical nature as the plate voltage of T_2 will do. The same equivalent circuits that were drawn to analyse the plate voltage of T_2, will explain the transient characteristics of the grid voltage in T_1.

Since the coupling condenser C_1 has negligible effect on the different electrode voltage waveforms during the period $t=0$ and $t=t_2$, the grid voltage of T_1 which is the voltage across C_s (figures 17 and 19), is also the voltage in the plate of T_2. So equations (12) and (14) will determine the transient voltage waveform in the grid of T_1 during the two intervals between

$$(i)\ t=0 \ \text{ and } \ t=t_1$$

$$(ii)\ t=t_1 \ \text{ and } \ t=t_2$$

After time $t=t_2$, the voltage across R_2 (figure 20) is the grid voltage of T_1. The differential equation for the circuit in figure 23 is

$$\frac{de_3}{dt}+\frac{e_3}{T}=\frac{R_1R_2}{R_1+R_2}\,\frac{di_1}{dt} \qquad (23)$$

where i_1 is given by equation (17). Solving this equation we have

$$e_3'(t)=\frac{R_1R_2}{R_1+R_2}\,I'_0\,\epsilon^{(-t/T)}; \qquad (t>t_2) \qquad (24)$$

$$e_3(t_3)=-\frac{R_1R_2}{R_1+R_2}\,I'_0[\epsilon^{-t_3/T}-1] \qquad (t=t_3) \qquad (25)$$

where $$T=(R_1+R_2)C_1$$

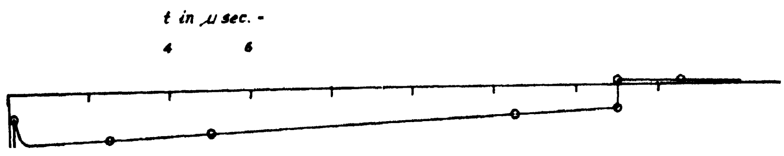
When $t>t_3$, the equivalent circuit shown in figure 22 is to be considered where $i_1=0$ and R_2 is very large compared to r_{g1}. So with the help of equation (23), the differential equation for the circuit in figure 22 can be written as

$$\frac{de_3}{dt}+\frac{e_3}{T}=0 \qquad (26)$$

Solving this, we have

$$e_3(t)=e_3(t_3)\epsilon^{-(t-t_3)/T} \qquad \ldots \ (27)$$

So the grid voltage waveform can be drawn with the help of equations (12), (14), (24), (25) and (27) (figure 25).



Grid voltage of T_1

FIG. 25

The theoretical analysis has been made for the voltage waveforms at the different electrodes of the tubes of the multivibrator when the input pulse at the grid of T_3 is of group (*iii*).

This analysis also holds good for the pulses of group (*ii*). This type of pulse can be represented by figure 26. Initially the plate current of 6AK5 is very small so that it can be regarded as virtually open for a very short time after the negative pulse has been applied to the grid of 6AK5. So the equivalent circuit for coupling between the plate of T_1 and grid of T_2 is given by figure 3 at that time and equation (1) then gives the plate-point voltage of T_2. Since the T_1 -plate voltage does not rise so much as it would if 6AK5 becomes non-conducting, the transferred voltage in the grid of T_2 is also less in this case and so r_{a2} is higher than it was when 6AK5 was non-conducting.

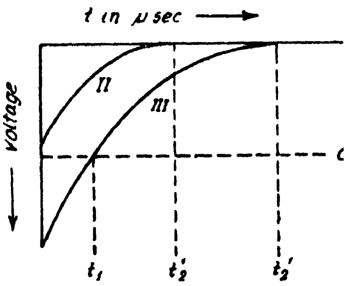


FIG. 26

Steps 2, 3 and 4 are evidently valid in this case also and this is why we can now conclude by saying that the voltage waveforms at the different electrodes of the multivibrator tubes which are obtained when triggering is done by a pulse of group (*ii*), are almost exactly identical with those found previously in our analysis for a negative pulse of group (*iii*) at the input.

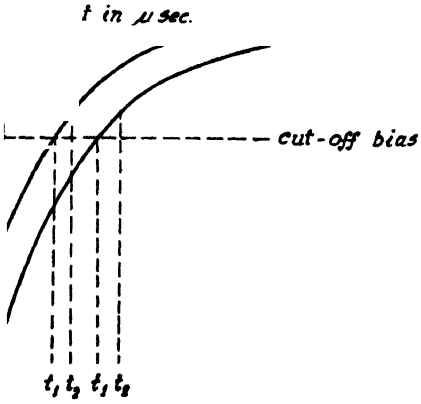


FIG. 27

The effect of narrow and big pulses : When the pulse is narrow and big (figure 27) the time t_1 is slightly greater than that assumed for the pulses of group (*iii*). For the interval ($0 < t < t_1$) the voltage waveforms at the plate of T_1 and at the plate of T_2 and grid of T_1 are drawn with the help of equations (1) and (12) respectively.

During the period between $t=t_1$, and $t=t_2$, 6AK5 is gradually reaching the phase of full conduction and the grid voltage of T_2 will begin to come down. Since the amplitude of the pulse is now big, this period (t_2-t_1) is now greater than that in the case of pulses of group (*iii*). This is the interval when T_2 -plate voltage and T_1 -grid voltage will begin to rise (eqn. 14). Since (t_2-t_1) is large in this case, the voltage in the grid of T_1 will rise above its cut off value in the mean time making T_1 conducting and simultaneously T_2 non-conducting.

Thus the multivibrator waveforms at the different electrodes are altered markedly in this case.

The overshoot cannot rise too much since the grid voltage of T_1 is increasing exponentially and as soon as the grid becomes positive, grid current is drawn and the overshoot is limited.

When $t>t_2$, T_2 -plate voltage and T_1 -grid voltage will be given by equations (20) and (22). The T_2 -plate voltage curve can then be plotted with the help of equations (8) and (9) respectively. Figures 28 and 29 show the theoretically plotted curves of T_1 -plate voltage and T_2 -grid voltage respectively.

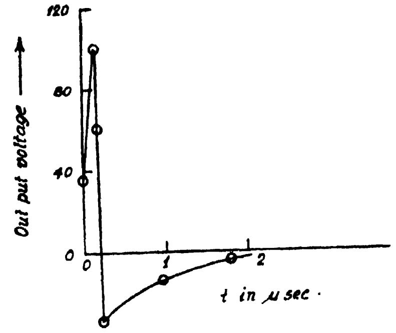
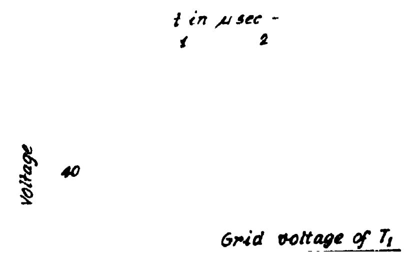


Plate - voltage of T_1

FIG. 28



Grid voltage of T_1

FIG. 29

SUMMARY

The equivalent circuits have been considered and the expressions for the voltage waveforms of the different electrodes of the multivibrator have been deduced at three distinct time-intervals namely between (*I*) $t=0$ to $t=t_1$ when both 6AK5 and T_1 are non-conducting, (2) $t=t_1$ and $t=t_2$ when only 6AK5 draws negligible current and (3) $t=t_2$ and $1=t_3$ when 6AK5 plate current is more or less steady, T_1 being still non-conducting. These times have all been reckoned from the instant a negative pulse is

applied at the input of 6AK5 and so all the expressions could be related with the width of the input pulse.

Pulses of diffrent amplitudes and widths have been considered. The experimental findings could well be explained by the theoretical analysis. The former conclusion that the triggering of such a multivibrator depends largely on amplitudes has been established as well by theoretical analysis. Theoretical curves for the voltage waveforms of the different electrodes of the multivibrator have been plotted with the equations derived and are found to fit well with the oscillograms.

ACKNOWLEDGMENTS

The authors' best thanks are due to Prof. M. N. Saha, F.R.S. and Dr. B. D. Nag for their keen interest in the work. They are grateful to Sri B. M. Banerjee for helpful discussions. The authors also wish to thank Sri A. P. Patro and Miss Sobhana Dhar for their help in taking photographs presented here.

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