A MONOSTABLE MULTIVIBRATOR WITH THE TIMING PERIOD

INDEPENDENT OF SUPPLY VOLTAGE.

by

Gordon K. Shipp

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This thesis has been approved on the date shown below:

Paul G. Griffith   *May 4, 1961*
_____   _____
        PAUL G. GRIFFITH   Date
Associate Professor of Electrical Engineering

ABSTRACT

A MONOSTABLE MULTIVIBRATOR WITH THE
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This thesis presents an analysis of a vacuum-tube triode
and a transistor monostable multivibrator. It is shown that the
timing period of the monostable multivibrator is independent of the
power supply voltage, thereby making it ideally suited wherever
well-regulated supplies are not available.

Circuit models are developed that will approximate the
behavior of the vacuum-tube triode and transistor. By the proper
use of these linear circuit models, a nonlinear problem is solved
by the method of linear circuit analysis.

The description of the operation of the multivibrators is
presented concurrently with the analysis of the circuits. The
design criteria, voltage waveforms, and performance characteristics
evolve from this analysis. Mathematically, the timing period of
these multivibrators is proven to be independent of the value of
the supply voltage.

An experimental circuit is designed, constructed, and
tested for both the vacuum-tube and transistor multivibrators.
The measured results show excellent correlation with the values
calculated from the mathematical formulas. For the vacuum-tube
circuit, a change of 50% in the supply voltage caused only a
2.3% change in the timing period. Correspondingly, only a 0.51%
variation was noted in the timing period of the transistor
monostable multivibrator.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The multivibrator is a versatile type of circuit that finds widespread application in pulse and digital circuits. In its most common form, the multivibrator incorporates two stages of amplification with feedback from the output of one stage to the input of the other stage. Any disturbance or signal at an input will be amplified through the two stages, which are effectively in cascade, and then will reappear at the original input with such a polarity as to aid the initial disturbance. This action constitutes the regenerative property of the circuit, the property that can be shown to cause the circuit to drive itself into one or the other of its two states of operation; i.e., stable or quasi-stable. The circuit action is stable if it remains permanently in the same operating condition until acted upon by an external trigger pulse. In contrast, the circuit action is quasi-stable if it remains only temporarily in a particular mode of operation. At the end of the quasi-stable state, the circuit will automatically regenerate to its other state of operation, which may be either stable or quasi-stable.

The existence of these two states allows the multivibrator to be divided into three principal sub-classes: the bistable, astable,

and monostable. The bistable multivibrator can remain indefinitely in either of its stable states when free of external influences. In contrast, the astable multivibrator has two quasi-stable states and oscillates between the two states with a temporary period of time expended in each state. The monostable multivibrator is a combination of these two circuits, having one stable and one quasi-stable state. The monostable multivibrator will remain permanently in its stable state until placed in the quasi-stable state by the application of a trigger pulse. After a predetermined length of time, the circuit will automatically regenerate back to its stable mode of operation. The circuit will then provide an output pulse of a particular width for each trigger input. The width of this output pulse is essentially independent of the trigger signal and is determined, in most cases, by an RC time constant. The monostable multivibrator will be the subject under discussion in this thesis.

1.2 STATEMENT OF THE PROBLEM

In pulse and digital circuits, there exists a definite need for pulses of a particular width. A few of these circuits are transmission gates, time delays, voltage comparators, coincidence comparators, and sawtooth generators. It is extremely important that the width of the pulse, which is provided by the monostable multivibrator, does not change with repeated cycling. It can be shown, however, that the

plate-coupled and cathode-coupled monostable multivibrators are very

sensitive to changes in the supply voltage.* In fact, it is not un-

common for a 10% change in the supply voltage to cause a 5 to 10%

change in the pulse width.[1] This is not a serious problem where

well-regulated power supplies are available. However, there are

many instances where it is not feasible to have a well-regulated

supply due to its excessive bulk and cost. In many cases, the supply

voltage will be provided by a source of power which has an output

voltage that is constantly changing as time progresses. For reliable

operation, the circuit behavior must be insensitive to this change

in supply voltage.

It will be the aim of this thesis to analyze and test a

monostable multivibrator that exhibits excellent independence of

changes in the supply voltage. In contrast to the popular plate-

coupled monostable multivibrator, this circuit also requires only a

single power supply. It is true that the cathode-coupled multivibrator

requires only a single power supply, but this circuit has the disadvan-

tage that it is very sensitive to changes that may occur in the supply

voltage.

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*This argument also applies to the transistor monostable
multivibrators.

[1]J. Millman and H. Taub, <u>Pulse and Digital Circuits</u>,
McGraw-Hill Book Company, Inc., New York, 1956, pg 194

1.3 SCOPE

Since the circuits to be analyzed operate in a nonlinear
fashion, the circuit models that will be used to approximate the be-
havior of the vacuum-tube triode and transistor will be developed in
Chapter 2. By the proper use of these circuit models, this nonlinear
problem will be solved by the methods of linear circuit analysis.
Since the circuits will be designed around ten per cent components,
it is not necessary to insist on a precision analysis. The circuit
can, of course, be adjusted to better than one per cent performance
since the first order analysis reveals the elements that govern the
circuit behavior.

The vacuum-tube monostable multivibrator will be analyzed in
Chapter 3 with the analysis of its transistor counterpart to follow
in Chapter 4. The design criteria, voltage waveforms, and performance
characteristics of the circuits will evolve from this analysis.

In order to substantiate the validity of the theoretical
analysis, experimental circuits are designed, constructed, and tested
for both the vacuum-tube and transistor circuits. The circuits are
tested to demonstrate the independence of the pulse width to changes
in the supply voltage. The comparison between the calculated and
measured values will be given in Chapter 5. A summary of the results
and recommendations for further study will be given in Chapter 6.

CHAPTER 2

VACUUM-TUBE TRIODE AND TRANSISTOR CIRCUIT MODELS

2.1 INTRODUCTION

The circuit models that will be used to represent the vacuum-tube triode and transistor must be developed in the beginning in order to simplify the operating principles and to avoid unnecessary duplications. Since an exact analysis of the circuits to be considered is not possible, these models will be used to approximate the properties of the nonlinear device. By the proper use of these linear circuit models, a nonlinear problem can be solved by the methods of linear circuit analysis. Even though these models will not be exact, it will be shown later in the experimental results that the approximations are sufficiently accurate for engineering purposes.

For these devices, it is possible to define three distinct regions of operation. These regions will be referred to as Regions I, II, and III and are briefly defined as follows:

1. Region I is that region of operation where the device is said to be cut off; that is, no current is allowed to flow in the output circuit.

2. Region II is normally referred to as the active or linear region of operation and is where the device is usually utilized for linear amplification.

3. Region III is characterized by the action known as clamping. Clamping is a property where the output current is not influenced by the input circuit.

These three regions of operation will be considered separately, and the circuit models will be developed for each region.

2.2 VACUUM-TUBE TRIODE CIRCUIT MODELS

The circuit to be considered is shown in Fig. 2.1 where the appropriate current and voltages have been defined. By the overlay of a load line on the plate characteristic curves of the triode, it is possible to perform a graphical analysis of the circuit. The load line, as determined from the circuit, can be expressed by the equation

$$E_b = E_{bb} - I_b R_L \qquad\qquad 2.1$$

The plate characteristic curves represent a graphical plot of the relationship that exists among the plate current, plate voltage, and the grid voltage. An example of the solution for the plate current and voltage is shown in Fig. 2.2 using the assumed values of 200 volts for E_{bb}, 25 kilohms for R_L, and -4 volts for e_g. By the proper selection of e_g, the tube can be made to operate in any one of the three regions shown in Fig. 2.2.

2.2.1 REGION I OPERATION

When the grid voltage e_g becomes sufficiently negative to cause plate current to cease, the tube enters the cut off region. Since no current flows through R_L, the voltage at the plate of the
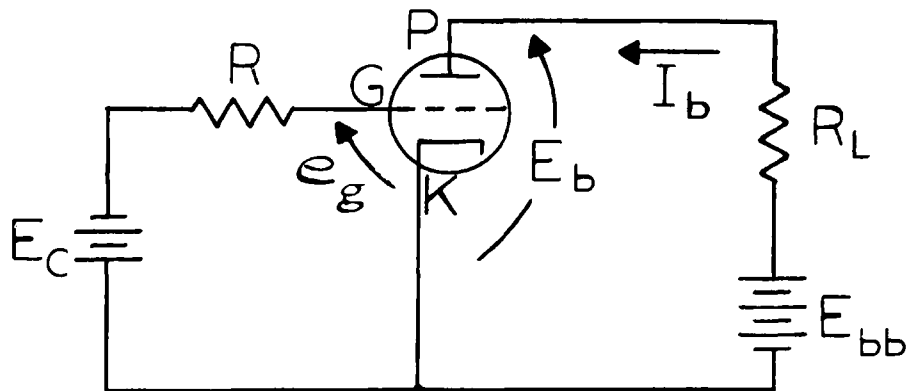
FIGURE 2.1

CIRCUIT UTILIZED FOR DEVELOPMENT OF THE VACUUM-TUBE TRIODE MODELS
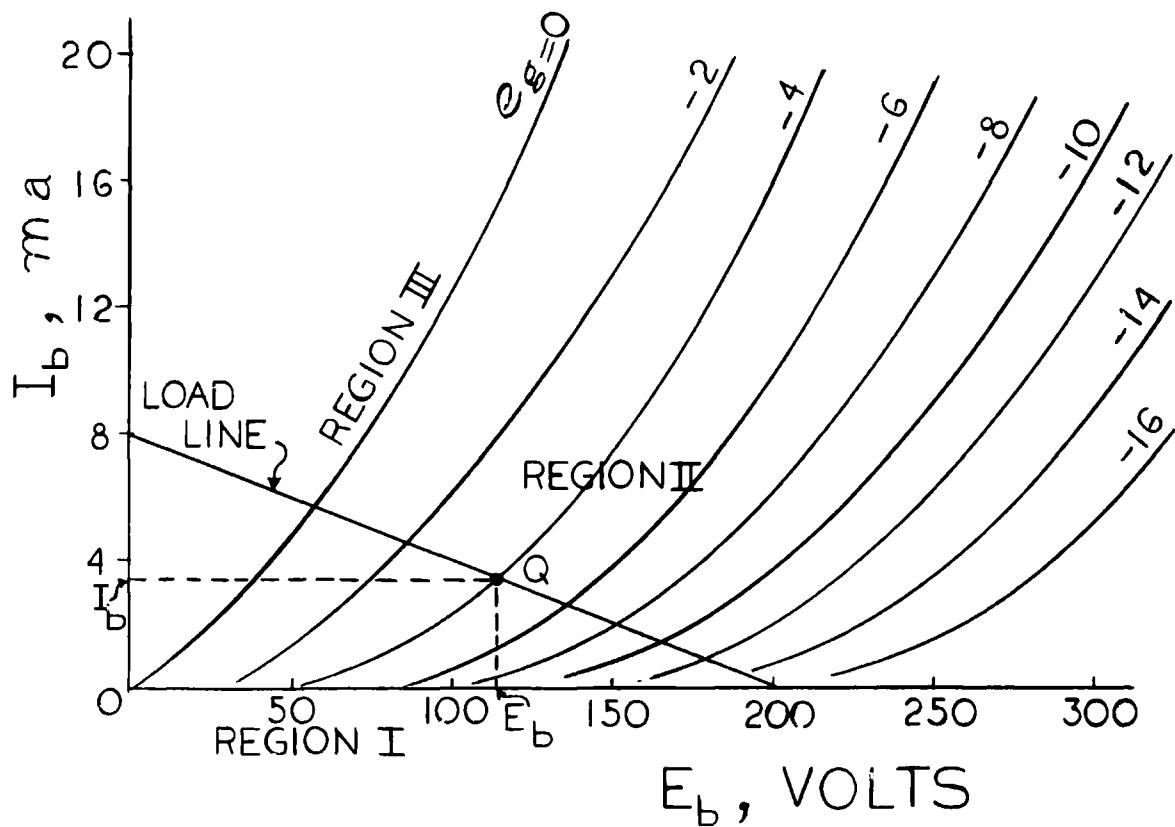
FIGURE 2.2

TYPICAL PLATE CHARACTERISTIC CURVES OF A VACUUM-TUBE TRIODE

tube becomes equal to E_{bb}. The operation in Region I, therefore, yields a very simple model as the action of the tube is approximated by an open circuit as shown in Fig. 2.5 (a).

2.2.2 REGION II OPERATION

Since there is no ac signal input to the circuit of Fig. 2.1, the operation of the tube in Region II is held to a single point which is located on the load line. The tube parameters μ and r_p are indicative of the spacing and slope, respectively, of the characteristic curves. Since the operating point is fixed, once the value for e_g is known, the tube parameters are considered to be constants and can be calculated at the point of interest. These values are given by:

$$\mu = -\frac{\triangle E_b}{\triangle E_c} \bigg/ I_b = \text{Constant} \qquad 2.2$$

$$r_p = \frac{\triangle E_b}{\triangle I_b} \bigg/ E_c = \text{Constant} \qquad 2.3$$

The assumption that the curves are linear, with the above spacing and slope, will introduce no error in the calculation of I_b and E_b if the point of operation is not changed. Extrapolation of the e_g curves around the operating point will yield the idealized curves shown in Fig. 2.3, where the voltage E_o is an intercept adjuster that compensates for the shift in the $e_g = 0$ curve.

The voltage at the intercept of an e_g curve is given by:

$$E = E_o - \mu e_g \qquad 2.4$$
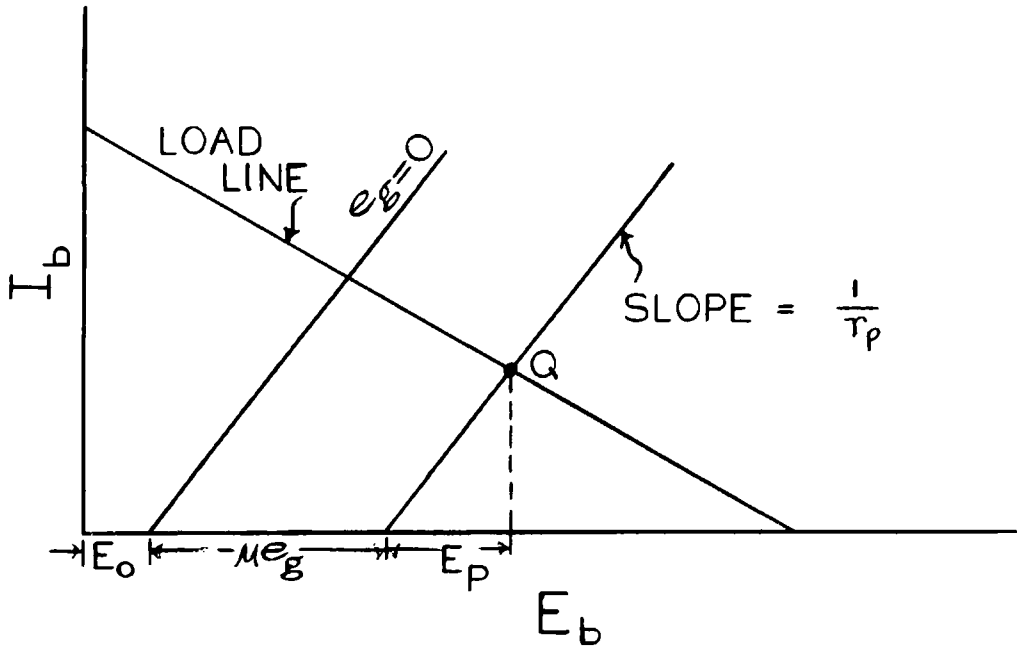
FIGURE 2.3

IDEALIZED CHARACTERISTIC CURVES FOR OPERATION IN REGION II
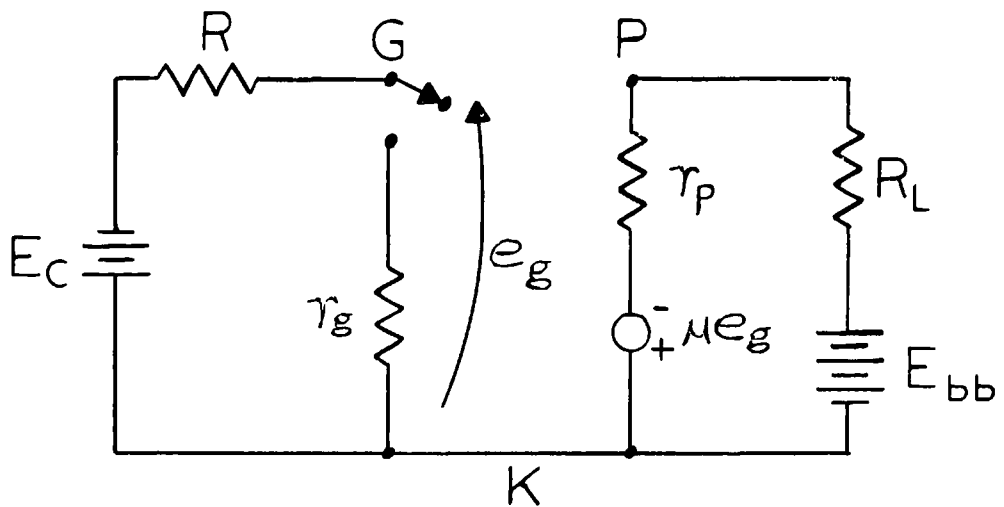
SWITCH IS SHOWN IN POSITION FOR OPERATION IN REGION II

FIGURE 2.4

EQUIVALENT CIRCUIT FOR OPERATION IN REGION II AND III

This voltage is not the total voltage across the tube, but has in addition the voltage specified as E_p. The voltage E_p is due to the finite slope of the e_g curve and has a value represented by:

$$E_p = I_b \, r_p \qquad\qquad 2.5$$

The voltage across the tube can be defined as the sum of these two equations and has a value of

$$E_b = E_0 \; - \mu \, E_c + I_b \, r_p \qquad\qquad 2.6$$

For this study, the voltage E_0 will be omitted from this equation since it is assumed to be negligible when compared with the magnitude of the other voltages.

On the basis of the above assumptions, a simplified expression for the cut-off voltage, E_{co}, will evolve from the solution of Eq 2.4. The value of this cut-off voltage is given by:

$$E_{co} = - \frac{E_{bb}}{\mu} \qquad\qquad 2.7$$

Replacing the tube with its equivalent voltage yields the circuit of Fig. 2.4. The switch is shown in the proper position for operation in Region II. When e_g reaches a value of zero, the switch will reverse its position. The circuit model that replaces the tube during Region II operation is depicted in Fig. 2.5 (b).

2.2.3 REGION III OPERATION

In Region III the tube is in saturation due to the grid-circuit clamping, thereby drawing its maximum plate current. In order to have

(a)

REGION I

(b)

REGION II

(C)
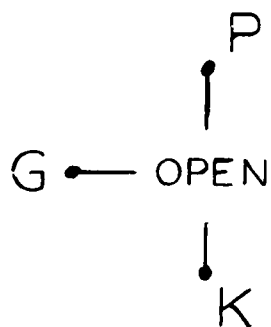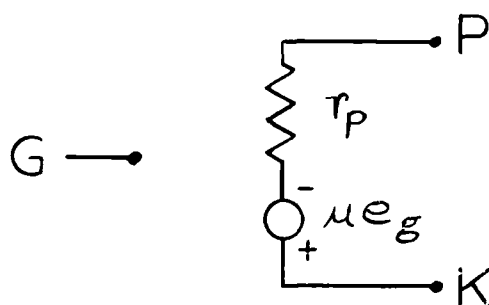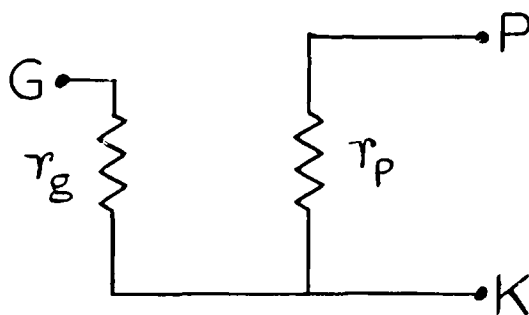
REGION III

FIGURE 2.5

VACUUM-TUBE TRIODE CIRCUIT MODELS

FIGURE 2.6

CIRCUIT UTILIZED FOR DEVELOPMENT OF THE TRANSISTOR MODELS

The collector characteristic curves represent a graphical plot of the relationship that exists among the collector current, collector voltage, and base current. An example of the solution for the collector current and voltage is shown in Fig. 2.7 (a) using the assumed values of -10 volts for E_{cc}, 5 kilohms for R_L, and 20 μa for I_B.

The curves shown in Fig. 2.7 (b) give the relationship that exists among the base current, base voltage, and collector voltage. These curves define the input circuit of the transistor and correspond to the grid characteristics of the triode when grid voltage is positive and grid current flows. By the proper selection of I_b, the transistor can be made to operate in any one of the three regions shown in Fig. 2.7 (a).

2.3.1 REGION I OPERATION

When the base current is reduced to zero, the transistor enters the cut-off region. For this study, the small residual current that does flow in the circuit is of such insignificance that this current can be neglected. Since no current flows through R_L, the collector voltage drops to a value equal to E_{cc}. For the operation in Region I, the input (base) and output (collector) circuits are approximated by open circuits as shown in Fig. 2.10 (a).

2.3.2 REGION II OPERATION

Reasoning similar to that of Section 2.2.2 indicates that the operating point of the transistor will be held to a single point located on the load line. The transistor parameters, β and r_c, are

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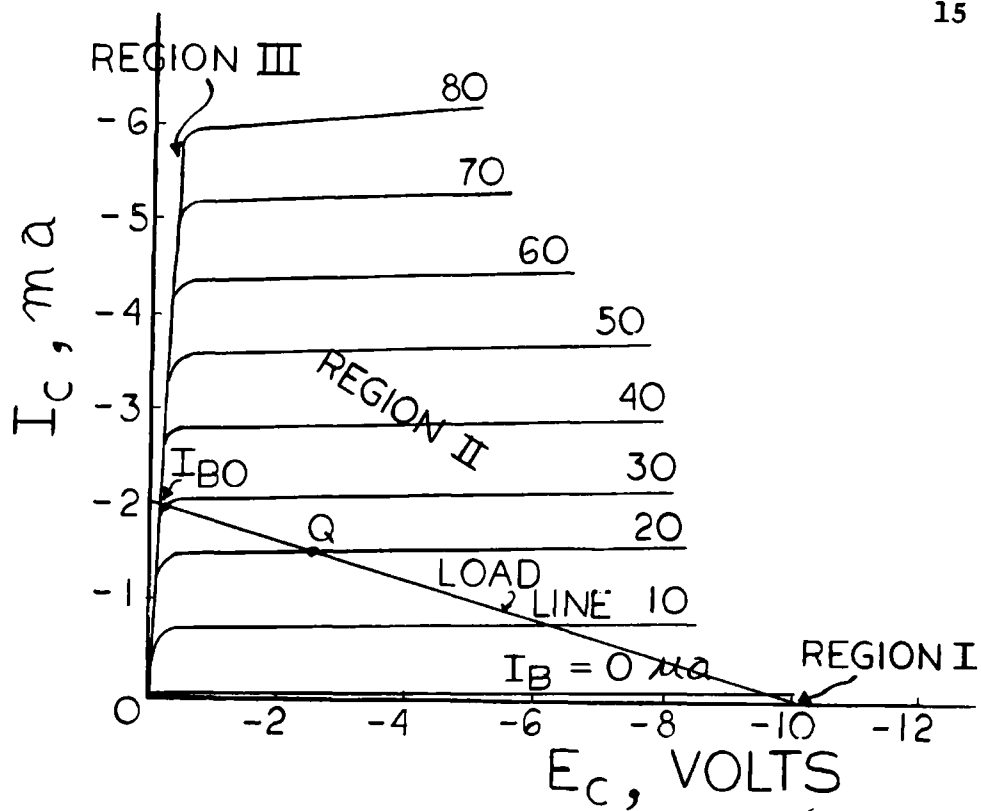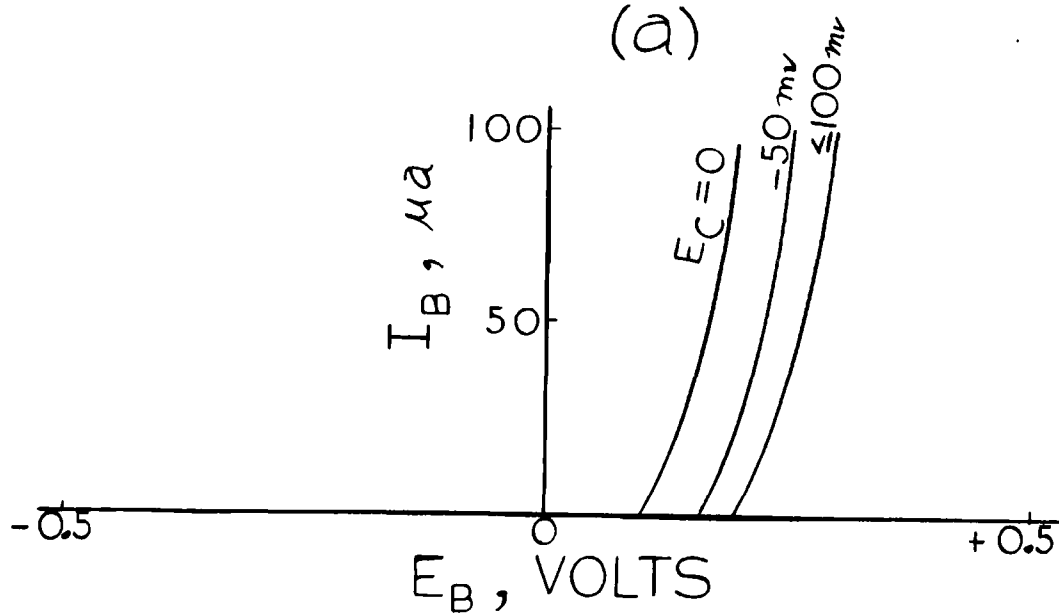
FIGURE 2.7

TYPICAL TRANSISTOR CHARACTERISTIC CURVES
a) OUTPUT CHARACTERISTICS
b) INPUT CHARACTERISTICS

indicative of the spacing and slope, respectively, of the collector characteristic curves. Since the operating point is fixed, once the value for I_B is known, the transistor parameters are considered to be constants and are calculated at the point of interest. These values are given by:

$$\beta = \frac{\Delta I_c}{\Delta I_B} \bigg/ \quad E_c = \text{Constant} \qquad 2.10$$

$$r_c = \frac{\Delta E_c}{\Delta I_c} \bigg/ \quad I_B = \text{Constant} \qquad 2.11$$

The assumption that the curves are linear, with the above spacing and slope, will introduce no error in the calculation of E_c and I_c if the point of operation is not changed. The I_B curves of interest now appear as shown in Fig. 2.8. The current I_0 is an intercept adjuster necessary to translate the family of current-voltage lines so that they coincide with the actual curves in the area of interest. The value of this current may be positive or negative and will be determined by the interception of the $I_B = 0$ curve as shown in Fig. 2.8.

The current at the intercept of an I_B curve is given by:

$$I_c = I_0 + \beta I_B \qquad 2.12$$

It is assumed that this is the total current since the curves are almost horizontal. For the input circuit model, reference is made to the input characteristic curves of Fig. 2.9. Since the operation of the base is in the region where E_c is larger than 0.1 volt, see Fig. 2.7 (b), the input circuit is replaced by a battery and a resistor
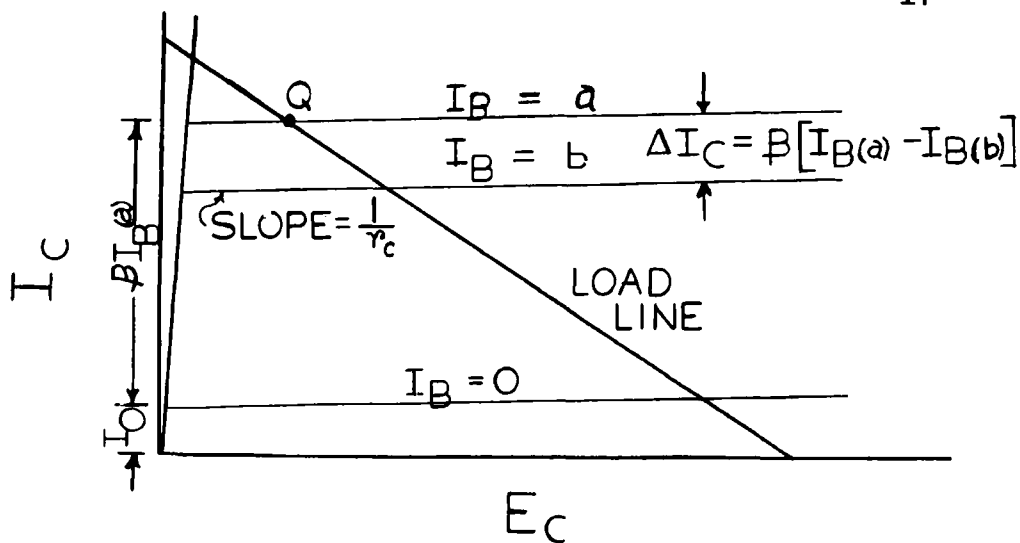
FIGURE 2.8

IDEALIZED COLLECTOR CHARACTERISTICS FOR OPERATION IN REGION II
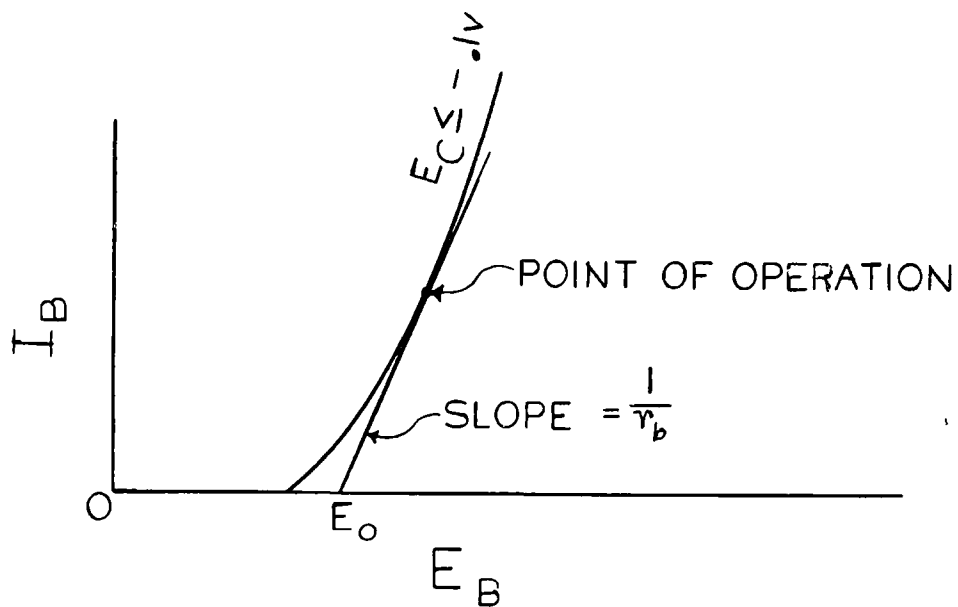
FIGURE 2.9

BASE PARAMETERS FOR OPERATION IN REGION II

which are calculated as shown in Fig. 2.9.

The input and output circuit models for the transistor during operation in Region II are shown in Fig. 2.10 (b).

2.3.3 REGION III OPERATION

In this saturation region, the collector behaves like the anode of a simple diode with a low internal resistance, in the vicinity of 20 ohms for the transistors to be employed in this thesis. This resistance can be neglected when compared with R_L and the model then becomes a short circuit.

The development of the input model for Region III is identical to that of Region II. Its operation has now shifted, however, to the $E_c = 0$ curve of Fig. 2.7 (b) and the values for r_b and E_o may be neglected.

The circuit model for the input and output of the transistor during operation in Region III is given in Fig. 2.10 (c).

(a)

REGION I

(b)

REGION II

(C)
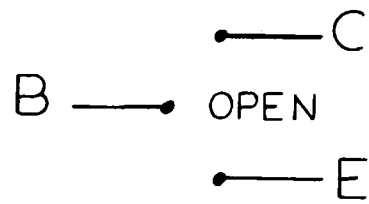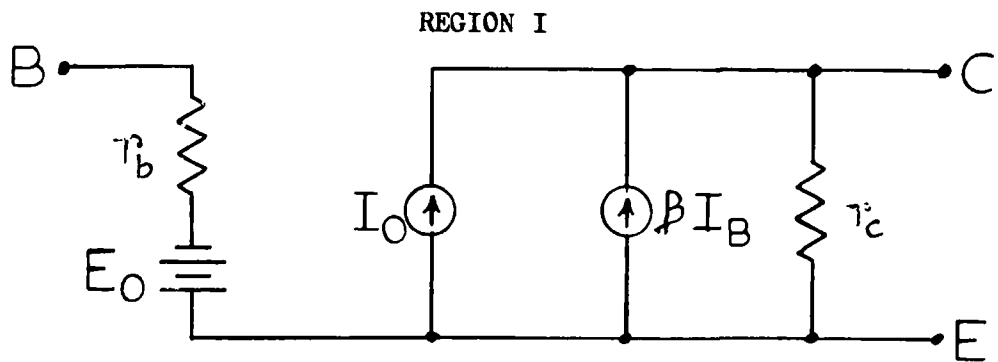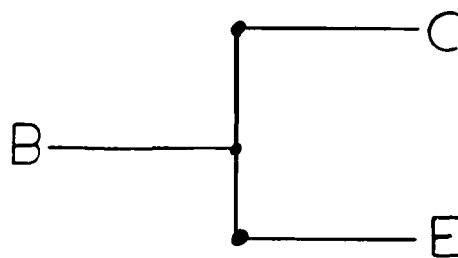
REGION III

FIGURE 2.10

TRANSISTOR CIRCUIT MODELS

CHAPTER 3

ANALYSIS OF THE VACUUM-TUBE MONOSTABLE MULTIVIBRATOR

3.1 INTRODUCTION

A monostable multivibrator whose timing period is independent
of the power supply will be analyzed in this chapter. The description
of the operation of this multivibrator will be divided into two parts,
corresponding to the two states attributable to monostable action.
The stable state will be considered first with the operation of the
quasi-stable state to follow. The design criteria, voltage waveforms,
and performance characteristics will evolve from this analysis.

The circuit under consideration is shown in Fig. 3.1 where
the appropriate voltages and currents have been defined. It will be
shown that the timing period of this circuit is independent of the
supply voltage. In Chapter 5, experimental results will be given to
substantiate the theoretical results of this chapter.

3.2 STABLE STATE OPERATION

In order to assure reliable operation of the monostable multi-
vibrator, it is necessary to have tube T_1 cut off and tube T_2 clamped
during the stable state. The grid of T_2 is connected, by the resistor
R, to the positive voltage existing at the cathode of T_1 which places
T_2 in a clamped condition $(e_g \cong 0)$. Since the values for the resistors
R_1 and R_2 are selected to be much larger than R_{L2}, it is assumed that

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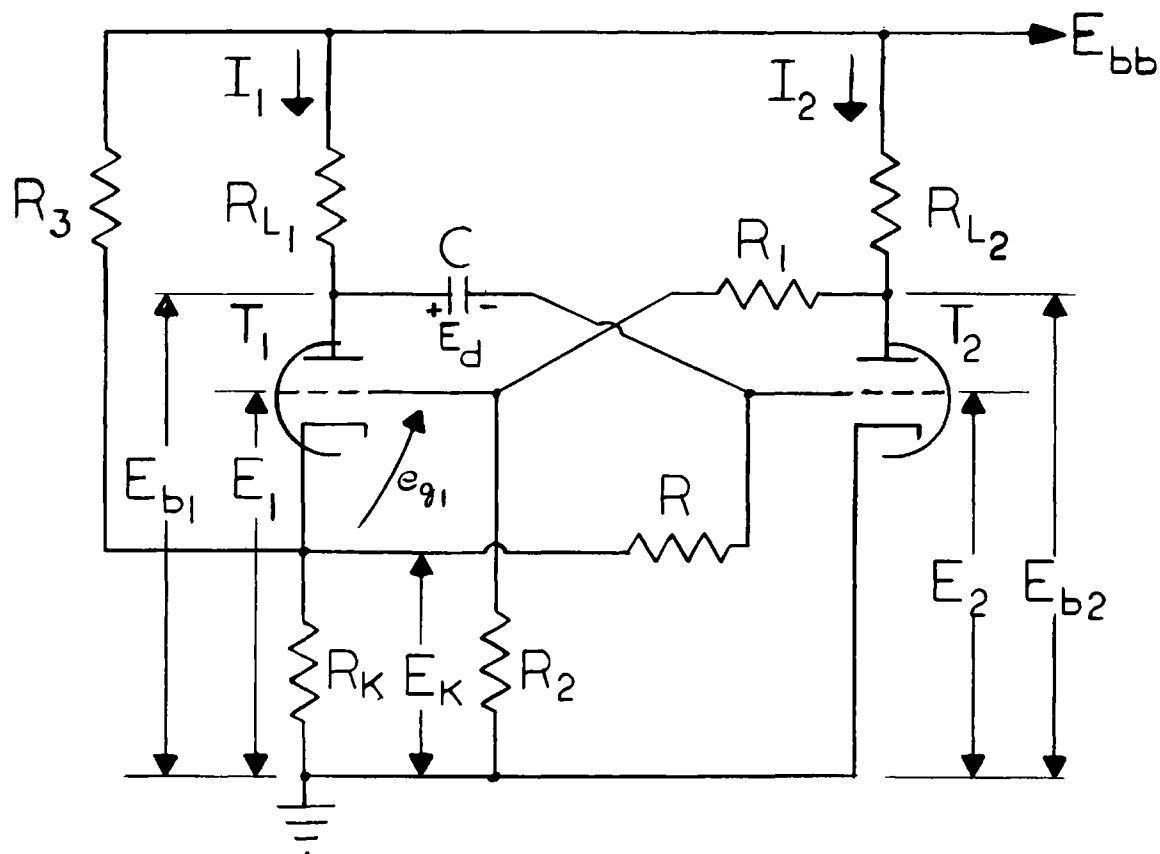
FIGURE 3.1

VACUUM–TUBE MONOSTABLE MULTIVIBRATOR

the current I_2 flows entirely through the tube. The value of I_2 is found graphically from the intersection of the load line and the $e_g = 0$ curve.

By the proper selection of R_3 and R_K, tube T_1 is held in the cut-off condition. With T_1 cut off and T_2 in clamp, the circuit reduces to that of Fig. 3.2 where the tubes have been replaced by their circuit models.

The voltage E and resistor R_K' are products of the application of Thevenin's Theorem to the E_{bb}, R_3, and R_K network and have values given by:

$$E = \frac{R_K \; E_{bb}}{R_K + R_3} \qquad\qquad 3.1$$

$$R_K' = \frac{R_3 \; R_K}{R_3 + R_K} \qquad\qquad 3.2$$

The voltages that result from operation in this state are given in Table I where

$$R \gg R_K' \qquad\qquad 3.3$$
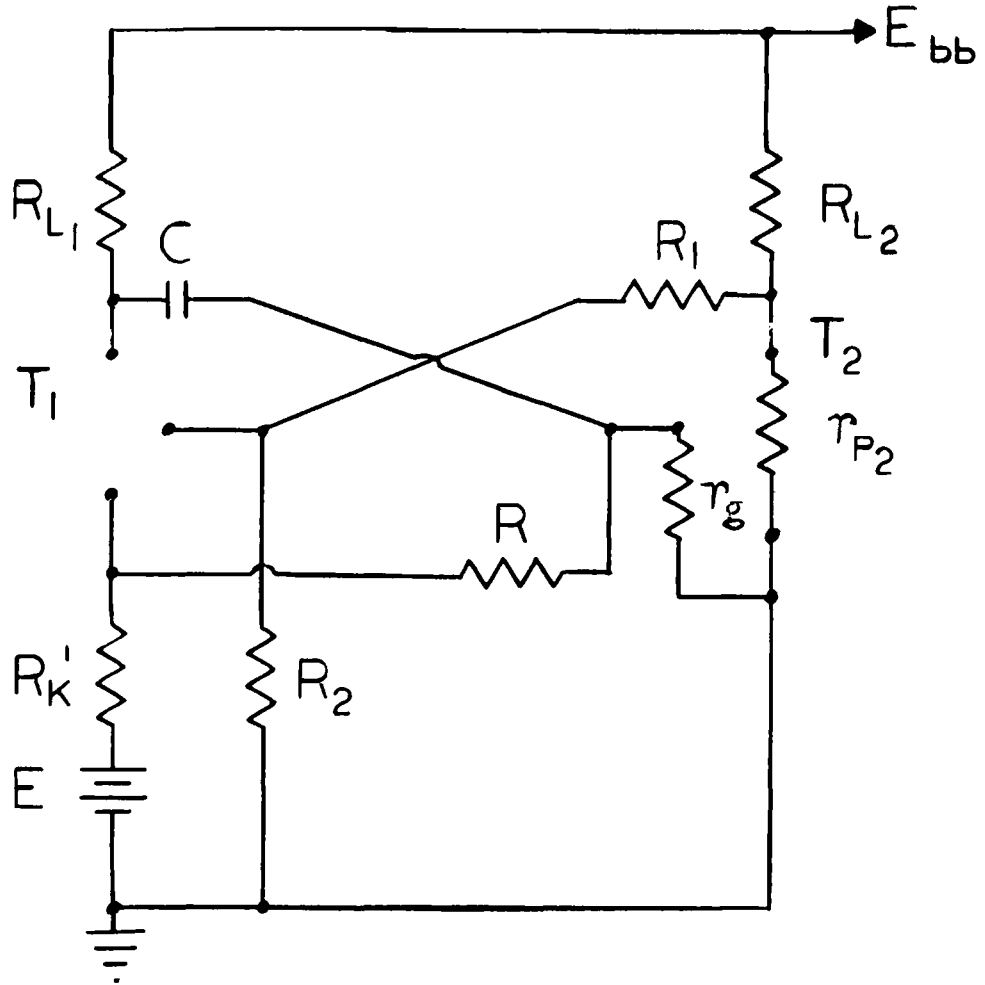
FIGURE 3.2

EQUIVALENT CIRCUIT FOR OPERATION IN THE STABLE STATE

TABLE I

STABLE-STATE VOLTAGE EQUATIONS

VOLTAGE	VALUE
E_{b1}	E_{bb}
E_{b2}	$E_{bb} - I_2 R_{L2}$
E_1	$\dfrac{R_2}{R_1 + R_2} E_{b2}$
E_2	0
E_K	E
e_{g1}	$E_1 - E_K$
E_d	E_{bb}

The requirement that T_1 be in a cut-off condition specifies that

$$E > E_1 - E_{col} \qquad\qquad 3.4$$

where E_{col} is the cut-off voltage of T_1 corresponding to an effective plate voltage of $E_{bb} - E$. Equation 3.4 will be satisfied over the expected range of E_{bb} if the proper values are selected for R_3 and R_K. Factors to be considered in this selection include: the current drain from the power supply must be kept small, reasonable values for R_3 and R_K must be used, and Eqs. 3.1 and 3.4 must be satisfied.

These conditions will prevail until the application of an external trigger causes a transition from the stable state to the quasi-stable state.

3.3 QUASI-STABLE STATE OPERATION

Let us reserve the discussion on triggering for a later section and assume that a transition has placed the circuit in the quasi-stable state of operation. The action during the transition drives T_2 into cut off and T_1 into operation in either the active region or the saturation region.* In either case, a current I_1 now flows in T_1 and E_{b1} will drop by an amount equal to $I_1 R_{L1}$, with the same voltage change appearing at the grid of T_2 due to the capacitive coupling between these two points.

The circuit at this instant appears as shown in Fig. 3.3 and calculation of the voltages, as defined in Fig. 3.1, yields the data given in Table II. The voltage E_1' will have a value of

$$E_1' = E_K \qquad\qquad 3.5$$

or

$$E_1' = \frac{R_2}{R_1 + R_2} E_{bb} \qquad\qquad 3.6$$

depending on the region of operation of T_1. Equation 3.5 applies when T_1 is in the clamped condition and Eq. 3.6 applies when T_1 is operating

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*Both of these regions of operation will be considered when the equation for the timing period is developed.
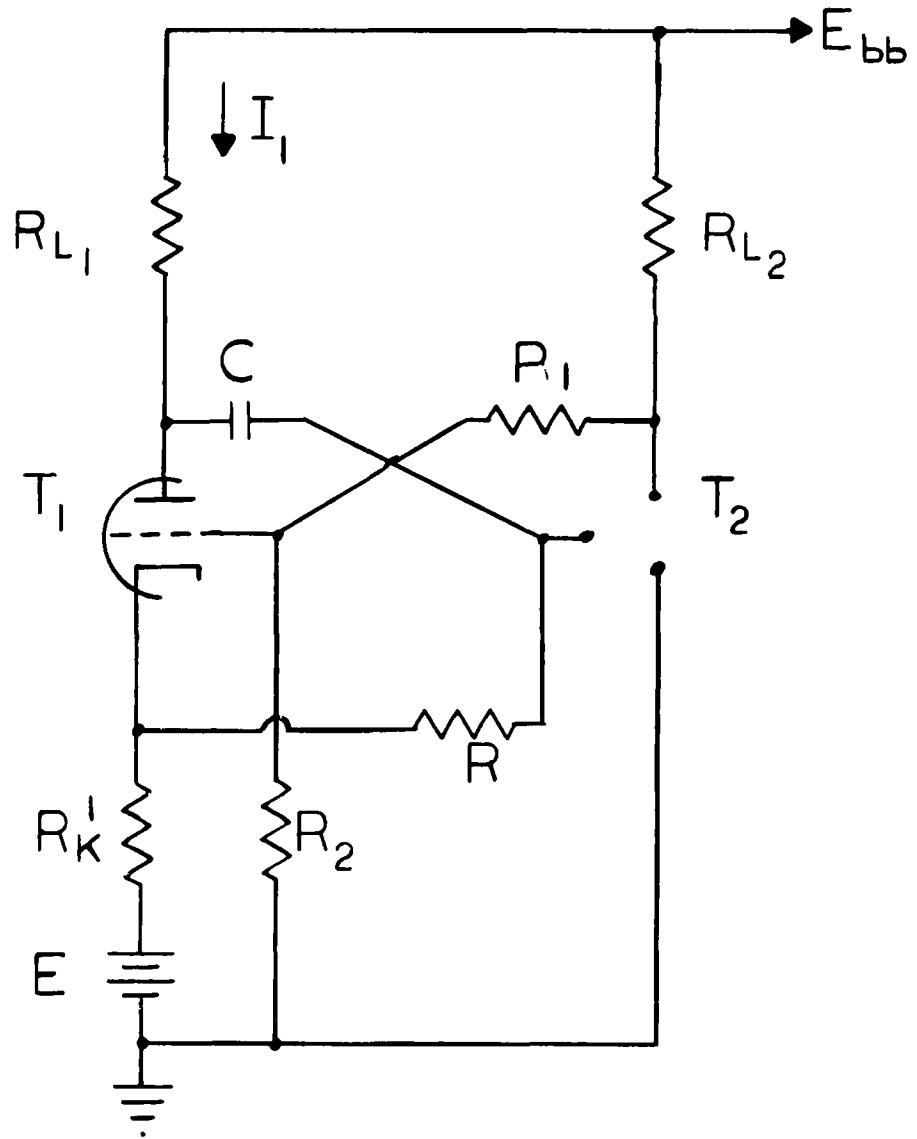
FIGURE 3.3

EQUIVALENT CIRCUIT FOR OPERATION IN THE QUASI-STABLE STATE

within its linear region. These two cases will be individually considered when the current I_1 is calculated.

TABLE II

QUASI-STABLE STATE VOLTAGE EQUATIONS

VOLTAGE	VALUE
E_{b1}	$E_{bb} - I_1 R_{L1}$
E_{b2}	E_{bb}
E_K	$E + I_1 R_K'$
E_1	E_1'
E_2	$-I_1 R_{L1}$
e_{g1}	$E_1 - E_K$
E_d	E_{bb}

It can be shown that the circuit cannot remain for an infinite time in this state since the only d-c connection to the grid of T_2 is through the resistance to the cathode of T_1. If allowed to do so, E_2 would asymptotically approach a final value of E_K but is restrained from doing this since T_2 will begin to conduct current when the grid voltage reaches the cut-off voltage E_{co2}. At this time, the circuit will regenerate to its original stable state.

The voltage, as a function of time, at the grid of T_2 during this period can be given by the equation:

$$E_2 = E_f - (E_f - E_i) e^{-\frac{t}{\tau}} \qquad\qquad 3.7$$

where

$$E_f = E_K = E + I_1 R_K' \qquad\qquad 3.8$$

and

$$E_i = - I_1 R_{L1} \qquad\qquad 3.9$$

The time constant τ is defined as the product of the capacitance and the effective resistance through which the capacitor charges. This time constant will be determined once the region of operation; i.e., saturation or active, of T_1 is known.

By the substitution of E_{co2} for E_2 in Eq. 3.7, the solution for the period of time T spent in the quasi-stable state yields:

$$T = \tau \ln \left[\frac{E + I_1 R_K' + I_1 R_{L1}}{E + I_1 R_K' - E_{co2}} \right] \qquad\qquad 3.10$$

where

$$E_{co2} = - \frac{E_{bb}}{\mu} \qquad\qquad 3.11$$

The idealized voltage waveforms, as determined from the data given in Tables I and II, are given in Fig. 3.4, where the divergence from the calculated values is shown by the dotted lines. The grid of
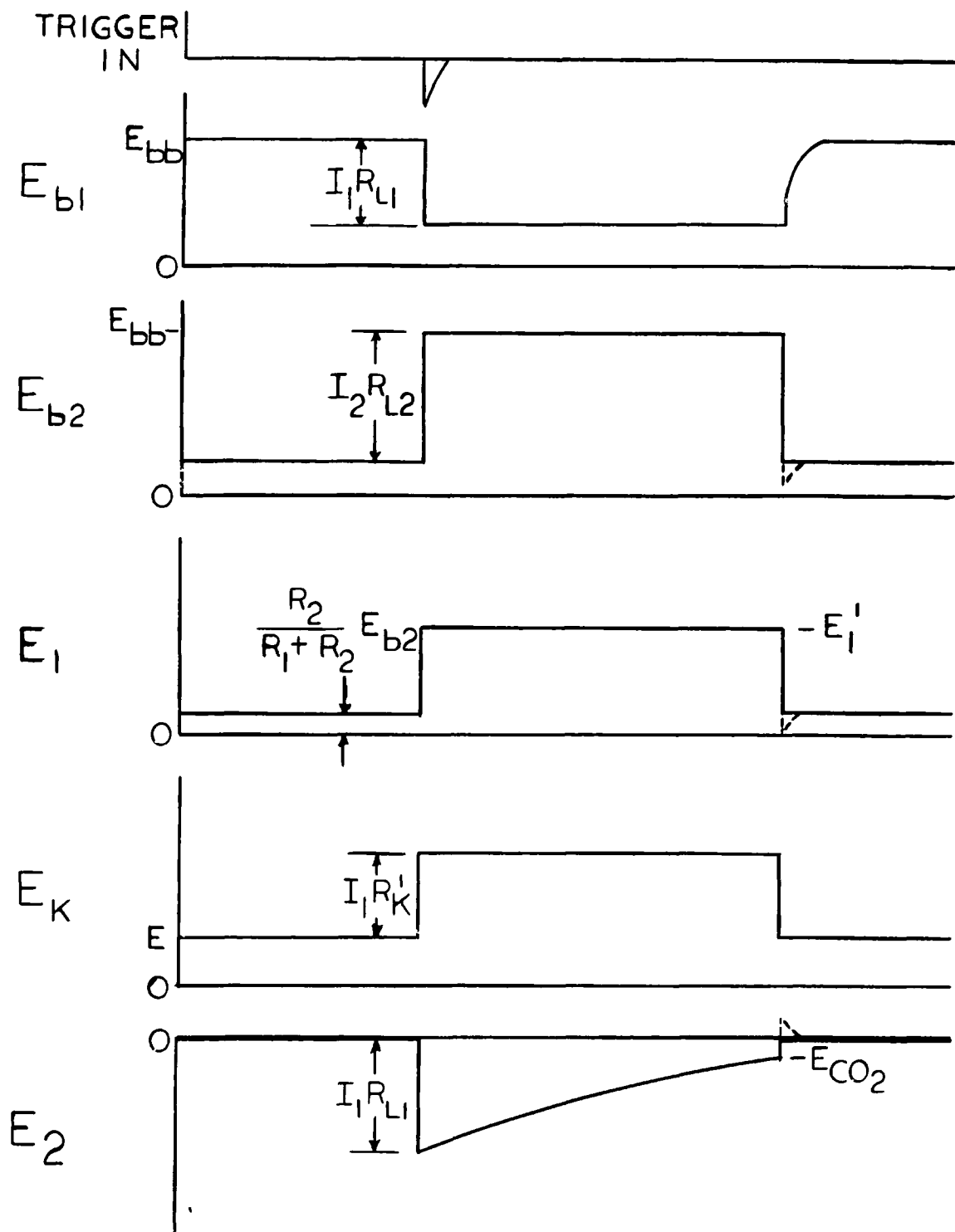
FIGURE 3.4

IDEALIZED VOLTAGE WAVEFORMS OF THE
VACUUM-TUBE MONOSTABLE MULTIVIBRATOR

T_2 is actually driven slightly positive and accounts for the various overshoots. Since the overshoots are small and the time needed for the voltages to decay to their final value is short, in comparison to T, the net effect on the operation of the circuit is negligible and will be omitted from the analysis to follow.

3.4 CALCULATION OF THE TIMING PERIOD

A value must be determined for I_1 and $\mathcal{T}$ in order to express Eq. 3.10 as a function of the circuit parameters. A load line must be plotted on the plate characteristic curves of T_1. In order to plot the load line, it is necessary to find the value of the effective plate voltage and load resistance that comprise the external circuit of T_1. The resultant circuit is shown in Fig. 3.5 where

$$R_t \cong R_{L1} + R_K'\qquad\qquad 3.12$$

$$E_t \cong E_{bb} - E\qquad\qquad 3.13$$

since

$$R \gg R_{L1} + R_K'\qquad\qquad 3.14$$

From these equations, the appropriate load line can be constructed. The value of e_{g1} which locates the operating point of the tube is given by the equation

$$e_{g1} = E_1 - E - I_1 R_K' \le 0\qquad\qquad 3.15$$
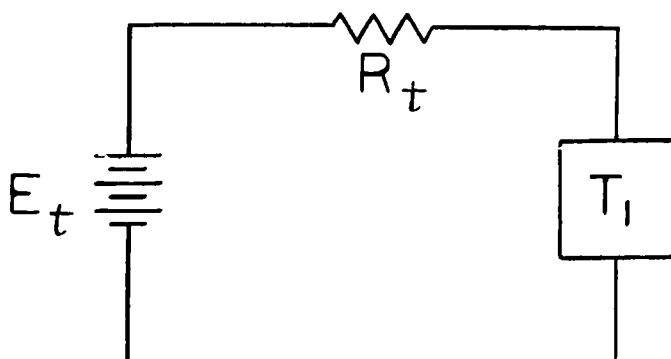
FIGURE 3.5

EFFECTIVE PLATE SUPPLY VOLTAGE AND LOAD
RESISTANCE OF TUBE T_1 FOR OPERATION IN REGION II

$$e_g = E_1 - E - I_1 R_K'$$
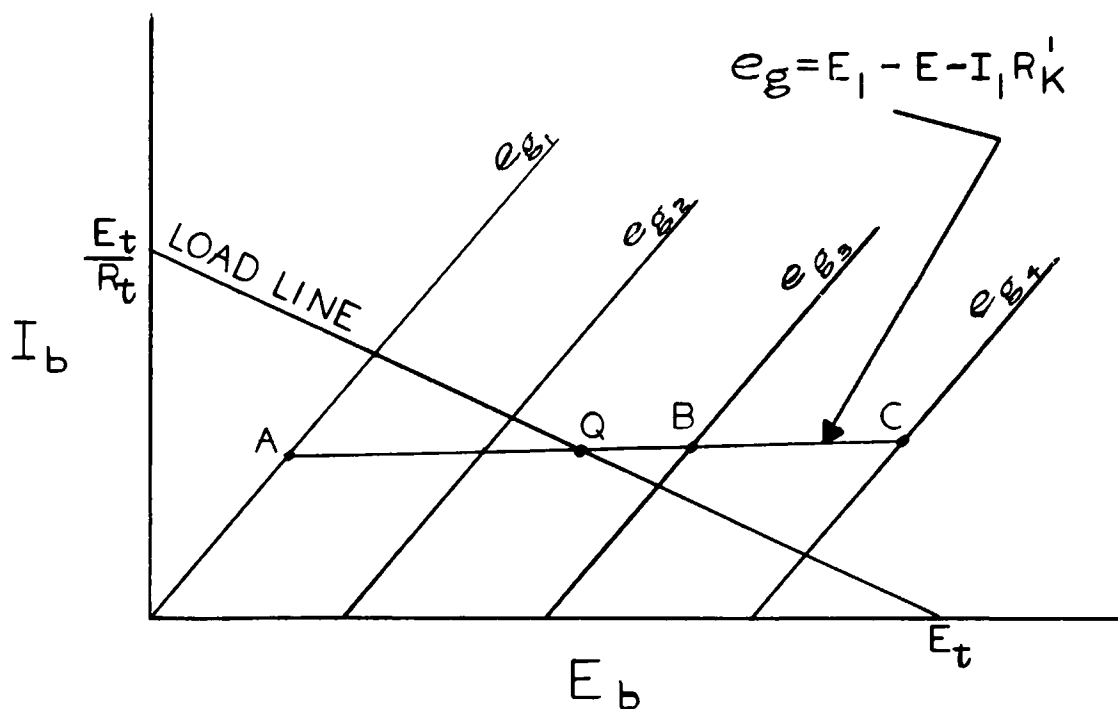
FIGURE 3.6

GRAPHICAL METHOD FOR DETERMINING THE OPERATING
POINT OF T_1 FOR OPERATION IN THE QUASI-STABLE STATE

The actual value for this voltage will be negative or zero but never positive due to the clamping action previously discussed. If Eq. 3.15 should yield a positive number it only indicates that the grid is clamped to the cathode voltage.

Since there are two variables present in the above equation, a trial and error solution is necessary. A graphical method is described by Millman and Taub[2] where values are assumed for I_1 with e_{g1} calculated from the equation. These values determine a curve which is also plotted on the plate characteristic curves. The intersection of this curve with the load line determines the operating point of the tube. This method is depicted in Fig. 3.6. It is possible that the operating point could fall to the left of the $e_{g1} = 0$ curve which would emphasize the fact that T_1 is in clamp.

Replacing the tubes with their appropriate circuit models yields the circuit shown in Fig. 3.7 where the switch is closed, and T_1 is in a clamped condition. The current I_1, as determined from this circuit when the current through R is assumed to be negligible, is given by the equations:

$$I_1 \text{ clamp} = \frac{E_{bb} - E}{R_{L1} + r_p + R_K'} \qquad 3.16$$

$$I_1 \text{ active} = \frac{E_{bb} + \mu_1 E_1 - E(\mu_1 + 1)}{r_p + R_{L1} + R_K'(\mu_1 + 1)} \qquad 3.17$$

[2] J. Millman and H. Taub, Pulse and Digital Circuits, McGraw-Hill Book Co., Inc., 1956, pp. 13-15
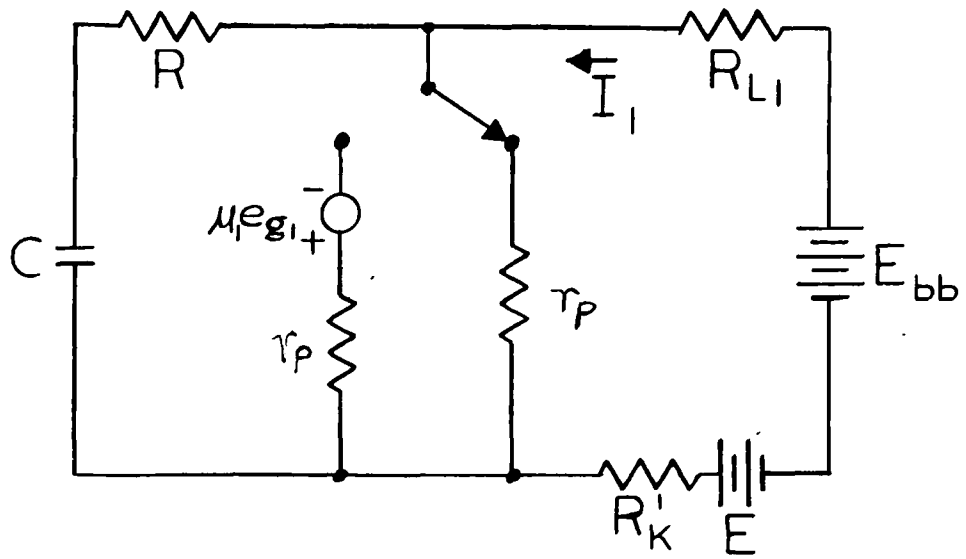
FIGURE 3.7

SIMPLIFIED EQUIVALENT CIRCUIT FOR
OPERATION IN THE QUASI-STABLE STATE
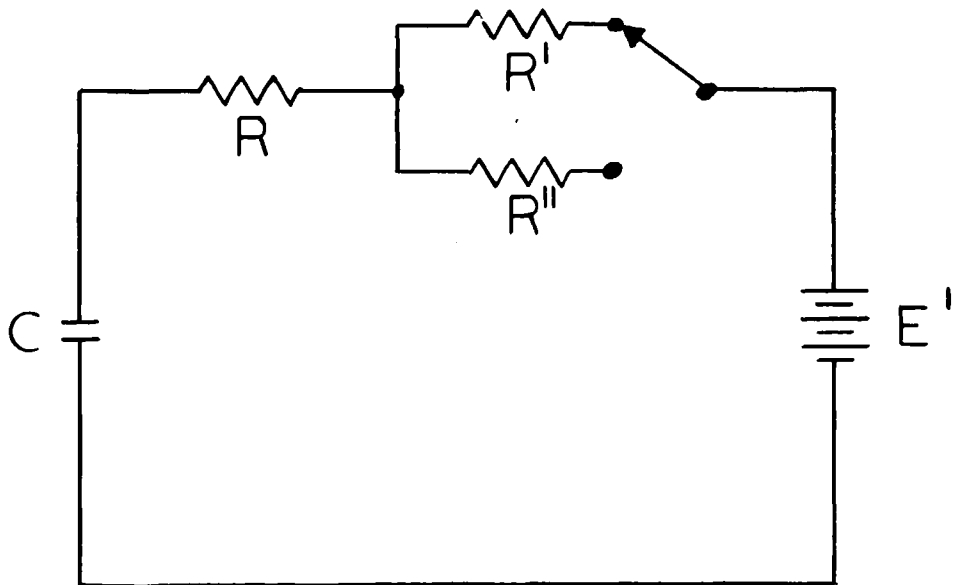
FIGURE 3.8

CALCULATION OF THE TIME CONSTANT FOR
OPERATION IN THE QUASI-STABLE STATE

where the values for r_p and μ_1 are determined graphically at the point of operation of T_1.

By simplifying the circuit in Fig. 3.7 to that of Fig. 3.8, we can determine the time constant τ, which has a value of:

$$\tau_{clamp} = (R' + R)\, C \cong RC \qquad\qquad 3.18$$

$$\tau_{active} = (R'' + R)\, C \qquad\qquad 3.19$$

where the assumptions

$$R' \cong r_p \qquad\qquad R \gg R'$$

$$R'' \cong R_{L1} + R_K' \qquad r_p < R_{L1} + R_K'$$

have been made.

Equations 3.16 through 3.19 make it possible to express Eq. 3.10 in terms of the circuit parameters, and after simplification has values given by the equations:*

$$T_{clamp} = (R)\,(C)\, \ln \left[\frac{R_K(r_p + R_{L1} + R_3) + R_{L1}\, R_3}{R_K(r_p + R_{L1} + R_3) + \dfrac{R_3}{\mu_2}\,(r_p + R_{L1})} \right] \qquad 3.20$$

$$T_{active} = (R'' + R)C\, \ln \left\{ \frac{R_K R_1\left[r_p + R_{L1}(1 - \mu_1) + R_3 \right] + R_K R_2 R_3(\mu_1 + 1) + R_2 R_3 R_{L1}(\mu_1 + 1)}{R_K R_1\left[r_p + R_{L1} + R_3\left(1 + \dfrac{\mu_1}{\mu_2}\right) \right] + R_K R_2 R_3\left(\mu_1 + 1 + \dfrac{\mu_1}{\mu_2}\right)} \right\} \quad 3.21$$

The plate supply voltage does not appear in these equations and illustrates the independence of the timing period of E_{bb}. However, the values for r_p, μ_1, and μ_2 depend to some extent on E_{bb} but will

_____

*See Appendix A

cause only a slight variation in T for moderate changes about the design value of E_{bb}. In Chapter 5, measurements will be made to determine the percentage change in T for various changes in the supply voltage.

3.5   TRIGGERING OF THE MONOSTABLE MULTIVIBRATOR

Upon the termination of the quasi-stable state, the circuit reverts to its stable mode of operation and remains there until another trigger pulse is applied. If the method to be discussed below is employed, the circuit will not respond to the incoming trigger until E_{bl} has reached its final value of voltage. The recovery time of E_{bl} then limits the rate at which the triggers may be applied.

Let us refer to Fig. 3.2 to obtain the value for the time constant that dictates the recovery of E_{bl}. The time constant τ_1 has a value given by the equation:

$$\tau_1 = (R_{L1} + r_g) \, C \cong R_{L1} \, C \qquad\qquad 3.22$$

where it has been assumed that R_{L1} is much larger than r_g. Fig. 3.9 shows an example of a decaying exponential waveform plotted with the percentage of voltage remaining versus the number of time constants that have elapsed. A trigger pulse which is applied prematurely to the circuit, before E_{bl} fully recovers, could cause the timing period to be foreshortened. In order to prevent this, it is necessary to allow E_{bl} to essentially reach its final value of voltage. As may be observed from the exponential waveform of Fig. 3.9, it takes an infinite number of time constants to reach the final value of voltage. For the

accuracies involved in this thesis, it will be adequate to allow ap-
proximately five time constants to elapse before the application of
the trigger. The maximum rate at which the trigger pulses should be
applied is then defined by the equation:

$$T \text{ (Trigger)} = T + 5\tau_1 \qquad\qquad 3.23$$

The method and type of triggering are also important and
there are a number of different ways in which triggering may be ac-
complished. One method of triggering is by the application of a
positive pulse to the normally off grid of T_1; however, this requires
a very large pulse in most instances because of the large negative
bias necessary to insure that T_1 is held cut off. For the circuit
under discussion, a positive pulse of amplitude

$$E_T \; > \; E_1 - E + E_{col} \qquad\qquad 3.24$$

would be required. It is also quite possible that the negative-
going portion of the positive triggering pulse will cause a reverse
transition and destroy the action of the multivibrator. This is
often the case since it requires a much smaller pulse to drive the
tube back into cut off than was necessary to place the tube into
operation. A negative trigger, therefore, is much more effective
than a positive one.[3]

A preferable method of triggering then, is the application
of a negative pulse to the grid of T_2 or to the plate of T_1 which is

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[3] J. Millman and H. Taub, Pulse and Digital Circuits, McGraw-Hill
Book Co., Inc., 1956, pp. 156-159
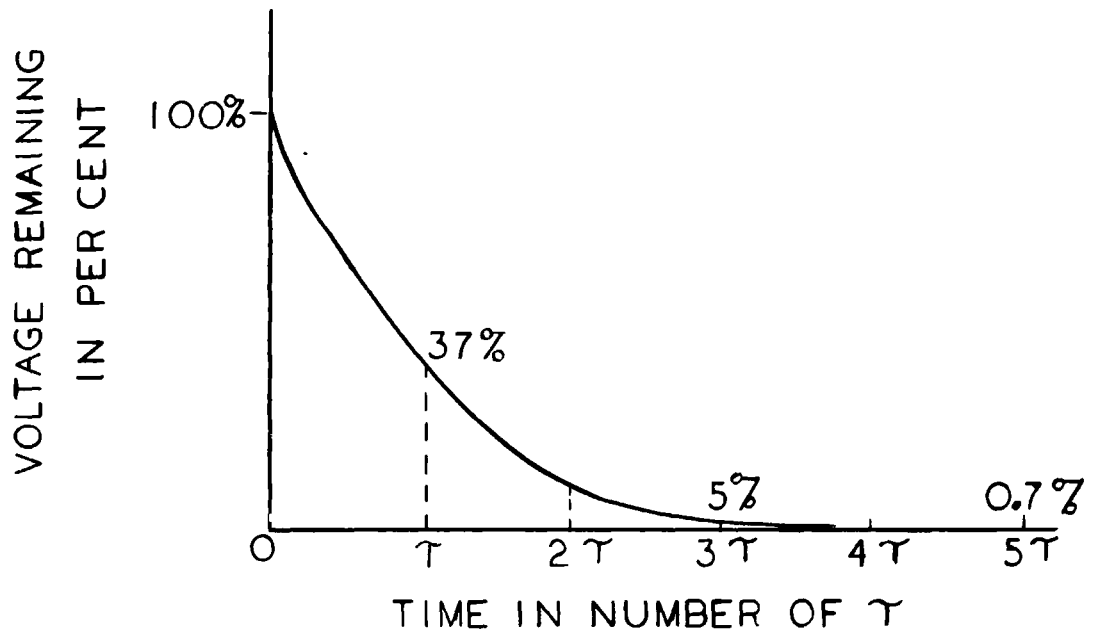
FIGURE 3.9

GENERALIZED EXPONENTIAL WAVEFORM
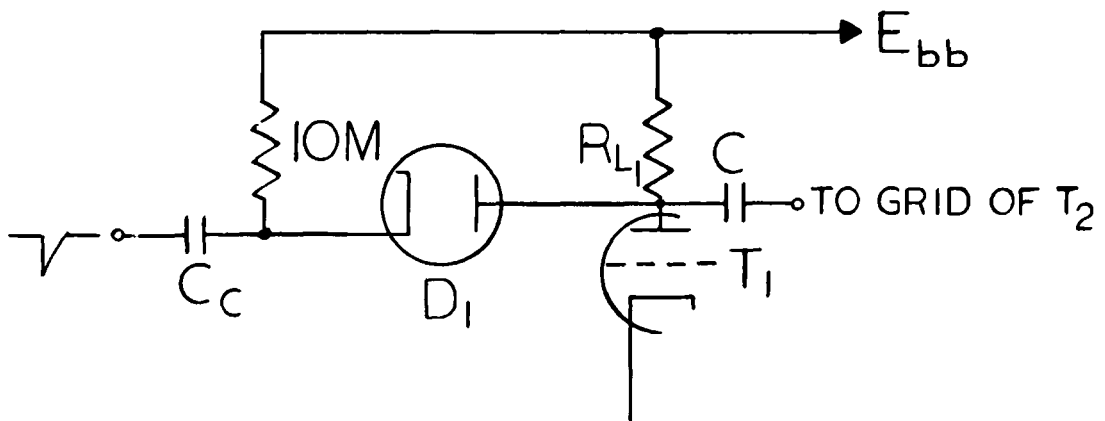
FIGURE 3.10

RECOMMENDED METHOD FOR TRIGGERING THE
VACUUM-TUBE MONOSTABLE MULTIVIBRATOR

coupled to the grid of T_2 by the capacitor C. This triggering arrangement is illustrated in Fig. 3.10. At the instant of the transition, the plate of T_1 will drop in voltage and reverse bias the diode causing the triggering signal to be decoupled from the multivibrator until the completion of the quasi-stable state. This results in a much more reliable action.

The method of triggering may be dictated by considerations other than those mentioned, however the importance of the subject is not intended to be deemphasized since proper circuit action is dependent upon reliable triggering.

CHAPTER 4

ANALYSIS OF THE TRANSISTOR MONOSTABLE MULTIVIBRATOR

4.1 INTRODUCTION

Transistors have numerous advantages over vacuum tubes, in particular: they are much smaller in size, they require no filament power, they operate at a lower supply voltage, they have lower power dissipation, and they normally have a longer operating life than tubes. The superior switching properties of transistors, as may be observed from the circuit models of Chapter 2, make them particularly well suited for application in switching circuits.

The circuit of Fig. 4.1 is the transistor counterpart of the vacuum tube circuit considered previously. The voltages and currents are defined as shown in Figure 4.1.

4.2 STABLE STATE OPERATION

By the proper selection of R_2 and R_E, the operation of transistor T_1 is designed to be held in the cut-off condition and transistor T_2 to be in clamp. This condition is necessary to assure reliable operation of the circuit and to take advantage of the excellent switching properties of the transistors. For this condition, the circuit can be reduced to the circuit given in Fig. 4.2 where the transistors have been replaced by their circuit models and the values
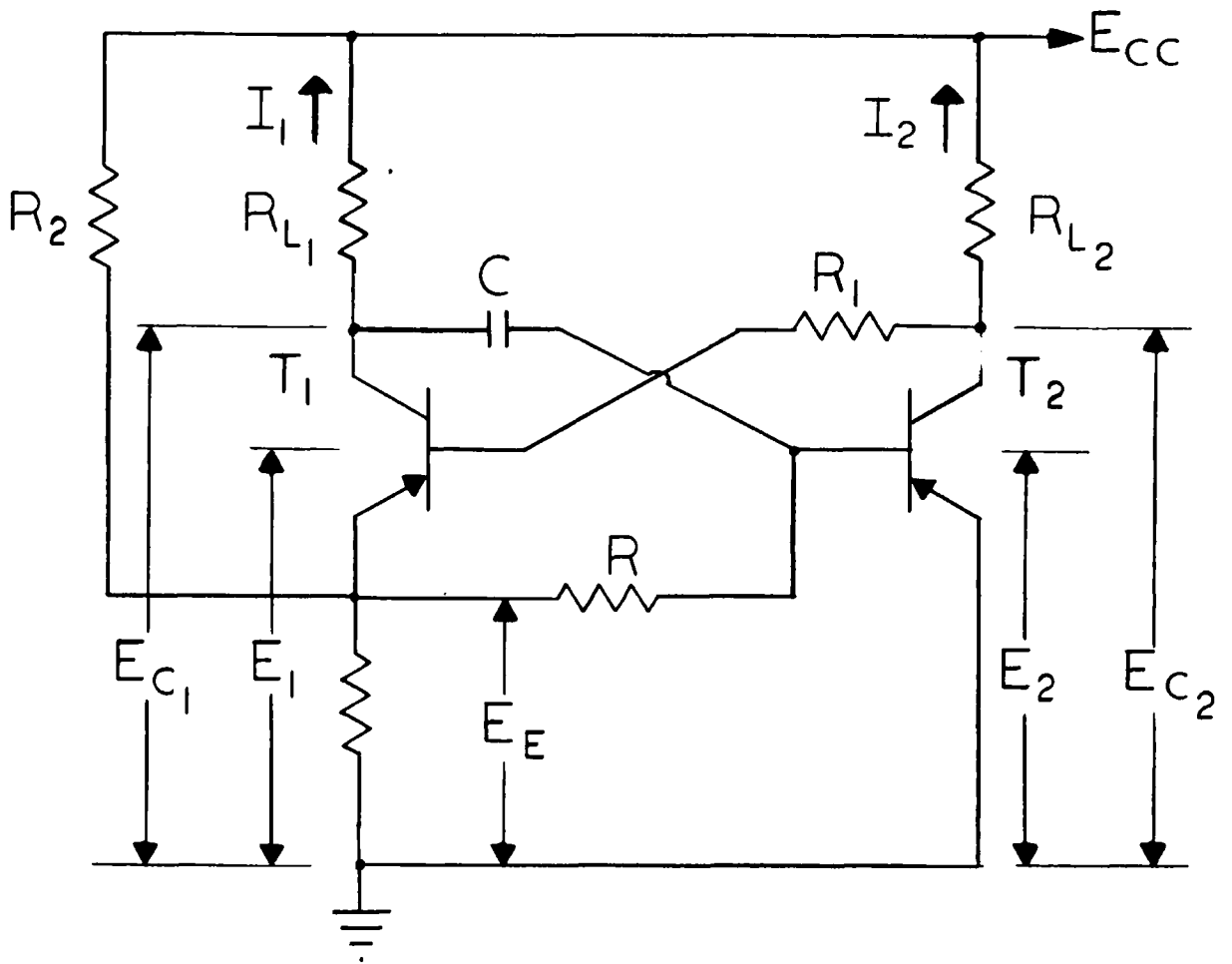
FIGURE 4.1

TRANSISTOR MONOSTABLE MULTIVIBRATOR
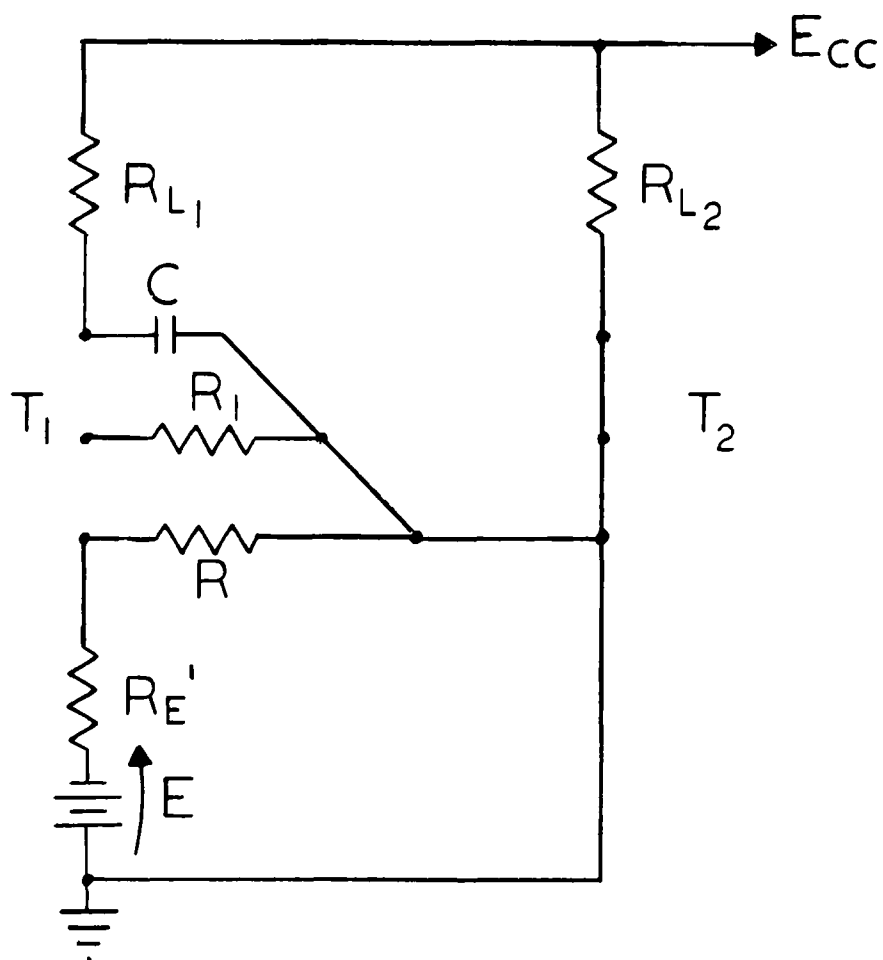
FIGURE 4.2

EQUIVALENT CIRCUIT FOR OPERATION IN THE STABLE STATE

for R_E' and E are given by the equations:

$$R_E' = \frac{R_E \; R_2}{R_E + R_2} \qquad\qquad 4.1$$

$$E = \frac{E_{cc} \; R_E}{R_E + R_2} \qquad\qquad 4.2$$

A selection for the value of either R_2 or R_E is initially made with the other to be calculated after the desired magnitude for E has been established.

The base current necessary to drive T_2 into saturation specifies that E have a magnitude of:

$$E \quad > \quad I_{BO} \; R \qquad\qquad 4.3$$

where I_{BO} is defined by the intersection of the load line with the line created by the merging of the current curves as shown in Fig. 2.7(a). The requirement that T_1 be cut off is also satisfied by the value of E as given in Eq. 4.3.

The voltages that result from operation in this state are given in Table III where

$$R \quad \gg \quad R_E' \qquad\qquad 4.4$$

TABLE III

TRANSISTOR STABLE STATE VOLTAGE EQUATIONS

VOLTAGE	VALUE
E_{c1}	E_{cc}
E_{c2}	$\cong 0$
E_1	$\cong 0$
E_2	$\cong 0$
E_E	E

These conditions, specified by Table III, will prevail until the application of an external trigger causes a transition to the quasi-stable state.

4.3 QUASI-STABLE STATE OPERATION

Upon the application of a trigger pulse, transistor T_2 is cut off and E_{c2} drops quickly to E_{cc}; this, in turn, causes T_1 to be driven into saturation through its base connection to the collector of T_2. At this instant of time, the equivalent circuit is given by Fig. 4.3 where the transistors have again been replaced by their circuit models. The voltages are calculated from this circuit and have the values given in Table IV.
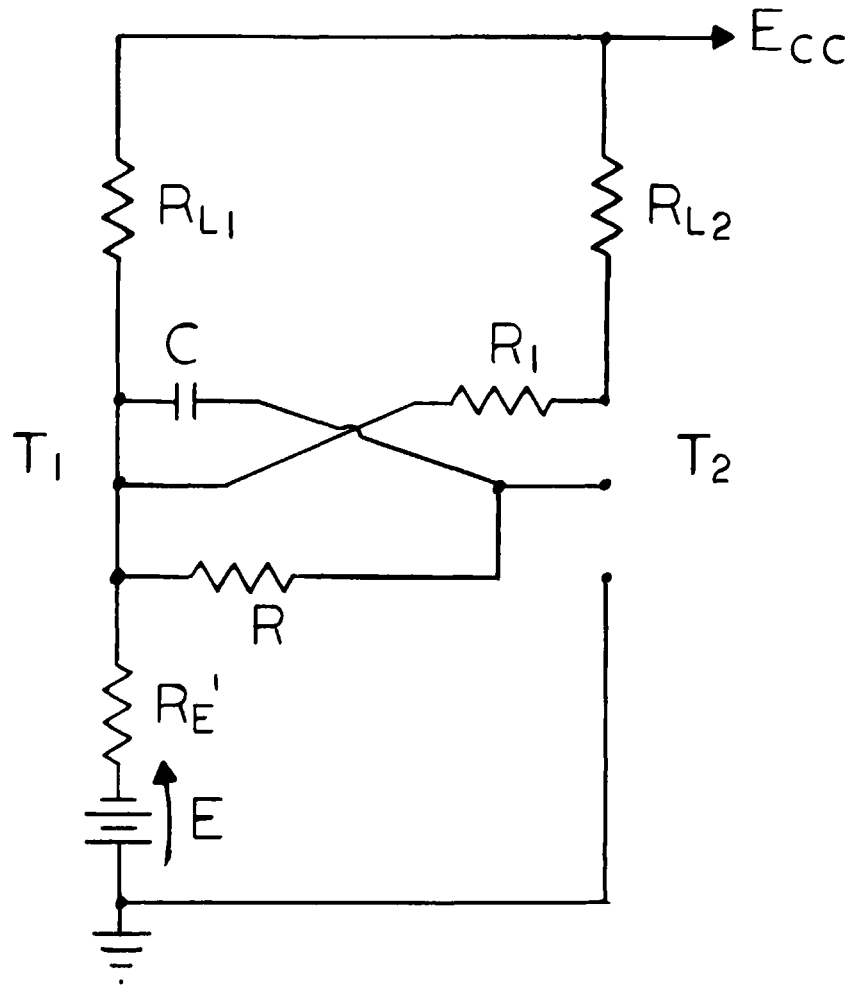
FIGURE 4.3

EQUIVALENT CIRCUIT FOR OPERATION IN THE QUASI-STABLE STATE

TABLE IV

TRANSISTOR QUASI-STABLE STATE VOLTAGE EQUATIONS

VOLTAGE	VALUE
E_{c1}	$E_{cc} + I_1 R_{L1}$
E_{c2}	E_{cc}
E_1	E_E
E_2	$I_1 R_{L1}$
E_E	$E - I_1 R_E'$

The current I_1 and time constant τ are also calculated from Fig. 4.3 and have values represented by:

$$I_1 = \frac{-E_{cc} + E}{R_{L1} + R_E'} \qquad\qquad 4.5$$

$$\tau = RC \qquad\qquad 4.6$$

where it is assumed that

$$\frac{R_E'}{R_E' + R_{L2} + R_1} \quad << \quad 1 \qquad\qquad 4.7$$

If allowed to do so, the voltage at the base of T_2 would asymptotically approach a final value of E_E. The voltage E_2 is restrained from doing this, however, by the conduction of T_2 when the voltage reaches a value of zero which causes regeneration to the stable state.

FIGURE 4.4

IDEALIZED VOLTAGE WAVEFORMS OF
THE TRANSISTOR MONOSTABLE MULTIVIBRATOR

again limited by the decay of E_{Cl} to its final value. This is

defined by Eq. 3.23 where τ_1 for this circuit is calculated from

Fig. 4.2 and is given by:

$$\tau_1 = \left(R_{L1}\right)\left(C\right)$$

<div align="right">4.12</div>

This completes the analysis of the transistor circuit.

CHAPTER 5

EXPERIMENTAL TEST RESULTS

5.1 TEST PROCEDURE

In order to substantiate the validity of the mathematical analysis, experimental circuits were constructed and tested for both the vacuum-tube and transistor circuits. Figure 5.1 shows a block diagram of the experimental setup used to obtain the various measurements. The measured values will be compared with the values calculated from the mathematical formulas of Chapters 3 and 4. The vacuum-tube circuit is considered first.

5.2 VACUUM-TUBE EXPERIMENTAL RESULTS

Since the equation for the timing period of the unclamped case is much more complex and more dependent upon the tube parameters, it is anticipated that more reliable and satisfactory results are obtained from the clamped case. It is felt, however, that the unclamped case would exhibit excellent independence of changes in the supply voltage, but would be very sensitive to other factors, such as tube replacements, tube aging, and filament voltage change. Since preliminary tests verified these assumptions, the author highly recommends the circuit where T_1 is in clamp during the quasi-stable state. A circuit of this configuration was designed and is shown in Fig. 5.2.

49
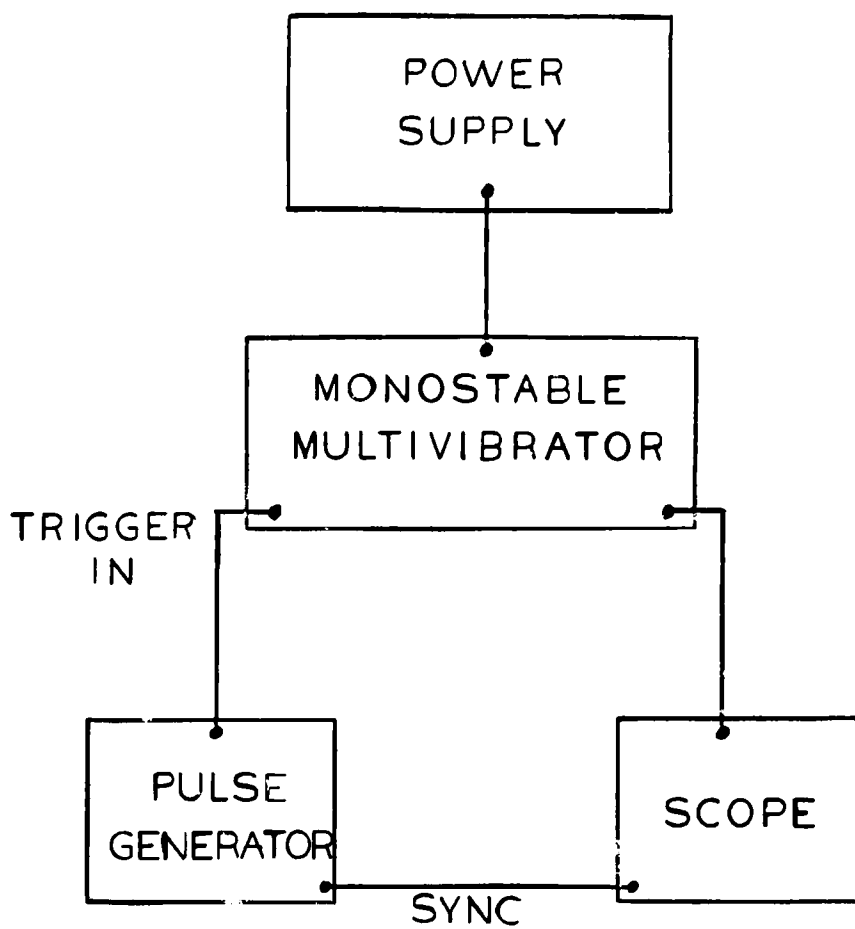
FIGURE 5.1

BLOCK DIAGRAM OF THE EXPERIMENTAL SETUP
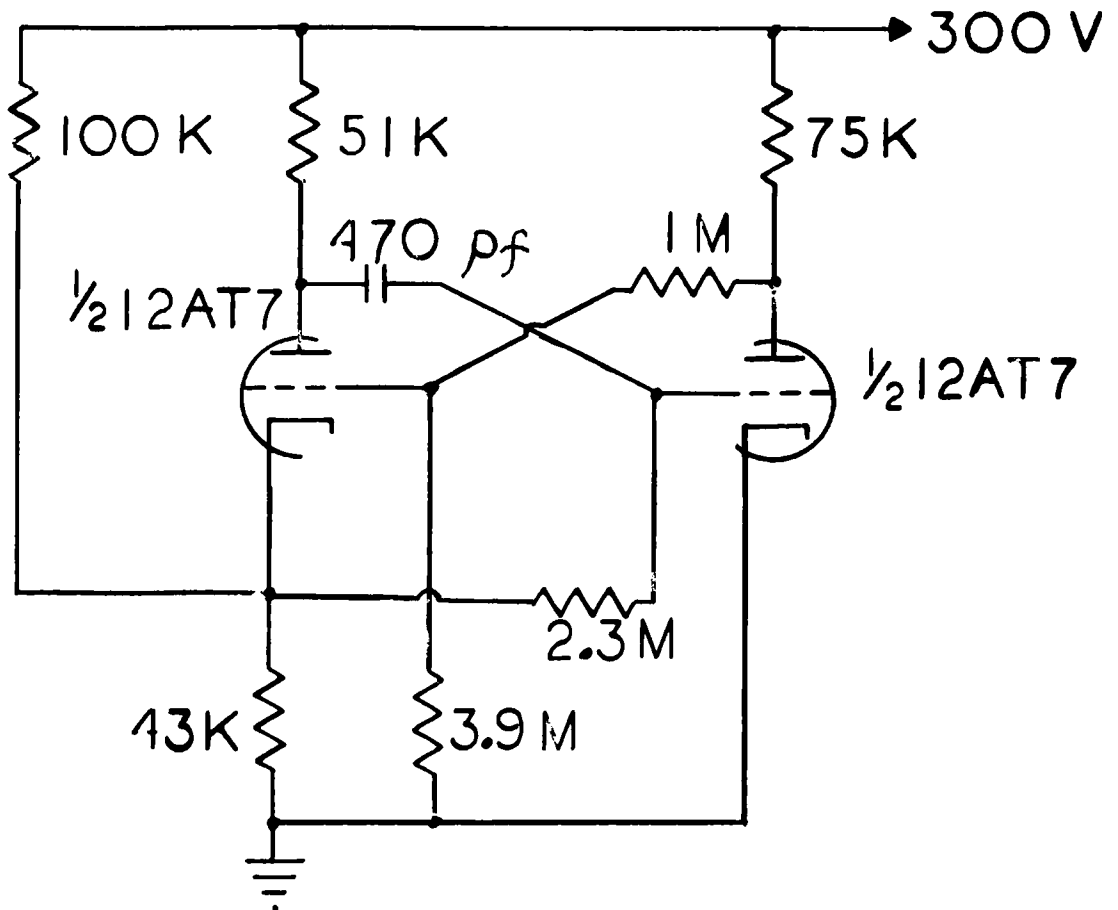
FIGURE 5.2

EXPERIMENTAL VACUUM-TUBE MONOSTABLE MULTIVIBRATOR

The indicated circuit parameters were selected for the following reasons: R_{L2} to provide an output swing of approximately 200 volts, R_3 and R_K to satisfy Eqs. 3.1 and 3.4, R_1 and R_2 to hold T_1 in clamp during the quasi-stable state, R and C to give a timing period of 500 microseconds, and R_{L1} to cause the argument of the logarithm of Eq. 3.20 to have as large a value as possible. The argument of the logarithm must be kept large in order to minimize the effect that small changes in r_p and μ_2 will have on the value of the timing period. The resistor R_{L1} is selected to satisfy this requirement since the remaining components are speci-fied by other considerations. This resistor cannot have too large a value, however, and a compromise must be made.

The load lines, corresponding to the above components, are plotted on the plate characteristic curves of the 12AT7, a twin-triode frequently used as an oscillator, and appear as shown in Fig. 5.3. The values for r_p and μ_2 are found graphically from these curves and have values of 30 kilohms and 25 respectively. Since it is verified, both mathematically and experimentally, that T_1 is in clamp during the quasi-stable state, the above values may be utilized to solve Eq. 3.20 for the resistance R and capacitance C. For the given value of 470 picofarads for C, a value of 2.3 megohms for R is necessary in order to have a timing period duration of 500 microseconds. It is normal practice for the components to be 10% units whenever possible, and this practice is followed here with the exception of R and C which are 1% precision units. This choice allows a more realistic
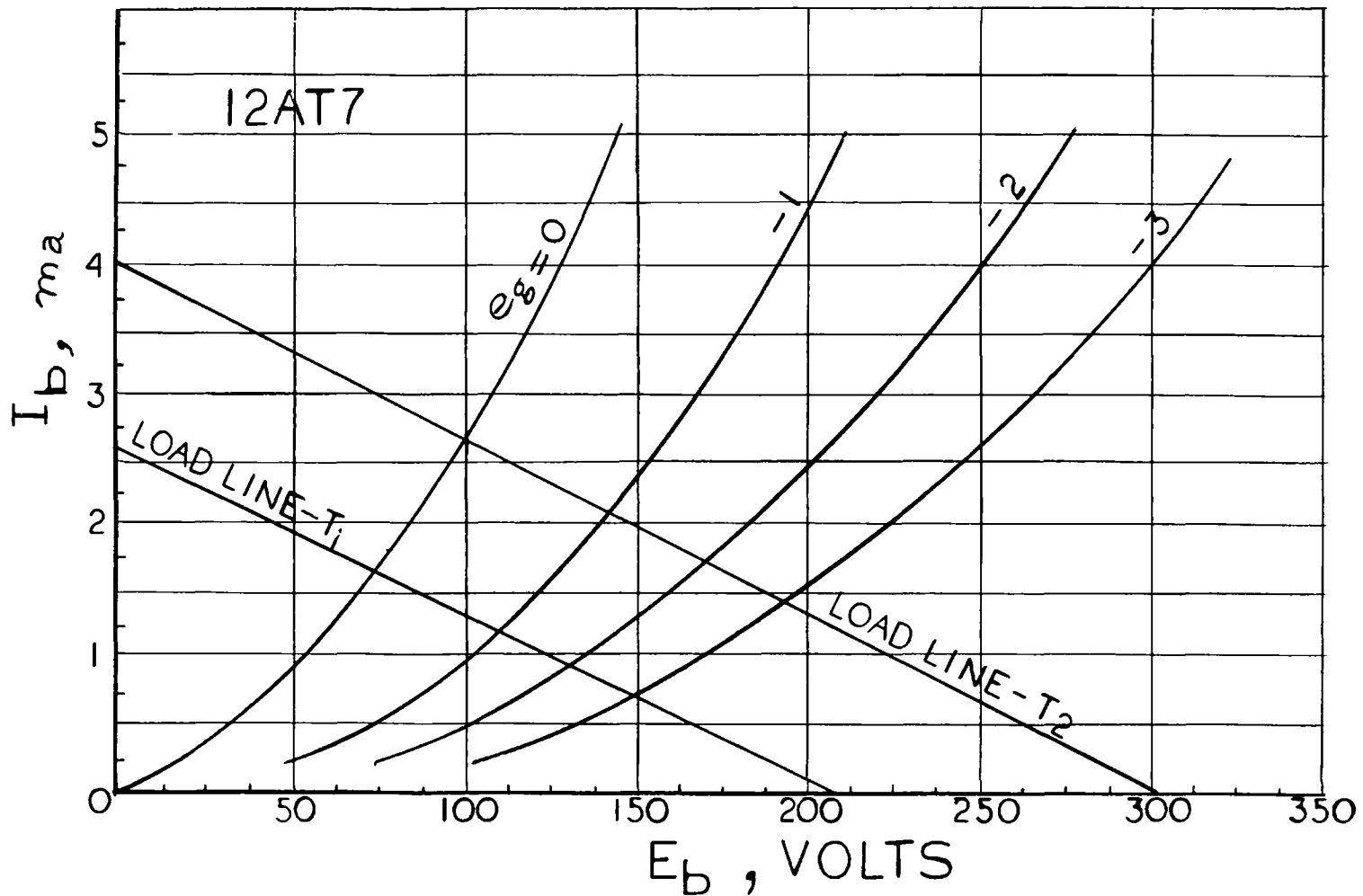
FIGURE 5.3
CHARACTERISTIC CURVES FOR A 12AT7
VACUUM-TUBE TRIODE

comparison to be made between the calculated and measured results.

Table V gives the calculated versus measured values of voltage

for both the stable state and the quasi-stable state.

TABLE V

EXPERIMENTAL RESULTS FOR THE VACUUM-TUBE
MONOSTABLE MULTIVIBRATOR CIRCUIT

MEASURED AND CALCULATED VOLTAGE VALUES

VOLTAGE	STABLE STATE		QUASI-STABLE STATE	
	CALCULATED	MEASURED	CALCULATED	MEASURED
E_{b1}	300	300	216	200
E_{b2}	100	90	300	290
E_1	79	60	140	160
E_2	0	0	-84 to 0	-100 to 0
E_K	90	90	140	160

The measured value for T is 485 microseconds and compares favorably

with the design value of 500 microseconds, an error of only three

per cent. A measurement was made to determine the sensitivity of the

timing period to changes in the supply voltage. The waveforms of

Fig. 5.4 indicate the change in T when E_{bb} is varied in 50 volt

increments from 300 volts to 150 volts. The lower set of waveforms

in Fig. 5.4 shows the expanded trailing edge of E_{b2}, which allows

an accurate measurement to be made when E_{bb} is varied in the above

manner. These results are summarized in Table VI where

100 v/cm

50 μs/cm

100 v/cm

2 μs/cm
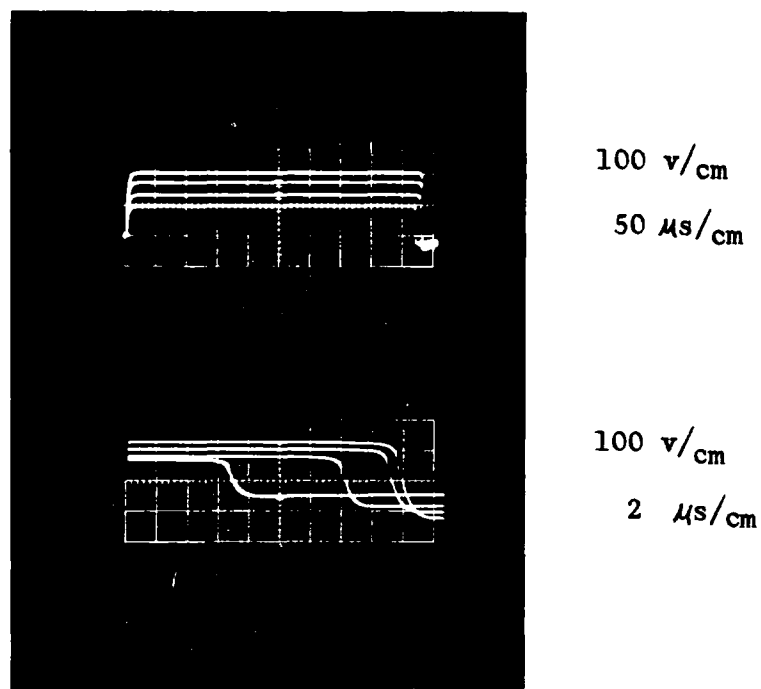
FIGURE 5.4

OUTPUT WAVEFORM OF THE VACUUM-TUBE MONOSTABLE
MULTIVIBRATOR FOR DIFFERENT VALUES OF SUPPLY VOLTAGE

$$\% \text{ change in } E_{bb} = \frac{300 - E_{bb}}{300} \times 100 \% \qquad 5.1$$

$$\% \text{ change in } T = \frac{T_{300} - T}{T_{300}} \times 100 \% \qquad 5.2$$

TABLE VI

EXPERIMENTAL RESULTS FOR THE VACUUM-TUBE MONOSTABLE
MULTIVIBRATOR CIRCUIT

PER CENT CHANGE IN T VERSUS PER CENT CHANGE IN E_{bb}

E_{bb}	% Change in E_{bb}	T	% Change in T
300	0	485	0
250	16.7	485	0
200	33.3	481	0.83
150	50	474	2.3

5.3 TRANSISTOR EXPERIMENTAL RESULTS

The values of the circuit parameters shown in Fig. 5.5 were selected for the following reasons: R_{L2} to limit the current that flows through the collector of T_2, R_2 and R_E to satisfy Eqs. 4.2 and 4.3, R_1 to limit the base current of T_1 when it is in clamp, R and C to provide a timing period of 50 microseconds, and R_{L1} to cause the argument of the logarithm of Eq. 4.11 to have as large a value as possible. It is again necessary to make a compromise as the value of R_{L1} should not become excessive.
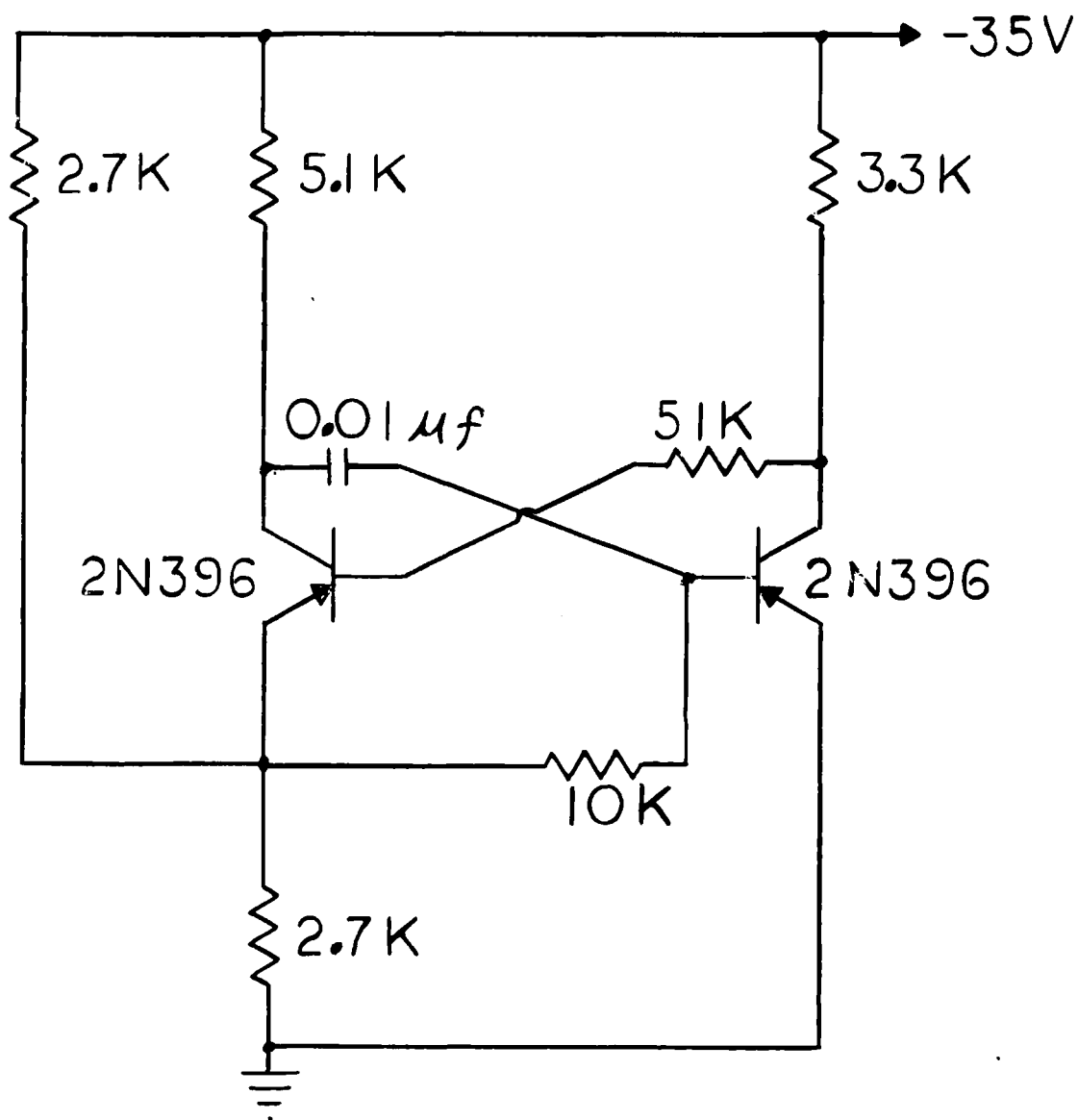
FIGURE 5.5

EXPERIMENTAL TRANSISTOR MONOSTABLE MULTIVIBRATOR

Two p-n-p switching transistors, 2N396's, were utilized in the experimental circuit. For a given value of 0.01 microfarads for C, a value of 10 kilohms for R is necessary in order to have a timing period of 50 microseconds. In order to make a more realistic comparison between the calculated and measured values, precision units were again selected for R and C. Table VII shows the calculated versus measured values of voltage for both the stable state and quasi-stable state. The measured value for T is 49 microseconds and indicates excellent correlation with the calculated value of 50 microseconds.

TABLE VII

EXPERIMENTAL RESULTS FOR THE TRANSISTOR MONOSTABLE
MULTIVIBRATOR CIRCUIT

MEASURED AND CALCULATED VOLTAGE VALUES

VOLTAGE	STABLE STATE		QUASI-STABLE STATE	
	CALCULATED	MEASURED	CALCULATED	MEASURED
E_{c1}	-35	-35	-21	-21
E_{c2}	0	0	-35	-32
E_1	0	0	-21	-22
E_2	0	0	14 to 0	14 to 0
E_E	-17.5	-16	-21	-22

The waveforms of Fig. 5.6 indicate the change in T when E_{cc} is varied from -35 volts to -17.5 volts. The lower set of waveforms shows the trailing edge of E_{c2} which gives a very accurate indication

10 $v/_{cm}$

5 $\mu s/_{cm}$

10 $v/_{cm}$

.2 $\mu s/_{cm}$
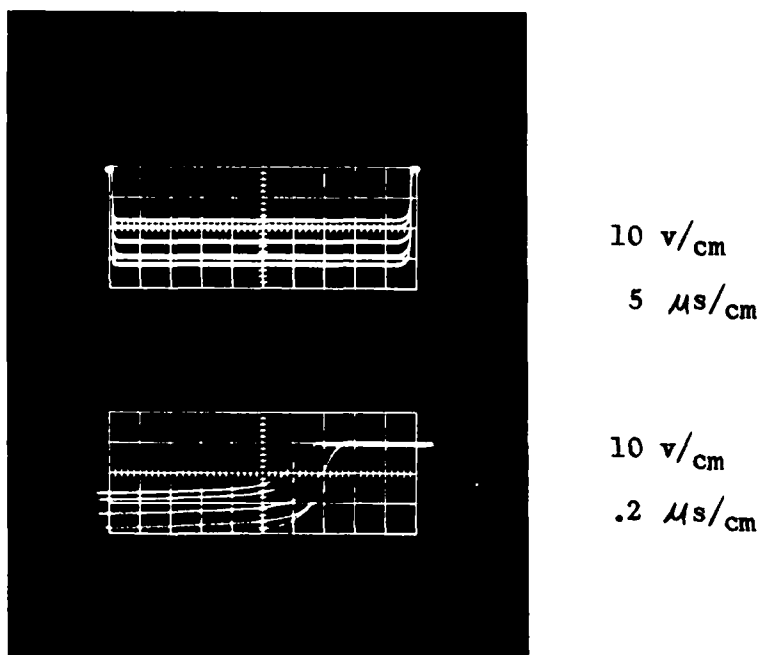
FIGURE 5.6

OUTPUT WAVEFORM OF THE TRANSISTOR MONOSTABLE
MULTIVIBRATOR FOR DIFFERENT VALUES OF SUPPLY VOLTAGE

of the timing period's independence of the supply voltage. These results are summarized in Table VIII where

$$\% \text{ change in } E_{cc} = \frac{35 + E_{cc}}{35} \times 100\% \quad 5.3$$

$$\% \text{ change in } T = \frac{T_{35} - T}{T_{35}} \times 100\% \quad 5.4$$

TABLE VIII

EXPERIMENTAL RESULTS FOR THE TRANSISTOR MONOSTABLE
MULTIVIBRATOR CIRCUIT

PER CENT CHANGE IN T VERSUS PER CENT CHANGE IN E_{cc}

E_{cc}	% Change In E_{cc}	T	% Change in T
-35	0	49.0	0
-30	14.3	49.04	0.08
-25	28.6	49.0	0
-20	42.9	48.9	0.2
-17.5	50	48.75	0.51

CHAPTER 6

CONCLUSIONS

6.1 PERFORMANCE EVALUATION

The experimental results of Chapter 5 show excellent correlation

with the values calculated from the mathematical formulas of Chapters

3 and 4. The validity of the equations that were developed has been

established, and it may also be observed that only negligible errors

have occurred due to the approximations that were made. For the

specified design conditions, there was only a 3% difference between

the measured and calculated values of the timing period. This error

can, of course, be made negligible by an adjustment of either R or C.

The desired objective that the timing period be independent

of supply voltage has been achieved. A 50% change in the supply

voltage resulted in a timing period variation of only 2.3% for the

vacuum-tube circuit and 0.51% for the transistor circuit.

6.2 RECOMMENDATIONS FOR FURTHER STUDY

An investigation should be conducted to determine what

limits exist on the timing period of these monostable multivibrators.

In order to obtain faster waveforms, the rise and fall times of the

pulse must be shortened. A study should also be made to determine

what effect different trigger pulses would have on these circuits.

A possible trouble area, in obtaining longer timing periods, is in

the loading caused by the input resistance of the second stage. This is especially true of the transistor circuit.

The feasibility of obtaining a variable delay from these multivibrators should be investigated. It may be possible to achieve results that are superior to those obtained from the cathode-coupled monostable multivibrator, thus providing a circuit that compares favorably with the phanastron[4] as a stable delay device.

[4]J. M. Pettit, Electronic Switching, Timing, and Pulse Circuits, McGraw-Hill Book Company, Inc., New York, 1959, pp 182-187

APPENDIX A

THE DERIVATION OF THE TIMING PERIOD FOR

THE CASE WHERE T_1 IS IN CLAMP

The equation for the timing period of the vacuum-tube monostable multivibrator will be expressed as a function of the circuit parameters. In order to do this, the equations that define E, I_1 and E_{co2} will be substituted into Eq. 3.10 and the ensuing result simplified.

$$T = \mathcal{T} \ln \frac{E + I_1 R_K' + I_1 R_{L1}}{E + I_1 R_K' - E_{co2}} \qquad 3.10$$

where

$$E = \frac{E_{bb} R_k}{R_k + R_3} \qquad\qquad R_K' = \frac{R_K R_3}{R_K + R_3}$$

$$I_1 \text{ (clamp)} = \frac{E_{bb} - \dfrac{E_{bb} RK}{R_K + R_3}}{R_{L1} + r_p + \dfrac{R_K R_3}{R_K + R_3}}$$

$$= \frac{R_3 E_{bb}}{R_{L1} R_K + R_{L1} R_3 + r_p R_K + R_3 r_p + R_K R_3} \qquad\qquad E_{co2} = - \frac{E_{bb}}{\mathcal{M}_2}$$

Therefore:

$$T = \tau \ln \left\{ \frac{\dfrac{E_{bb}R_k}{R_k + R_3} + E_{bb}\left\{ \dfrac{R_K R_3^2 + (R_{L1}R_3)(R_K + R_3)}{[R_{L1}(R_K+R_3) + r_p(R_K+R_3) + R_K R_3]\,[R_K+R_3]}\right\}}{\dfrac{E_{bb}R_K}{R_K+R_3} + \left[\dfrac{E_{bb}}{R_K+R_3}\right]\left[\dfrac{R_K R_3^2}{R_{L1}(R_K+R_3) + r_p(R_K+R_3) + R_K R_3}\right] + \dfrac{E_{bb}}{\mu_2}} \right\}$$

$$= \tau \ln \left\{ \frac{R_K\left[R_{L1}(R_K+R_3) + r_p(R_K+R_3) + R_K R_3\right] + R_K R_3^2 + R_3 R_{L1}(R_K+R_3)}{\left[R_k + \dfrac{R_k}{\mu_2} + \dfrac{R_3}{\mu_2}\right]\left[R_{L1}(R_K+R_3) + r_p(R_K+R_3) + R_K R_3\right] + R_K R_3^2} \right\}$$

when

$$\mu_2 \gg 1$$

$$T = \tau \ln \left[\frac{(R_K + R_3)(R_{L1} \times R_K + R_K r_p + R_K R_3 + R_{L1}R_3)}{(R_k + R_3)\left(R_{L1}R_K + R_K r_p + R_K R_3 + \dfrac{R_3 R_{L1}}{\mu_2} + \dfrac{R_3 r_p}{\mu_2}\right)} \right]$$

$$= \tau \ln \left[\frac{R_K(R_{L1} + r_p + R_3) + R_{L1}R_3}{R_K(R_{L1} + r_p + R_3) + \left(\dfrac{R_3}{\mu_2}\right)(R_{L1} + r_p)} \right] \qquad 3.20$$

The derivation for the case where T_1 is operating in the active region
is much more involved but follows the same pattern as the above
derivation. The simpler case, then, will suffice to illustrate the
manner in which the equations for the timing period were derived.

APPENDIX B

THE DERIVATION OF THE TIMING PERIOD

FOR THE TRANSISTOR CIRCUIT

The equation for the timing period of the transistor monostable multivibrator will be expressed as a function of the circuit parameters. In order to do this, the equations that define E and I_1 will be substituted in Eq. 4.10 and the ensuing result simplified.

$$T = \tau \ln\left[\frac{E - I_1 R_E' - I_1 R_{L1}}{E - I_1 R_E'}\right] = \tau \ln\left[1 - \frac{I_1 R_{L1}}{E - I_1 R_E'}\right]$$

$$= \tau \ln\left[1 - \frac{R_{L1}}{\dfrac{E}{I_1} - R_E'}\right]$$

where

$$E = \frac{E_{cc} R_E}{R_E + R_2} \qquad\qquad R_E' = \frac{R_E R_2}{R_E + R_2}$$

$$I_1 = \frac{-E_{cc} + E}{R_{L1} + R_E'} = -E_{cc}\left[\frac{-R_E + (R_E + R_2)}{R_{L1}(R_E + R_2) + R_E R_2}\right]$$

$$= -E_{cc}\left[\frac{R_2}{R_{L1}(R_E + R_2) + R_E R_2}\right]$$

$$\frac{E}{I_1} = \left[\frac{E_{cc} R_E}{R_E + R_2}\right]\left[-\frac{R_{L1}(R_E + R_2) + R_E R_2}{E_{cc} R_2}\right] = -\frac{R_E R_{L1}(R_E + R_2) + R_E^2 R_2}{R_2(R_E + R_2)}$$

$$T = \tau \ln \left[1 + \frac{R_{L1}}{\dfrac{R_E R_{L1}(R_E + R_2) + R_E^2 R_2 + R_2^2 R_E}{R_2(R_E + R_2)}} \right]$$

$$T = \tau \ln \left[1 + \frac{R_2 R_{L1}(R_E + R_2)}{R_E(R_{L1} + R_2)(R_E + R_2)} \right]$$

$$T = \tau \ln \left[1 + \frac{R_2 R_{L1}}{R_E(R_{L1} + R_2)} \right] \qquad 4.11$$

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