A STUDY OF CIRCUIT TECHNIQUES FOR VISUAL ANALYSIS OF TRANSISTOR PARAMETERS

by

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A STUDY OF CIRCUIT TECHNIQUES FOR VISUAL ANALYSIS OF TRANSISTOR PARAMETERS

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PREFACE

The transistor is a new electronic device which has already replaced the vacuum tube in many applications. The methods of manufacturing these devices are still not completely understood or controllable. However, when circuits are designed utilizing transistors, it is necessary that certain characteristics of the units be known. Due to the inability of the manufacturer to definitely state and guarantee the value of these characteristics over a narrow range, a method must be available for determining these characteristics for any specific unit which may be used.

It is the object of this work to present a means of visually displaying the essential characteristics of a transistor which will enable the design engineer to use the transistor in a manner which will deliver optimum results. As a sidelight, it is also noted that the visual display of a transistor's characteristics would be a valuable instructional aid for classroom lectures.

The writer is indebted to Dr. Harold T. Fristoe, Professor of Electrical Engineering, for the valuable guidance and able assistance which he has furnished. Gratitude is also due to Associate Professor Paul A. McCollum and to Mr. Winfred Day of Texas Instruments, Inc. for their assistance.

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CHAPTER I

INTRODUCTION

General Discussion

Semiconductor devices are being incorporated into various electronic circuits on a rapidly increasing scale. This makes it essential that for proper design work, specific engineering data must be supplied by the manufacturer or must be determined by the engineer himself. Many times the engineering data supplied by the manufacturer is not readily available. Also, the data supplied by the manufacturer represents an average unit of a certain type. With the transistor field still in its infancy, it is obvious that this data supplied by the manufacturer cannot represent the exact characteristics of a specific unit. This makes it essential that the engineer himself have a convenient means of rapidly obtaining the various characteristics he desires.

A point by point plot of various parameters is a tedious, time consuming job which should be avoided if at all possible. It is also unsuitable in the range where self-heating is significant because isothermal conditions cannot be maintained. Naturally, a piece of test equipment which could display or determine all the various characteristics of a transistor would be an extremely complex piece of electronic equipment. Many times only the fundamental electrical characteristics are necessary for design work. Also, the majority of the circuits utilizing transistors are connected in the so-called "common emitter" type of connection. Therefore, a piece of test equipment which could display or determine the fundamental, static, electrical characteristics of a transistor connected in the "common emitter" type connection would be a great aid to a design engineer.

A curve tracer which could visually display the family of output characteristics (V_C, I_C) of various transistors in the "common emitter" type connection would satisfy the previously stated requirements.

It would also be of great advantage if the curve tracer itself utilized strictly transistorized circuits. This would result in a portable piece of equipment with low power consumption due to the size, weight, and power requirements of a transistor.

The scope of this work is to present the essential circuits, using transistors, which would be necessary in the construction of a calibrated curve tracer which could visually display the static output characteristics of any NPN or PNP transistor in the low to medium power classification when connected in the "common emitter" type circuit.

Parameters

Figure 1 displays the "common emitter" output characteristics of a Texas Instruments Type 2N185 germanium PNP alloy junction transistor. This unit is especially designed for audio output applications.

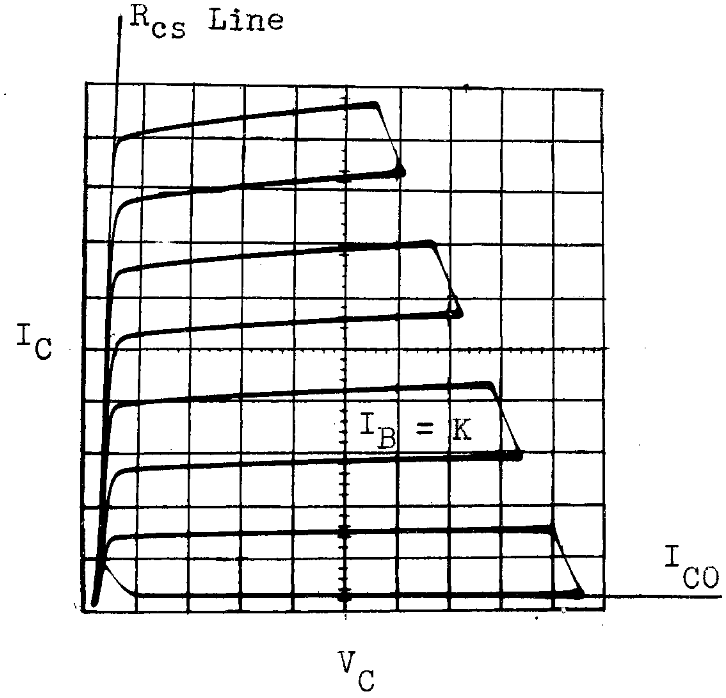

Figure 1. Common Emitter Output
Characteristics For
T. I. Type 2N185
Transistor

From these output characteristics various parameters may be determined. Some of these parameters are discussed below.

The D. C. current gain of a "common emitter" type connection is a very important property. It has various designations such as β (Beta), α_{CB}, and h_{FE}. It is the ratio of the steady state value of I_C (collector current) over the steady state value of I_B (base current) for a constant V_C (collector voltage). It may be shown as $\left.\frac{I_C}{I_B}\right|_{V_C = K}$. It is easily seen that by projecting vertically from a desired value of V_C to a desired value of I_B, a value of I_C may be obtained by projecting horizontally to the I_C axis. This gives the three requirements for obtaining Beta, namely

$$\beta = \left.\frac{I_C}{I_B}\right|_{V_C = K.}$$

The quantity α is defined as the ratio of I_C to I_E and is important in the grounded base connection. Therefore, $\left.\alpha = \frac{I_C}{I_E}\right|_{V_C = K} = \frac{I_C}{I_B + I_C}$ since $I_E = I_B + I_C$.

From these relationships, expressions for converting from α to β and β to α can be derived.

$$\alpha = \frac{I_C}{I_E} = \frac{I_C}{I_B + I_C} \qquad \text{so} \quad \alpha I_B + \alpha I_C = I_C$$

or $\alpha I_B = I_C - \alpha I_C$ and $\alpha I_B = I_C\,(1-\alpha)$.

Therefore, $\frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} = \beta$.

Also, since $\frac{\alpha}{1-\alpha} = \beta$, $\alpha = \beta - \beta\alpha$.

or, $\alpha + \beta\alpha = \beta$ and $\alpha(1+\beta) = \beta$.

Therefore, $\alpha = \frac{\beta}{1+\beta}$.

It is easily seen that if the D. C. Beta is known, the D. C. Alpha may be computed from the relation $\alpha = \frac{\beta}{1+\beta}$.

Since the D. C. Beta may be obtained from the family of static characteristic curves, it is obvious that the

A. C. Beta, also known as h_{fe} and h_{21}, may also be calculated. Instead of the steady D. C. current values being used as in the case of the D. C. Beta, an incremental current must be used for computing the A. C. Beta. Therefore, the expression is $h_{fe} = \frac{\Delta I_C}{\Delta I_B} \Big|_{V_C = K}$. Likewise, as with the D. C. Alpha, the A. C. Alpha may be determined from the expression $\alpha = \frac{\beta}{1+\beta}$.

When designing a circuit, as in an amplifier stage, it is essential that a D. C. load line be drawn. Here again, the family of static output characteristics may be used to construct the load line. The proper operating point, bias voltages, distortion, etc. may be determined from the V_C - I_C curves in the same manner as these factors are determined from the V_b - I_b curves of a vacuum tube.

From the operating point which has been determined, the "4 pole" collector resistance can be calculated. It is merely the ratio of V_C over I_C with I_B held constant. Likewise, the slope of the line from the operating point to the origin is the D. C. output admittance of the device.

It is known that the h parameters are the most convenient ones to measure at low frequencies; therefore, they are the parameters which are used most often to characterize the transistor equivalent circuit. Two of the four h parameters, namely h_{21e} and h_{22e}, may be determined from the static output characteristics. The small-signal, short-circuit, current-transfer ratio value $h_{21e} = \frac{i_C}{i_B} = \frac{\partial I_C}{\partial I_B} \Big|_{V_C = K}$ is the A. C. Beta value previously described. The small-signal, open-circuit, output admittance value $h_{22e} = \frac{i_C}{v_B} = \frac{\partial I_C}{\partial V_C} \Big|_{I_B = K}$ is the other h parameter which is available.

The value of R_{cs}, the collector saturation resistance, is another factor that is important in transistor circuit design. "It is the linear representation on Figure 1. of the boundary between the active and the saturation regions."[1] It originates at the origin of the V_C - I_C axes. The R_{cs} line can be seen to be a restriction on the applied signal. As the R_{cs} line moves to the right, the R_{cs} is increased, making the allowable undistorted signal smaller than if the line had a steeper slope. Therefore, it is desirable to have as low a R_{cs} as possible. This also represents an I^2R power loss in the transistor which is undesirable. The value of R_{cs} may vary from a few ohms to a few hundred ohms depending upon the unit. It causes the major part of the allowable power dissipation. The R_{cs} of any individual unit can readily be determined merely by a visual check on the display of the static output characteristics.

The saturation current symbolized by the terms I_{CO} or I_{CEO} also may be obtained from the static output character-

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[1] From personal contact with Mr. D. R. Fewer, Texas Instruments, Inc.

istics. It is defined as the collector current flowing when the collector is biased in the reverse (high resistance) direction with respect to the emitter electrode and the base electrode is open circuited.[2]

Summary

The advantages of the transistorized curve tracer are evident. The main asset is probably the speed with which the characteristics may be determined. The hours necessary to run tedious point by point plots are replaced by seconds. The equipment is accurate. The limiting point on the accuracy is possibly the size of the scope presentation. If a permanent record is desirable, photographs may easily be taken of the oscilloscope presentation.

The curve tracer would be extremely valuable in such applications as transistor life test studies, production line tests, and as an instructional aid. Units could be matched easily with this type of apparatus.

The result is a piece of test equipment capable of rapid, accurate measurements of the static output characteristics for various transistors in the low to medium power classification when connected in the "common emitter" type of connection.

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[2] A. W. Lo et al., Transistor Electronics (Englewood Cliffs, New Jersey) p. 137.

CHAPTER II

ESSENTIAL CIRCUITS

General Discussion

The curve tracers fundamental operation depends upon supplying the base with a series of constant current steps while simultaneously sweeping the collector voltage through a chosen voltage range for each step in the base current. Base bias current is then the parametric variable for plots of V_C and I_C and a family of characteristics may be displayed on a cathode ray oscilloscope.

There are several conditions which must be met first before the curve tracer may be considered safe and reliable. Some of these are listed in the IRE Standards on Methods of Testing Transistors.

> General Precautions in Transistor Measurement:
>
> Test conditions which cause large voltage or current surges, or exceed the safe limit of d.c. power dissipation should be avoided. Large overloads even for a small fraction of a second may cause damage to a transistor or modify its characteristics.
>
> The correct voltage polarity must be observed at all times. Incorrect voltage polarity may seriously damage the transistor and test equipment.[3]
>
> Repetition Rates:
>
> The upper limit of repetition rates is determined by the speed of response of the display mechanism, the display bandwidth required, the termination realizability, and the frequency response of the transistor. The lower limit of repetition rates in cathode-ray tube displays is determined

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[3] Proc. IRE, IRE Standards on Method of Testing Transistors, Vol. 44 p. 1545 Nov., 1956.

by flicker causing operator fatigue. A display repetition rate of less than 25 complete displays per second is usually found objectionable. Long-persistence cathode-ray tubes permit somewhat slower repetition rates, the actual rate depending on the characteristics of the phosphor used in the tube. It should be noted that in the case of the display of families of curves the entire family must be displayed within the minimum repetition rate.[4]

From the above statements, it is evident that the curve tracer must have closely controlled circuits which are stable and capable of being easily calibrated. The essential basic circuits have been developed in this work. Each essential circuit will be discussed briefly in this chapter. A complete chapter on each of the developed circuits will follow this chapter and their operation will be explained.

Figure 2. is a block diagram showing the essential, basic circuits which are necessary for the proper operation of a transistorized curve tracer that is capable of accurately displaying the static output characteristics of various transistors. The tracer is arranged to sweep the collector voltage from zero to a preset maximum value for each of the constant step values of I_B. In this piece of equipment the I_B has eight predetermined step values. Therefore, for each of the eight values of I_B, the V_C must vary through the entire range of voltage. After the V_C sweeps through its range for each of the eight I_B values, the complete

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[4] Proc. IRE, <u>IRE Standards on Method of Testing Transistors</u>, Vol. 44 p. 1545 Nov., 1956.

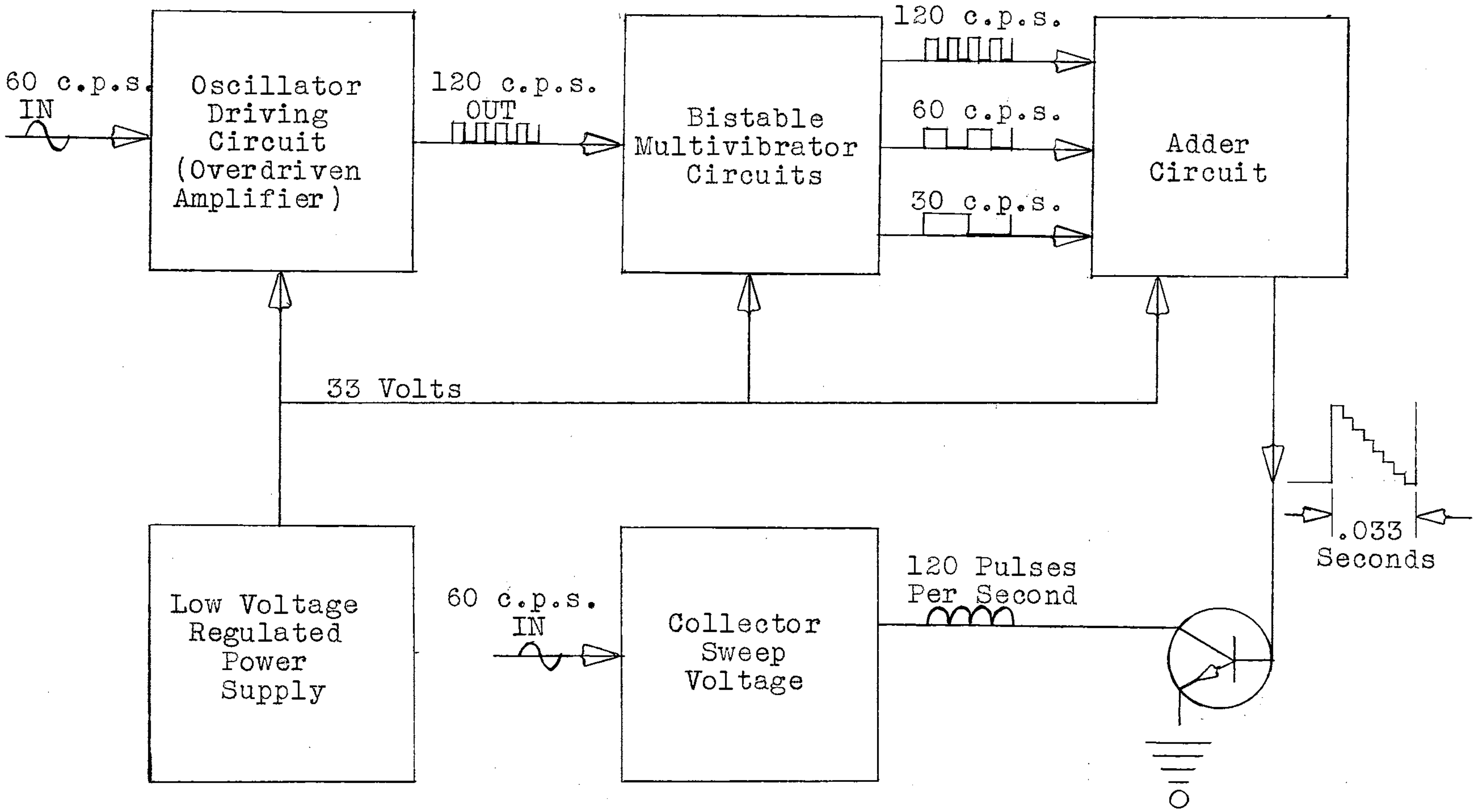

Figure 2. Block Diagram of The Curve Tracer

cycle is repeated. This results in the complete set of static output characteristics being presented. They appear as a steady, complete presentation on an oscilloscope.

Regulated Power Supply

The first and absolutely necessary circuit is a well regulated power supply. It is essential in a piece of test equipment such as this that the operating voltages do not vary. Any variations in the supply voltages could be reflected into the static output characteristics of the unit under test and non-consistent results may be encountered. This can not be allowed. Transistor life test studies, production line tests, matching, and other tests similar to these would be worthless under conditions of varying supply voltages.

The supply voltage used in this piece of equipment is obtained from a well-regulated, constant voltage supply. It utilized the series-type voltage regulator circuit. The output voltage is approximately 33 volts and may be adjusted over a narrow range. It is capable of supplying up to approximately 350 milliamperes before the regulation begins to fall off.

Oscillator or Driving Circuit

In any piece of equipment such as this, an oscillator or some type of driving circuit is necessary to originate the various pulses for proper synchronous operation of all the circuits. For simplicity and ease of construction, the operating frequency in this piece of equipment is the 60 c.p.s. line frequency. The driving circuit is merely a resonant circuit (120 c.p.s.) feeding an overdriven amplifier. This setup will provide an excellent square wave output of 120 c.p.s. The leading and lagging edges of the square wave are excellent for triggering a bistable multivibrator since the steep slopes can be differentiated so well.

Multivibrator Circuits

Three bistable multivibrators are used in this piece of equipment. The first one is fed by the 120 c.p.s. square wave from the overdriven amplifier. The output of this circuit is also a 120 c.p.s. square wave which feeds the second multivibrator. The output of the second multivibrator is a 60 c.p.s. square wave which feeds the third multivibrator. The output of the third multivibrator is a 30 c.p.s. square wave. It is obvious that the first multivibrator has a ratio of 1 to 1 for the input to output frequencies. The second and third multivibrators each have a ratio of 2 to 1 for the input to output frequencies. By combining these three outputs, various step values may be obtained which when applied to the base of the transistor under test will vary the parametric value I_B so that a number of sweeps can be presented.

Adder Circuit

The adder circuit is the circuit which must combine the three outputs (at different amplitudes and frequencies) of the multivibrators and give a common varying output which may be applied to the base of the transistor under test. It must be capable of rapidly switching from one base current value to another and at the same time appear as a constant current device so that the various sweeps represent a true constant I_B trace.

Collector Sweep Voltage

The final step necessary is to apply a collector to emitter bias voltage so that conduction may take place in the unit under test. It is necessary that this voltage vary from zero to some allowable maximum voltage while the I_B is at a constant step value. The collector sweep voltage circuit accomplishes this task. Again, the 60 c.p.s. line frequency is used; therefore, proper synchronization is guaranteed. By using a full-wave rectifier, 120 half wave pulses per second are obtained. These pulses, varying from zero to some preset peak voltage, give the necessary sweeping collector voltage so that the family of static output characteristics may be traced.

Summary

Naturally, these are not the only circuits necessary in this equipment. Others, such as the calibrating circuits and the NPN-PNP switching circuits are also necessary. However, these circuits are complementary to the essential, basic circuits discussed above which are necessary for the equipment to be capable of proper operation.

The basic circuits described perform the necessary function of this equipment. That is, they control the eight step values of I_B which are applied to the base of the unit under test. At the same time, the value of V_C is varied from zero to some predetermined maximum value of voltage for each of the eight step values of I_B. When this cycle is repeated rapidly, a complete, steady presentation of the static output characteristics is presented on an oscilloscope.

CHAPTER III

POWER SUPPLY

General Discussion

As stated before, a well-regulated power supply is not only desired but is essential in a piece of test equipment such as this. It is essentially a low voltage high current supply. The supply must furnish the current for all the control circuits in the curve tracer. The unit under test draws its current from the A. C. line and does not depend on the power supply for its collector current. This power supply was designed for a much heavier load than is being encountered here; therefore, regulation is not much of a problem.

A vacuum tube regulated power supply could have been utilized in this piece of equipment. However, statements such as the following made it apparent that a transistor regulated power supply would be more applicable to a piece of equipment such as this.

> Transistor regulators offer the advantages of compactness, less weight, and greater reliability over their electron-tube counterparts, and, in addition, have a performance equal to or better than that of the tube versions. Breakdown diodes may be used as voltage reference sources, and thus, complete solid-state regulator circuits are possible.[5]

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[5] Chow et al., Transistor Circuit Engineering (New York, 1957), p. 429

The design of vacuum tube regulated power supplies is well established. Such supplies are suited for powering equipment in which relatively low currents at high voltages are required. However, for high-current low voltage applications, vacuum tube supplies become bulky and inefficient, and the design is conveniently implemented with transistors instead of with tubes.[6]

The regulated power supply employes a D. C. amplifier. It could be a shunt-type or a series-type transistor regulator. However, constant-voltage regulators using a transistor in parallel with the load are inefficient if the variations of the load resistance and the input voltage are large. Therefore, a series-type regulator was used in this piece of equipment. Figure 3 is the schematic diagram of the constant voltage power supply used. The theory of operation of the circuit will be explained fully.

Operation of The Power Supply

To consider the operation of the power supply, it will be assumed that for some reason the output voltage has increased temporarily. The operation will be traced to see how the circuits compensate for this increase in voltage and bring it back to its original value.

The property of the reference or zener diode is that when it's biased in the reverse or high impedance direction, it will break down at some particular voltage and hold the voltage across it at that value (assuming the current flow does not become too high).

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[6] Proc. IRE, Design of Transistor Regulated Power Supplies, by R. D. Middlebrook, Nov., 1957 p. 1502

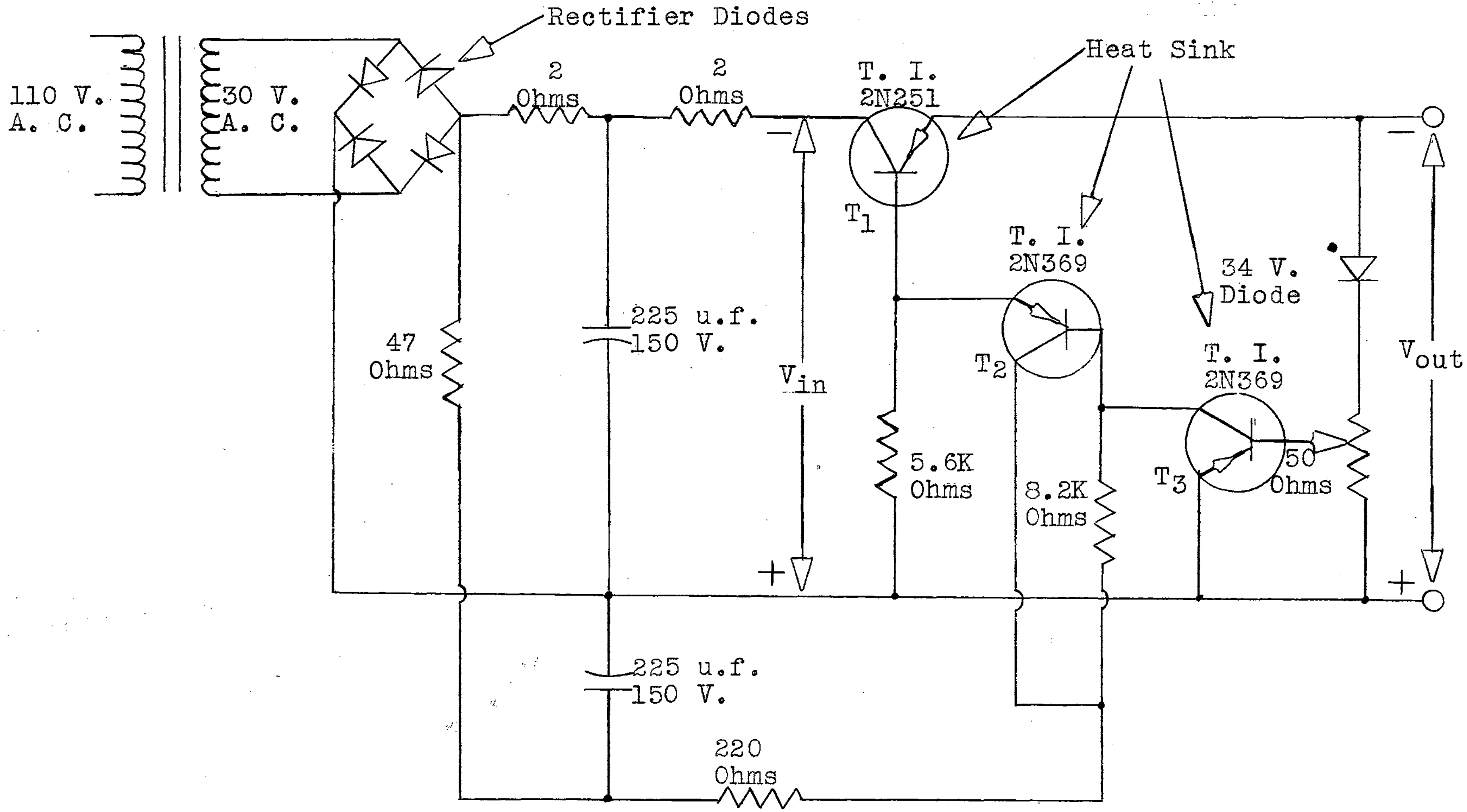

Figure 3. Series-Type Constant Voltage Power Supply

Therefore, if the output voltage is to be approximately 35 volts, the zener voltage of the diode should be slightly less than this value or about 34-34.5 volts.

In the case under consideration, it is assumed that the output voltage increased. Looking at Figure 3, since the voltage across the diode is a constant, the increase in voltage must appear across the 50 ohm potentiometer. As a result, the base of transistor T_3 becomes more negative with respect to its emitter. This causes T_3 to conduct more. The increase in current through T_3 causes a higher voltage drop across the 8.2K ohm resistor. The base of transistor T_2 is now more positive with respect to its emitter. Current flow through T_2 must now decrease and the voltage drop across the 5.6K ohm resistor also decreases. The base of transistor T_1, the series transistor, is now less negative. A lower negative potential on T_1 causes the current through it to decrease. As a result, the voltage across T_1 increases and the output voltage must drop back to its original value.

It is obvious that the input voltage minus the output voltage ($V_{in} - V_{out}$) is equal to the voltage drop across the series transistor T_1. Since transistors have the property of acting like a variable resistor as the base bias voltage is varied, an excellent method for controlling the output voltage is presented. This is the principle utilized in the series-type constant voltage regulator. An error signal, amplified by D. C. amplifiers, is used as the controlling factor for varying the apparent resistance of the series transistor. A similar process takes place for a decrease in output voltage but in this case, the error signal is a decreasing bias voltage on T_3. This causes transistor T_1 to appear as a lower resistance and hence, the output voltage is increased to its original value.

The 50 ohm potentiometer has a dual purpose. First, it limits the diode current to an allowable value. Second it provides the bias and error signal for T_3. As the arm is raised or moved toward the diode, more bias is applied to the base of T_3 and the output voltage is decreased. Therefore, it serves as a slight adjustment on the output voltage. Also, since it can control the amount of voltage that is applied to T_3, it likewise controls the amount of error signal that is fed back when there is a shift in voltage. Therefore, it is obvious that the best regulation and the lowest output voltage occurs when the arm is connected to the cathode of the diode.

The three transistors T_1, T_2, T_3, should all have a high Beta. The higher the Beta, the greater the amplification of the error signal, and the better the regulation. The transistors were all heat sinked to the chassis to prevent overheating in case of any heavy current flow. It is absolutely necessary that T_1, the series transistor, be heat sinked. This unit is a high power unit and must carry the full load current plus the diode current. Therefore, to guarantee against overheating, this unit <u>must be heat</u>

sinked.

Transistor T_3 serves as a voltage amplifier which amplifies the small error signal which is present when the voltage shifts. Transistor T_2 is a current amplifier. It provides the current gain necessary to drive the power unit, T_1.

The filter resistors of 2 and 47 ohms reduce the ripple but also provide a protection against high current surges through the diode rectifiers.

Temperature Stability

The diode used in this power supply is a single unit with a zener voltage of approximately 34 volts. However, it may be affected by changes in temperature and the zener voltage may shift slightly. Some silicon diodes have a positive temperature coefficient and some have a negative coefficient. If this is a critical problem in a piece of equipment such as this, a combination of smaller diodes which will add up to 34 volts may be used. By using the proper combination of positive and negative temperature coefficients while still arriving at the desired voltage, this problem of change in reference voltage with a change in temperature is eliminated.

Regulation

Figure 4 shows the voltage regulation curves for the power supply. The D. C. input voltage to the transistor regulator is shown to be a linear, decreasing line. As the load is increased, it is apparent that more and more

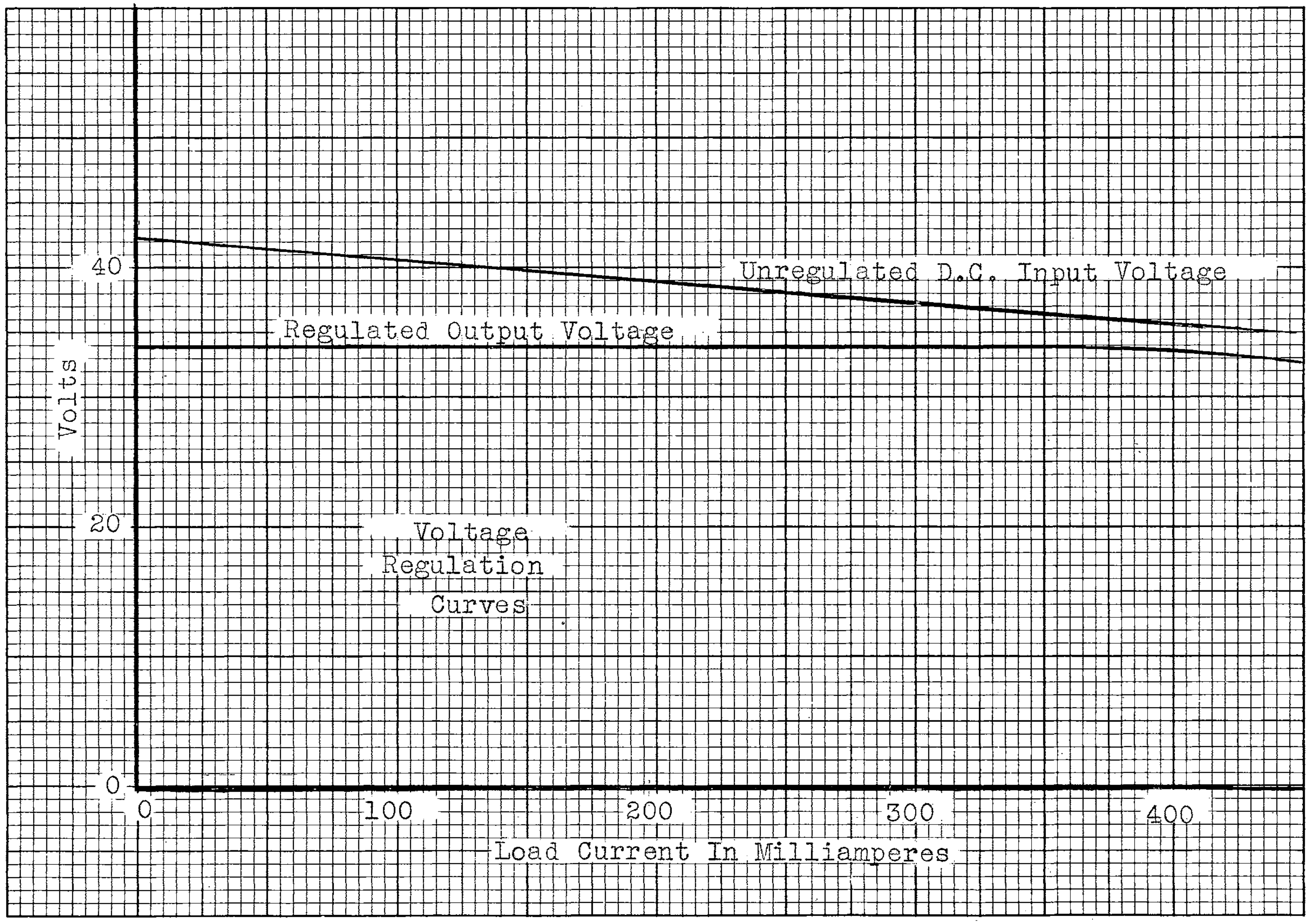

Figure 4. Voltage Regulation Curves For The Power Supply

of the voltage is lost in the transformer and filter and therefore, less is applied to the regulator. The output voltage is seen to be a very flat line at low values of load current. However, as the input voltage drops, the difference in the input and the output or zener voltage decreases. Finally, the difference, which is the voltage across T_1, gets too low for transistor T_1 to function properly. At this point, the output voltage falls off sharply and the regulation becomes very poor. It should be noted however, that the regulation became poor because of the transformer and filter losses and not because of the regulator. Therefore, at a lower zener voltage, the regulation would be very good for higher currents. Since most of the voltage is lost in the power transformer of this power supply, the regulation could be improved by using a transformer with a higher wattage rating. However, it is not necessary in this equipment.

General Summary

This power supply is capable of supplying 300 milliamperes at 34 volts. This is much more load current than is necessary for this curve tracer. However, tests were run on the power supply and the regulation curves are shown on Figure 4. These tests also showed that at 300 milliamperes load current, the ripple voltage was .0123 volts (R. M. S.). The output voltage at 300 milliamperes had dropped .15 volts. Therefore, the output impedance of this power supply was .15V/.3A = .5 ohms at 300 milliamperes.

The supply is quite capable of fulfilling all the requirements of this curve tracer.

CHAPTER IV

OSCILLATOR OR DRIVING CIRCUIT

General Discussion

It is absolutely essential that each circuit in this piece of equipment be triggered or synchronized properly. If this requirement is not met, improper information will be presented and the equipment has not performed its function.

Many different devices could be used to furnish the pulses necessary for proper operation. The simplest generator for the pulses would be a multivibrator. However, it was found that if a free-running oscillator or multivibrator was used, drift was encountered. This cannot be allowed. The oscillator frequency would also be susceptible to interaction with the 60 c.p.s. line frequency.

The unit under test will consume a considerable amount of power. Therefore, a very reliable amplifier and wave-shaping network, driven by the oscillator, would have to be designed. This is necessary so that the unit under test can draw the necessary amount of power and have the proper sweep voltage applied to its collector and emitter.

All of these difficulties can be eliminated by simply using the 60 c.p.s. line frequency as an oscillator and power source. This setup will eliminate any frequency drift since the line frequencies are controlled very closely.

The problem of interaction with the 60 c.p.s. line frequency is no longer present. The power consumed by the unit under test may now be drawn very easily from the A. C. line by using a transformer.

Obviously, the 60 c.p.s. line frequency is the ideal place to obtain the pulse for synchronizing all the circuits of the curve tracer.

Circuit Operation

The driving frequency necessary to supply the desired eight steps of constant current to the base of the unit under test was found to be 120 c.p.s. This will be explained in the following chapter. It is also necessary that the bistable multivibrators, which are used to supply the steps, must be driven by a sharp pulse. This sharp pulse form may be obtained by differentiating a square wave. This gives a positive spike for the differentiated leading edge and a negative spike for the differentiated lagging edge of the square wave. Therefore, a 120 c.p.s. square wave would satisfy all the requirements for triggering the multivibrators at their proper frequencies. The circuit in Figure 5 was used to obtain this square wave.

The 60 c.p.s. sine wave, when applied to a full-wave rectifier, produces 120 positive pulses per second. This output is then fed through a large capacitor to a parallel resonant circuit. The resonant frequency of this circuit is 120 c.p.s. The positive pulses feeding the resonant circuit cause it to oscillate and produce a sine wave at

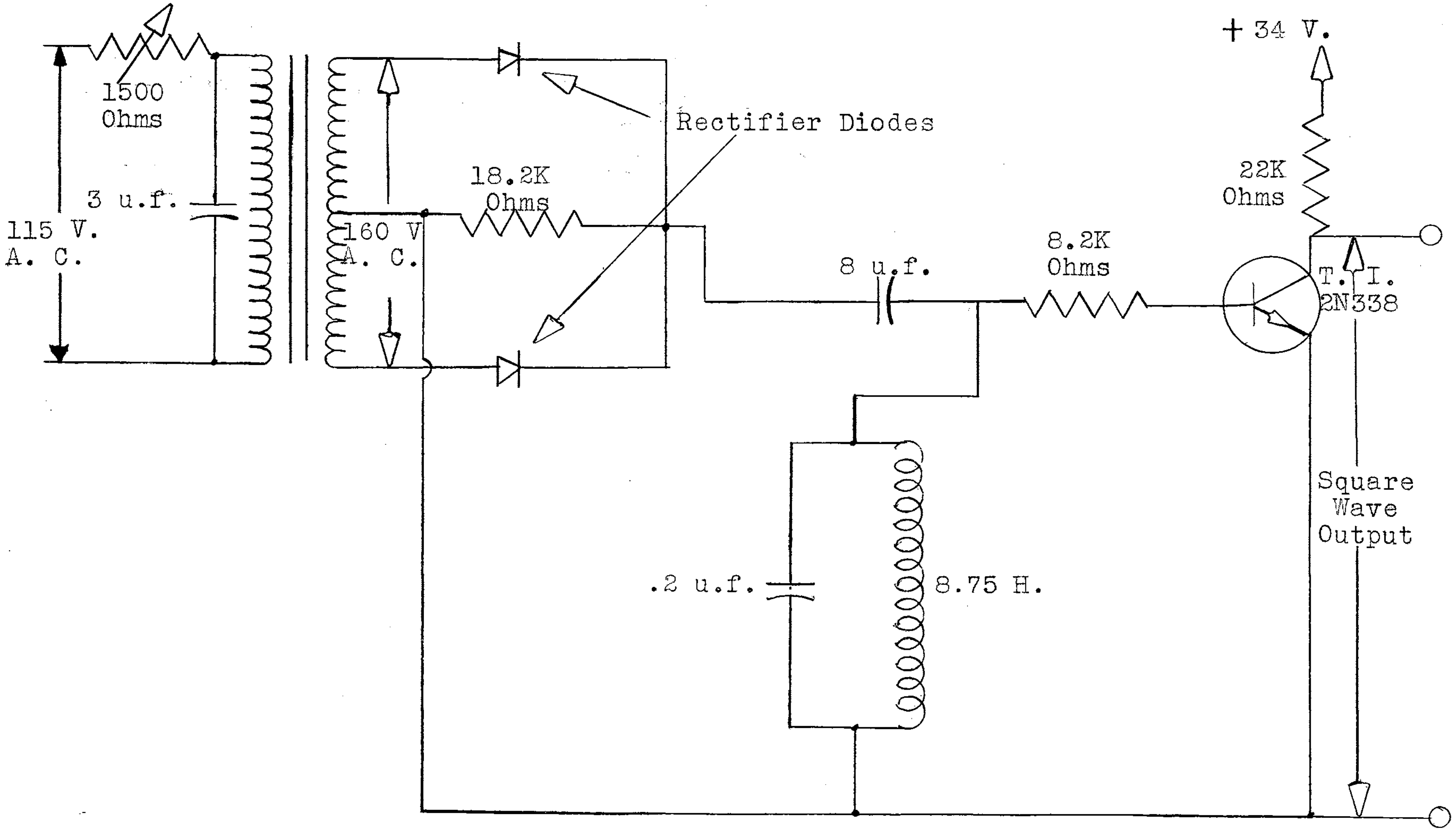

Figure 5. 120 c.p.s. Square Wave Generator

120 c.p.s. This is the desired frequency which was to be obtained.

The final signal which was necessary was a square wave with a frequency of 120 c.p.s. To obtain this square wave, the sine wave, which has a high amplitude, was fed into a high gain amplifier stage. The high value of input signal on the base of the transistor results in an overdriven amplifier stage. The 14.2K. ohm resistor in the base circuit is necessary to limit the base current with the high input signal, thus preventing transistor burnout.

When the positive half of the sine wave input is applied to the base of the transistor, the transistor is rapidly driven into saturation. A square, negative pulse results. When the negative half of the input wave is applied, the transistor is rapidly driven into cutoff. This results in a square, positive pulse. The slope of the edges of the square pulses is determined by the magnitude of the input signal. In this case, the magnitude is very high and very steep edges result. The final result is a 120 c.p.s. square wave that is synchronized with the A. C. line voltage. This square wave may be easily differentiated so that sharp pulses (120 per second) are easily attainable for triggering the first multivibrator.

Figure 6 shows the actual output of this stage. The four cycles represent 120 c.p.s. It can be seen that this circuit has produced an excellent square wave which can be easily differentiated. It has satisfied the requirements of generating a 120 c.p.s. square wave.

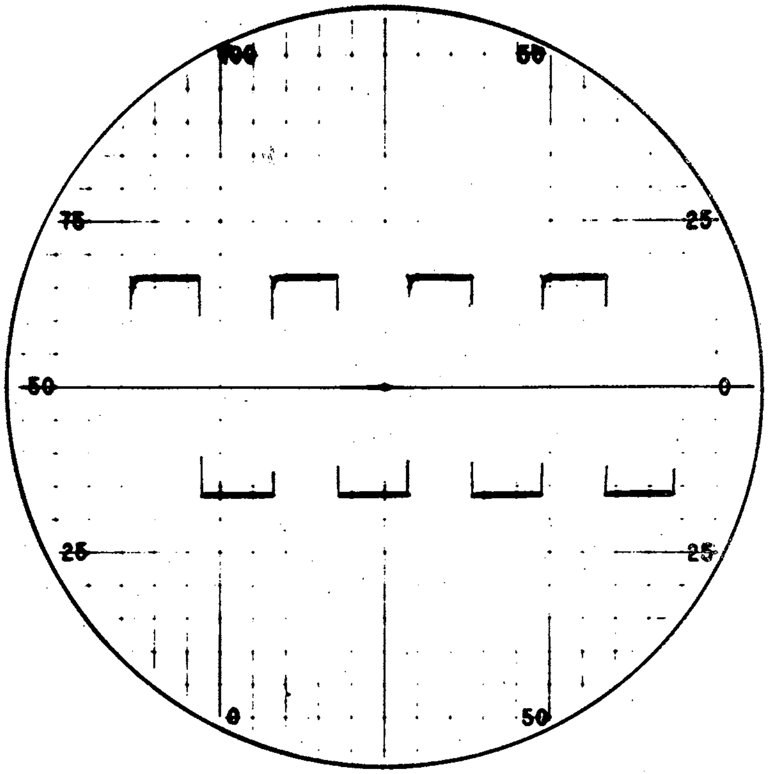

Figure 6. Output of The Overdriven Amplifier

Although it is not apparent here, the square wave output is actually 45 degrees out of phase with the zero point of the synchronous pulses from the line. That is, the switching time of the square wave is not at zero degrees (with respect to the line frequency) but occurs 45 degrees earlier. This results from the fact that the 120 positive pulses per second (60 c.p.s. full-wave rectified) from the A. C. line are causing the parallel resonant circuit to oscillate at 120 c.p.s. To sustain oscillations, the positive peaks of both signals must occur simultaneously. Since the oscillating frequency is twice that of the line frequency, it takes twice as long for the line frequency to reach zero as it does for the oscillations to reach zero. The actual difference in time is 45 degrees referred to the rectified 120 c.p.s. time base. As explained previously, the base current (I_B) of the unit under test must remain constant during the complete range of the collector sweep voltage. Therefore, the sweep must start at the exact time that the base bias is switched. To provide this and eliminate the 45 degree phase difference, the variable 1500 ohm resistor and the 3 u.f. capacitor were put in the circuit of the primary of the transformer to act as a phase shifting device. The resistor can easily be adjusted until the proper time reference has been obtained.

CHAPTER V

MULTIVIBRATOR CIRCUITS

General Discussion

The step voltage, which is applied to the unit under test, is necessary to vary the parametric value I_B. The method used in this equipment to generate the step function is to add various step voltages to obtain the desired values. By adding properly synchronized square waves which have various amplitudes and frequencies, the necessary base biases, to present the static output characteristics, are obtained.

Bistable Multivibrators

A bistable multivibrator is an excellent generator for a square wave. It can be driven by synchronized pulses so that an output of one half-cycle is alternately produced by a positive and then a negative pulse, or it can be arranged so that an output of one half-cycle is produced _only_ by a positive or _only_ by a negative pulse. Therefore, if alternating positive and negative pulses are applied to the input of the multivibrator, the output frequency may be equal to, or one-half of, the driving signal frequency. In this piece of equipment, both of the above types of circuits are used.

It will be stated here and illustrated later that if square waves of 120 c.p.s., 60 c.p.s., and 30 c.p.s. are added, eight different steps may be produced. These steps each occur 30 times per second with a duration of 4.16 milliseconds. The amplitude of each of these steps is controlled by the amplitude of the three square waves which are being added. It was found that if the 30 c.p.s. square wave had an amplitude of 1X (where X represents any value of amplitude), the 60 c.p.s. square wave had an amplitude of 2X, and the 120 c.p.s. square wave had an amplitude of 4X, the steps resulting when these square waves were added would have amplitudes of 0, 1, 2, 3, 4, 5, 6, and 7 times X. This is the step voltage range which is necessary to vary the parametric value I_B.

Figure 7 shows graphically the addition of the outputs of the three multivibrators. Figure 7A shows the addition when the output of each of the multivibrators is originally going in the positive direction. Figure 7B shows the addition when the outputs of the 30 c.p.s. and the 120 c.p.s. multivibrators are originally going positive, and the output of the 60 c.p.s. multivibrator is originally going negative. It is evident that the sequence of addition of the three outputs is not important. Although the final step voltages are not in the same order, the results are the same. That is, eight steps, each with a duration of 4.16 milliseconds, are produced which have values of 0, 1, 2, 3, 4, 5, 6, and 7 times X.

Multivibrator Circuits

As explained in Chapters III and IV, the output from the overdriven amplifier (120 c.p.s. square wave) is used

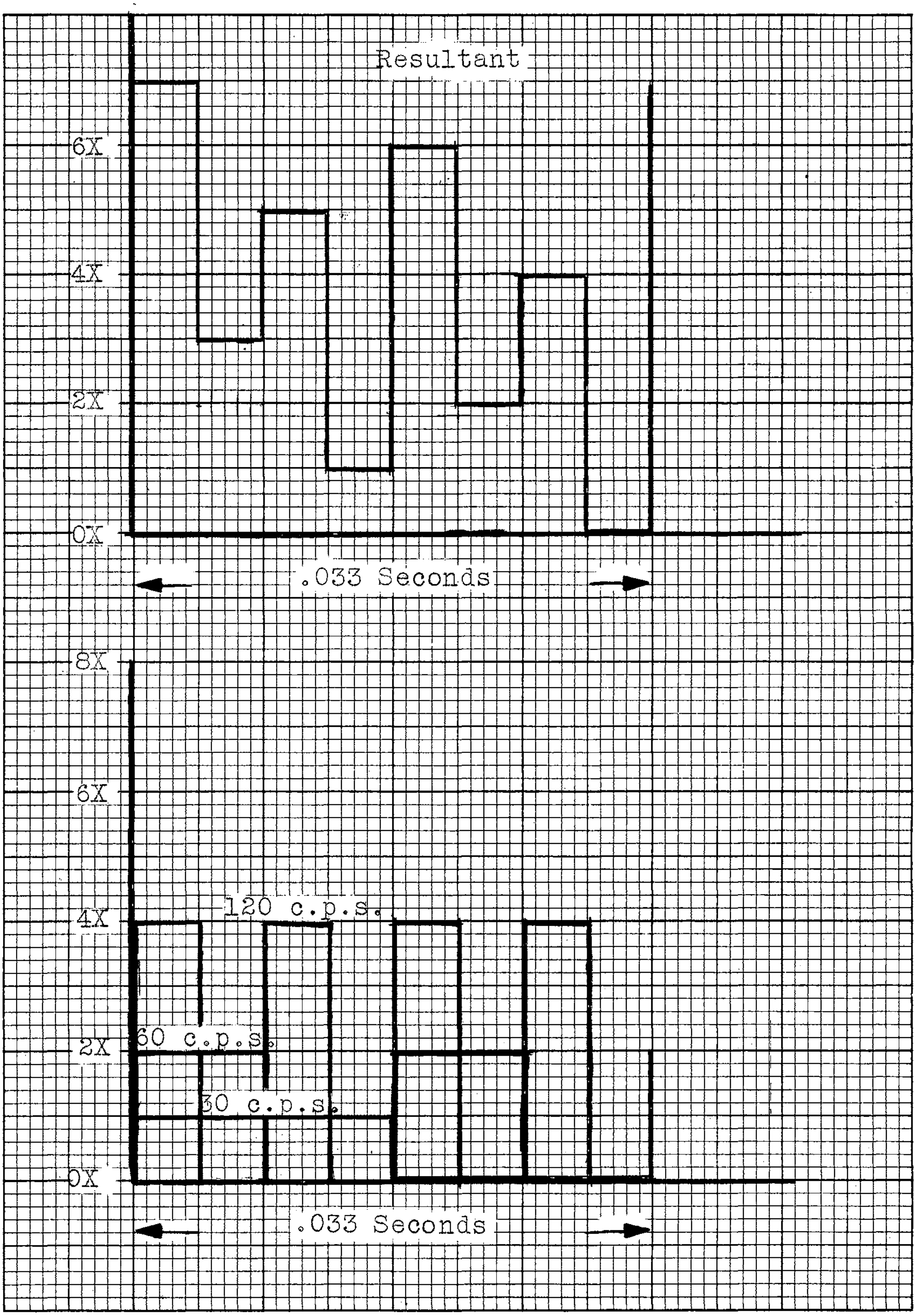

Figure 7A. Addition of A Sequence of Square Waves

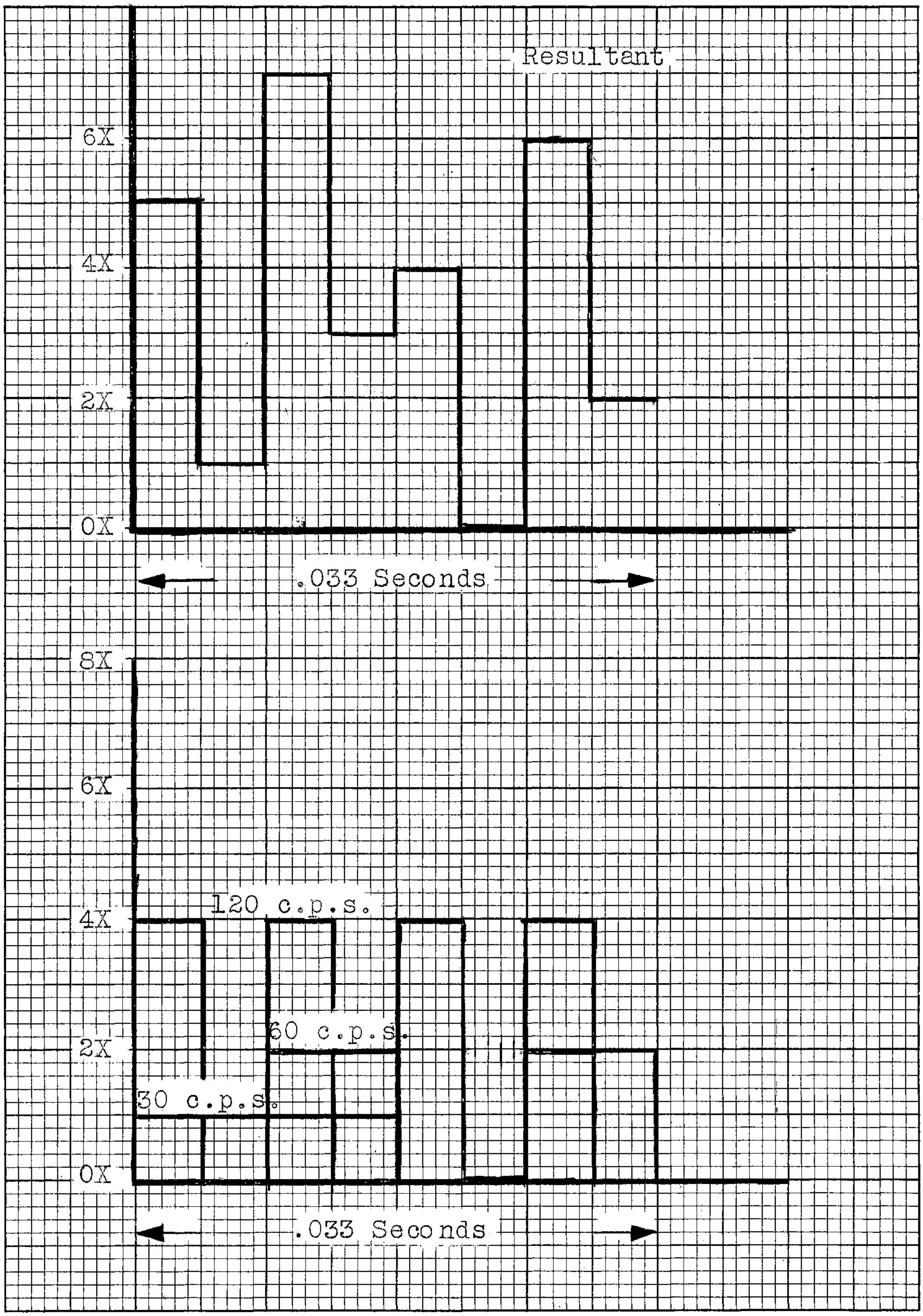

Figure 7B. Alternate Addition of The Sequence to drive the 120 c.p.s. multivibrator. Therefore, a 1 to 1 frequency ratio is needed for the first multivibrator. However, since the output of the overdriven amplifier is a square wave, it must first be differentiated to supply the sharp positive and negative spikes necessary to trigger the first multivibrator. The output of this multivibrator is to be 120 c.p.s., therefore, it has to be triggered by both the positive and negative spikes so that for each spike in, one-half cycle of a square wave is produced in the output. This will satisfy the 1 to 1 frequency ratio which was found to be necessary. Figure 8A is the differentiating circuit and bistable multivibrator which was used to produce these results.

> The principal characteristics of bistable multivibrators are: (a) They have two stable operating states. (b) The regenerative action carries the circuit from one state to another, and this action is essentially independent of the amplitude of the trigger pulse (provided that the trigger pulse has reached a certain critical minimum amplitude) except in high-speed operation.
> (c) The circuit remains in a stable state for an arbitrarily long time, when no trigger signal is applied, and this state is determined by the preceding pulse.[7]

The circuits of Figure 8 possess these characteristics. However, they also possess other characteristics which are necessary for proper operation in this piece of equipment. As explained previously, the multivibrators are being driven by a square wave which must be differentiated to obtain the desired trigger pulses. In Figure 8A, a positive going

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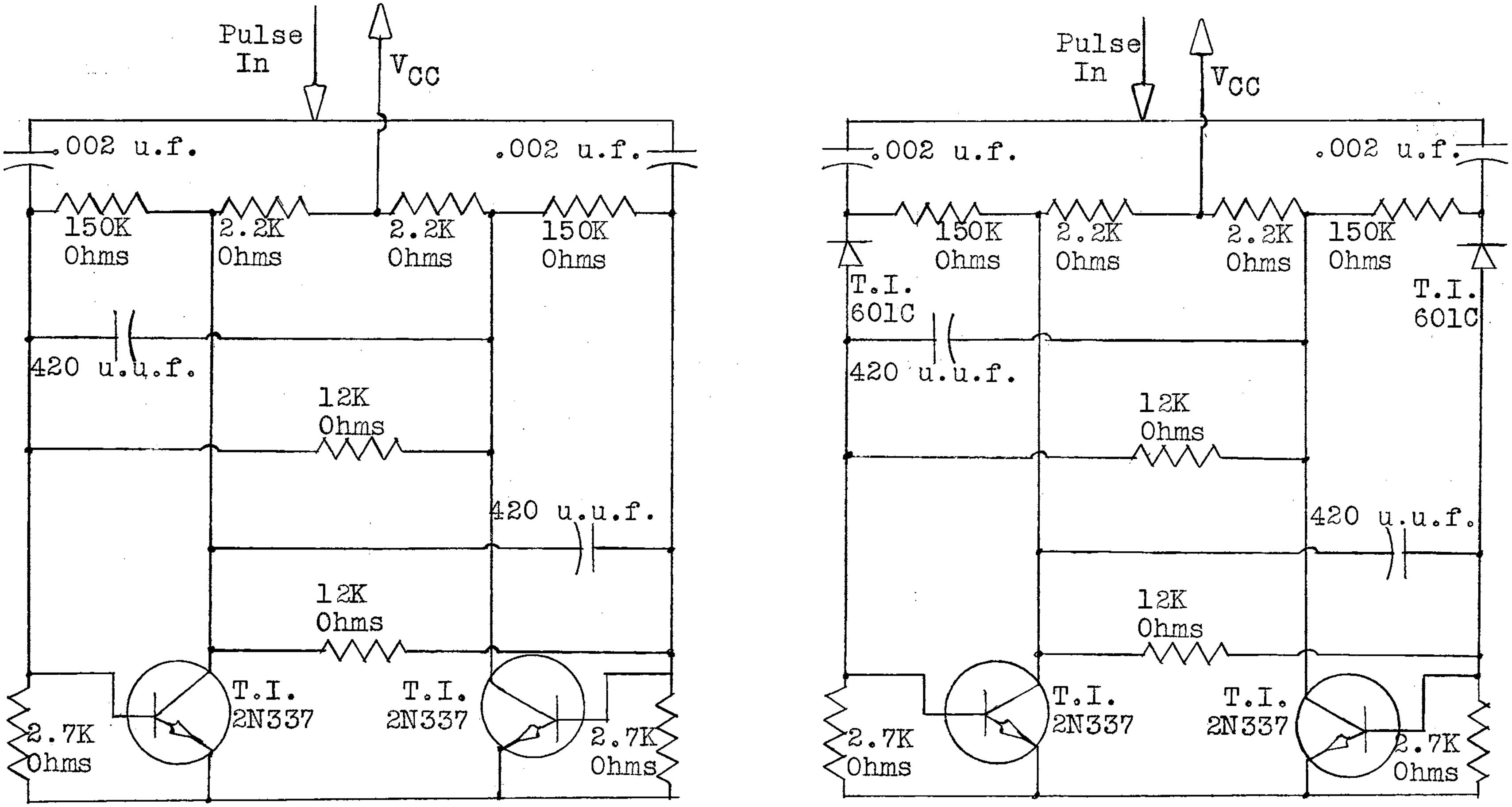
[7] Chow et al., _Transistor Circuit Engineering_ (New York, 1957), p. 324



(A) (B)

Figure 8. Differentiating and Bistable Multivibrator Circuits

square wave on the "pulse in" line will cause the .002 u.f. capacitor on the non-conducting side to charge. This charge is very rapid and a sharp positive pulse is developed which appears on the base of the non-conducting transistor. The differentiation has been accomplished and simultaneously the trigger pulse which results, has been applied to the non-conducting transistor. The pulse also appears on the side of the conducting transistor; but, since it is already conducting, the positive pulse has no effect on it. The sharp positive pulse on the base causes the non-conducting transistor to conduct heavily, reducing its collector voltage. This negative going voltage is coupled through the R-C network of the 12 K. ohm resistor and the 420 u.u.f. capacitor to the base of the conducting transistor and rapidly cuts it off. The 12 K. ohm resistors provide D. C. bias, and the 420 u.u.f. capacitors are used to bypass the coupling resistors for maximum regenerative drive during the switching transients.

A negative going square wave will cause the .002 u.f. capacitor on the non-conducting side to discharge. This discharge is very rapid and a sharp negative pulse is developed which appears on the base of the conducting transistor. Again, the differentiation has been accomplished and simultaneously, the trigger pulse has been applied to the conducting transistor. The pulse also appears on the side of the non-conducting transistor; but, as before, has no effect.

The square wave output of the multivibrator is at the same frequency as that of the overdriven amplifier and its resulting differentiated pulses. Therefore, the 1 to 1 frequency ratio has been accomplished.

In previous chapters, it was stated that the next two multivibrators are driven by the preceding multivibrator of each. They also have a ratio of 2 to 1 for the input to output frequencies. Thus, the input frequency of the second multivibrator is 120 c.p.s. and the output must be 60 c.p.s. The input frequency of the third multivibrator is 60 c.p.s. and the output must be 30 c.p.s. The circuit for these two multivibrators is shown in Figure 8B.

It is easily seen that this circuit is identical to that of Figure 8A except for two components. These are the two diodes which are tied between the "pulse-in" capacitors and the base of each transistor. These diodes will conduct easily in one direction but they have a high zener voltage in the reverse direction and will not break down in the reverse direction with the voltages encountered here.

When a negative pulse appears on the "pulse-in" line, the operation is identical to that of Figure 8A. That is, the conducting transistor is cut off and the other transistor is driven into conduction. This is because when a negative pulse is applied to the cathode of the diode, it conducts easily. However, when a positive pulse appears on the "pulse-in" line, the diode appears as an open circuit and the positive pulse has no effect on the transistors. When another negative pulse appears, the conducting transistor is cut off and the one that was conducting originally is driven into conduction by the regenerative drive of the circuit. This is the second half of the output, square wave, cycle. Therefore, the frequency input is divided by two in the second and third multivibrators.

The necessary signals to obtain the proper step function have now been generated.

Output Waveforms

Plate I, II, and III are the actual outputs of these multivibrators. The horizontal time scale is the same for each oscilloscope presentation. The presentation of four cycles, two cycles, and one cycle clearly shows the frequencies of 120 c.p.s., 60 c.p.s. and 30 c.p.s. for the first, second, and third multivibrators respectively.

In a piece of test equipment such as this, it is absolutely necessary, for proper accuracy, that the square waves reach their final value very rapidly. Therefore, rise time becomes very important. Plate IV shows the actual rise time presentation for the third multivibrator on an expanded scale. Each large square represents one microsecond. It is observed that the usually recognized final value figure of 90 per cent is reached in approximately four microseconds. This is much better than is necessary for proper operation of this equipment.

Summary

The three multivibrators developed for this equipment have an excellent square-wave output with the necessary

Plate I

Output of First Multivibrator

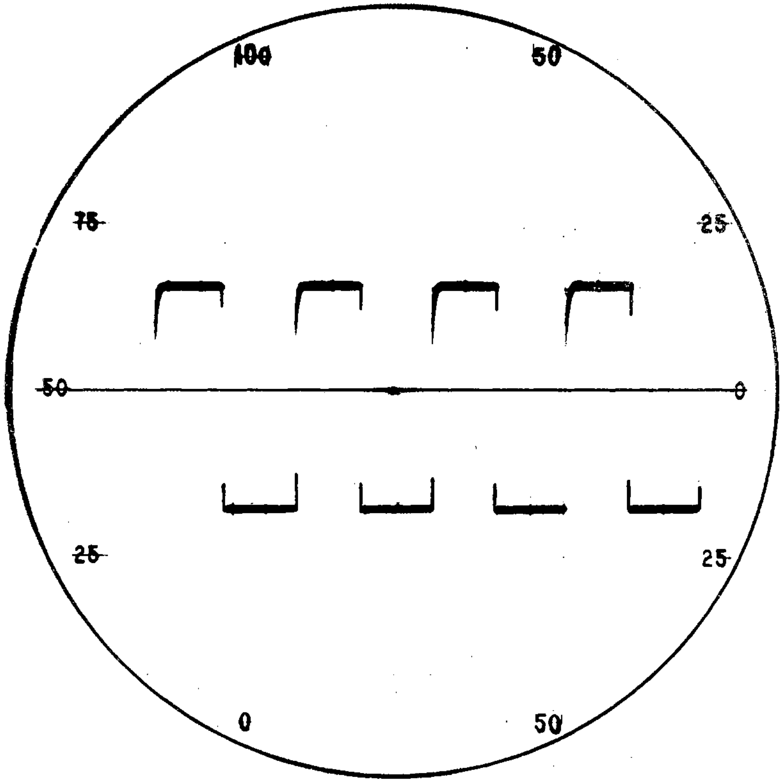


Plate II

Output of Second Multivibrator

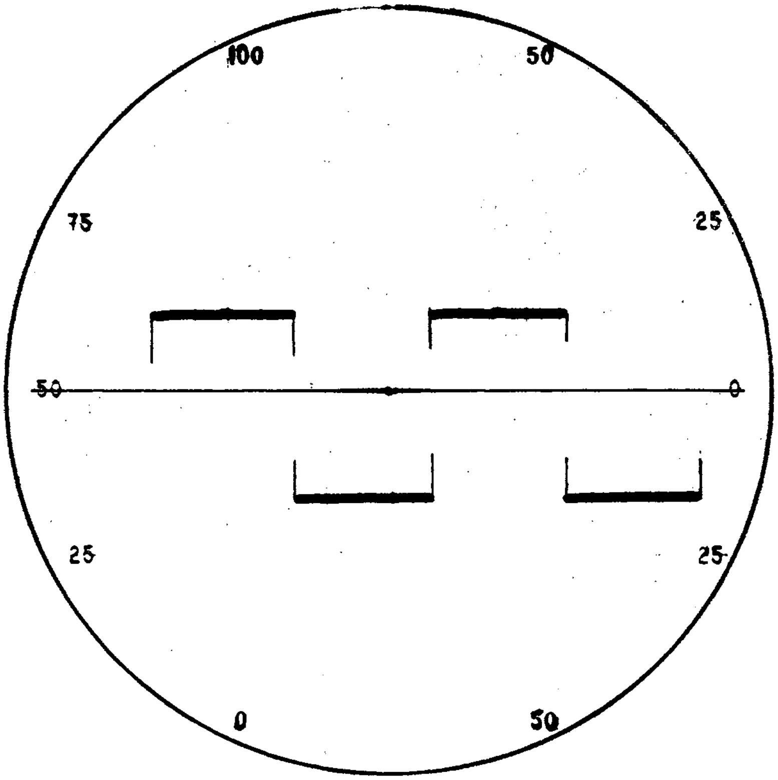


Plate III

Output of Third Multivibrator

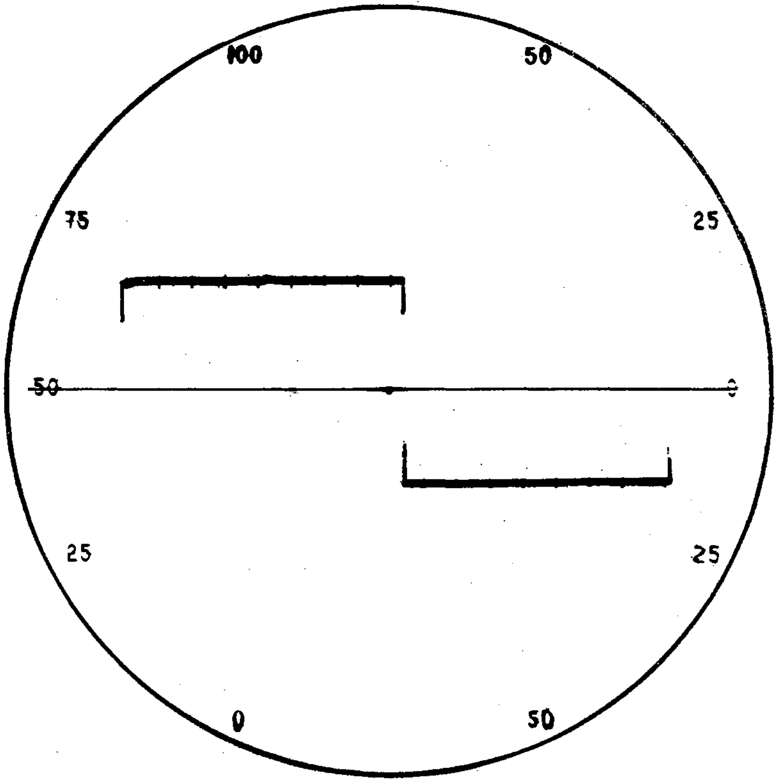
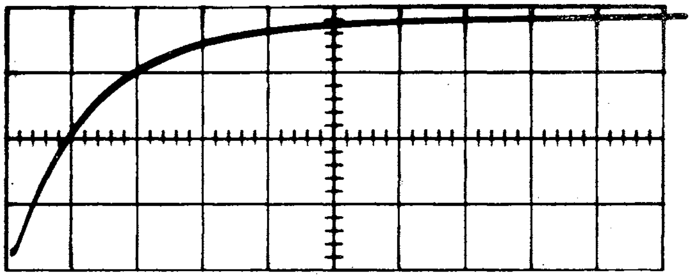


Plate IV

Rise Time of Third Multivibrator

(Each unit equals one microsecond)



frequencies of 120 c.p.s., 60 c.p.s., and 30 c.p.s. When the amplitude of each is controlled properly, the eight steps, that may be desired and which are to be applied to the base of the unit under test, may be obtained. The amplitude of each can be controlled by various resistors which are in series with the output of the multivibrator and the adder circuit. Therefore, it would be easy to adjust the amplitudes with various resistors for a number of step values. The desired step value could then be selected with an external, panel switch.

CHAPTER VI

ADDER CIRCUITS

General Discussion

The adder circuit serves the purpose of combining the outputs of the three multivibrators and at the same time applying these various combinations to the base of the unit under test. The circuit must appear as a constant current device. This is necessary because any uncontrolled change in the adder circuit current will cause a shift in the value of I_B. Since I_B is the parametric value, it must remain at constant, predetermined values.

It is evident that the adder circuit's purpose is two-fold and that this circuit is a very essential link in the chain of operations necessary for the curve tracer to function properly.

Theory Of Operation

The adder circuit, in this equipment, must be capable of taking three inputs and producing one output. The inputs and the outputs are all varying in a predetermined manner.

Figure 9 is the general schematic of a type of adder circuit and it has been used in this equipment. The three circuits and transistors used in the adder are identical except for the values of the collector and base resistors. The emitters of all three are tied together and are common to the base of the unit under test. Just as the complete

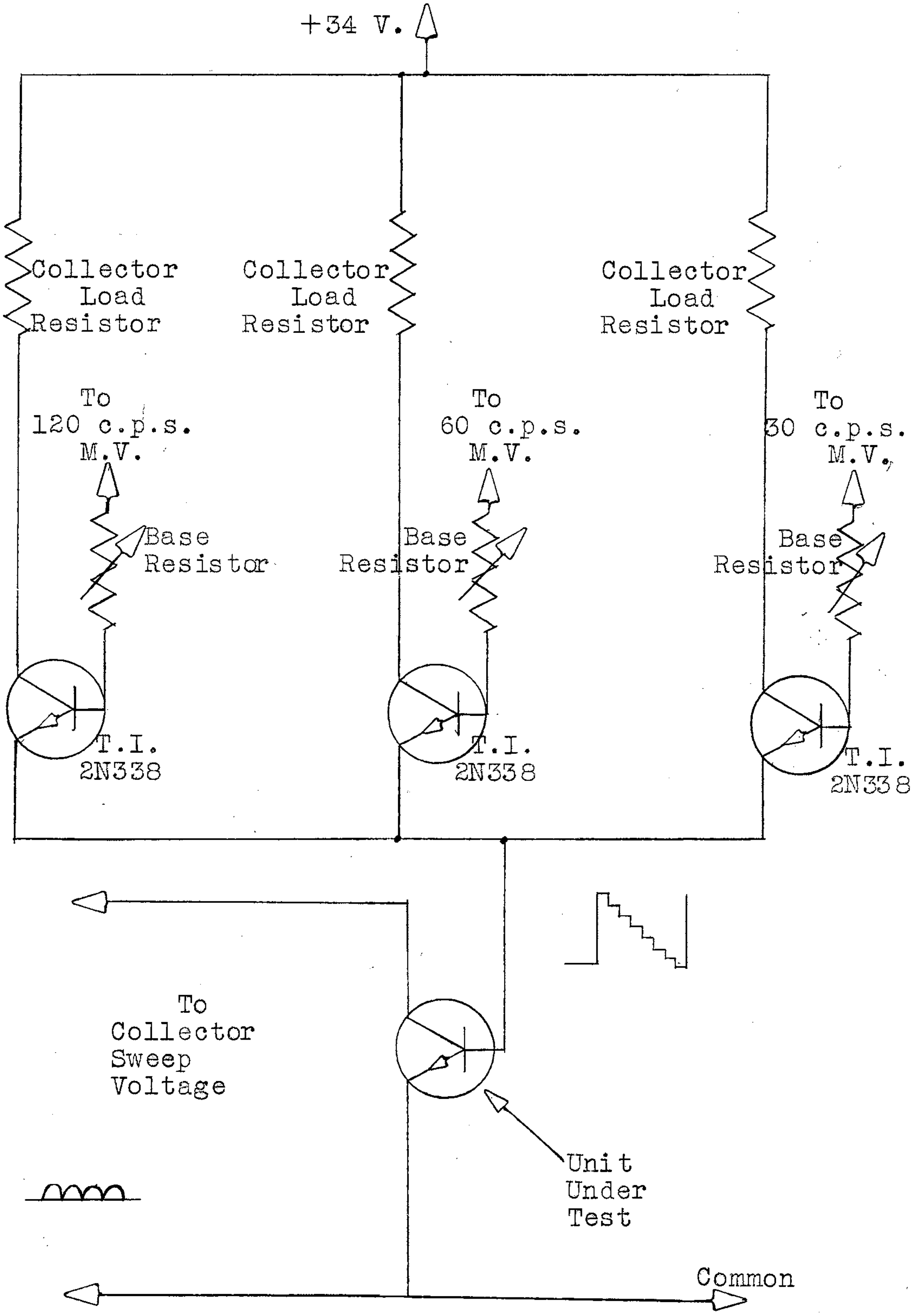


Figure 9. A Suitable Adder Circuit

adder circuit must appear as a constant current device, each of the three similar circuits must appear as a constant current device. At one time, when the input square wave is positive, a controlled amount of current will flow through the transistor. When the square wave goes negative (voltage drops to a minimum), the current must be as close to zero as possible. Because of the latter statement, it is essential that the transistors in the adder circuits have an extremely low I_{CO}. The units selected were T. I. type 2N338. These are silicon switching transistors which have an I_{CO} of approximately 1 microampere or less at a temperature of 150 degrees C. At the same time, they can carry enough current to supply the base drive for any transistor up to and including the medium-power classification. The collector current of the three transistors makes up the base current of the unit under test.

The collector current of each of the units in the adder circuit is controlled by the collector load resistor and the transistor itself. The emitter to base resistance of the unit under test is very low and can be neglected in most cases because the emitter to base diode is forward biased. When any or all of the transistors in the adder circuit are conducting, the ideal situation would be for all the voltage to be dropped across the respective collector load resistors and none across the transistor. Then, the current could be controlled by the value of the resistance. This situation is approached by applying a high level of forward bias to the various transistors. When the collector current is to drop to zero, the transistor should appear as an open circuit. Therefore, the transistors in the adder circuit should appear as a switch. That is, as an open circuit and as a closed circuit. The switching transistor chosen approaches these conditions.

It can be seen that the collector load resistor and the base bias of the switching transistor control the various collector currents, and, therefore, control the base current of the unit under test. When the transistor is biased heavily in the forward direction, the greatest control of the current is achieved by varying the collector resistance. However, since the transistor does not actually appear as a short circuit, some control is achieved by the base bias. Both the collector and base resistors could be constant value resistors, but it seems that the base resistor would give a fine calibration adjustment if it were variable. At any rate, these two resistors, in the proper combination, will give the correct value of collector current for each of the transistors in the adder circuit when they are conducting.

When the base bias of these units is reduced to zero, they appear as an open circuit and the other desired state is achieved. Therefore, an off-on combination is presented at the frequency rate of the multivibrator driving the individual unit. The proper amplitude is controlled by the resistors as previously described.

The proper combination for eight sweeps was previously stated as being 4X for the 120 c.p.s. signal, 2X for the 60 c.p.s. signal, and 1X for the 30 c.p.s. signal. The graphical addition of these signals has been shown in Chapter V.

In order to be able to test various units, a number of different step amplitudes are necessary. This would result in many different combinations of collector and base resistors for each transistor in the adder circuit. Some comments and suggestions concerning this are made in the final chapter of this work.

Again referring to Figure 9, it can now be easily seen that the base bias of the unit under test is actually in the form of eight steps. These steps are controlled by the individual resistors in the collector and base circuits of the transistors in the adder circuit. The sum of the collector currents in the adder circuit becomes the base current of the unit under test. When these constant values of I_B (the parametric value) are applied, and the proper collector sweep voltage is applied, a complete family of static output characteristics results. The collector sweep voltage is discussed in Chapter VII.

Actual Results

The actual family which is traced when the parametric value, I_B, is properly controlled is shown in Figure 10. It should be pointed out that this is merely a general family obtained by using the adder circuit previously described.

The circuits used were not calibrated so the exact values of V_C, I_C, and I_B are unknown. Note the similarity between Figure 10 which was obtained by using the circuits of this curve tracer and that of Figure 1 which was obtained with a commercial model curve tracer.

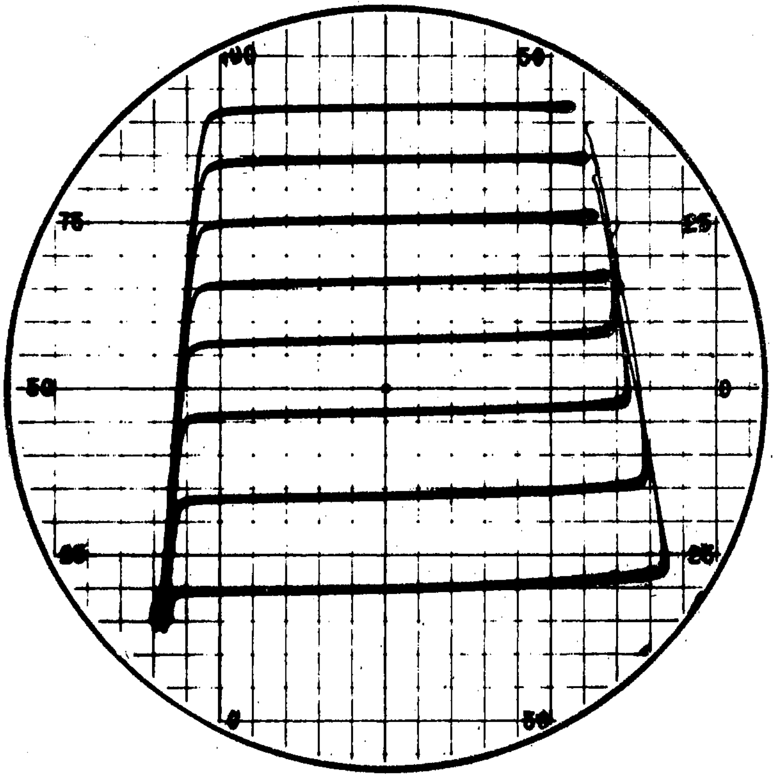


Figure 10. Actual Static Output Characteristics Using The Adder Circuit

CHAPTER VII

COLLECTOR SWEEP VOLTAGE

General Discussion

It has been stated that during the time that the base current, I_B, is at a constant value, the collector voltage must go through its entire range. That is, it must vary from zero to the maximum desired voltage or from the maximum desired voltage to zero. When this is done, the collector current, I_C, may be observed and determined at any allowable voltage V_C, and at a constant base bias. If the collector voltage goes through its complete range for each of the eight step values, the complete family of static output characteristics will be presented on the oscilloscope.

Circuit Operation

Any voltage waveform which would vary continuously from zero to some preset maximum value of voltage, while the step voltage is applied to the base of the unit under test, would satisfy the requirements for the collector voltage, V_C. Since each step occurs thirty times a second and there are eight steps, the collector sweep voltage would have to go through its entire range 240 times per second. It would also have to be in proper synchronization, so that when the step voltage shifts from one value to another, the collector sweep voltage is just starting its cycle. The cycle may start from zero and go to the maximum voltage; or it may start at the maximum and drop to zero voltage. Either way is satisfactory.

The most acceptable collector voltage waveform would be a sawtooth which varies linearly from zero to the maximum value. However, with the sawtooth, many difficulties would be encountered. The first problem would be to generate a sawtooth with different amplitudes for the various transistors to be tested. Proper synchronization would be another problem. Finally, since the unit under test may draw a considerable amount of power, a very reliable, push-pull amplifier would be required to satisfy this problem if transistors are to be used in the circuits.

A sine wave would also satisfy the requirements of the collector sweep voltage. Although it is not a linear variation, the range of voltage is continuous from zero to a maximum value. The sine wave is easily synchronized by merely using the line voltage for the driving signal. This was explained in Chapter IV. There is no problem with the amount of power being drawn. A transformer may easily replace the push-pull amplifier circuit, and any amount of power may be drawn, assuming the transformer's rating is high enough. Therefore, a variable transformer was decided on to furnish the collector sweep voltage. The maximum amount of voltage which is to be applied to the transistor under test can be easily controlled by adjusting the transformer's output voltage.

Figure 11 shows the circuit used to supply the collec-

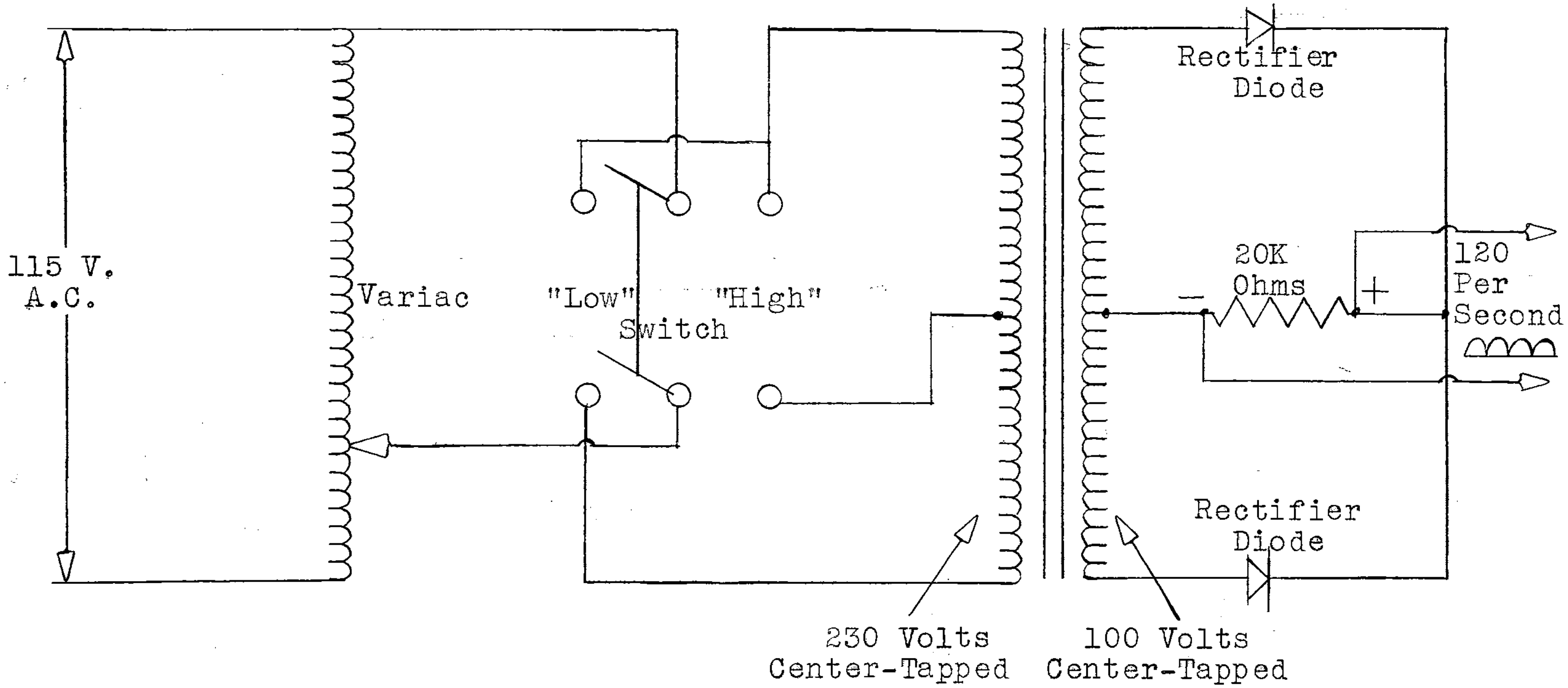


Figure 11. Collector Sweep Voltage Circuit

tor sweep voltage. The maximum value of the collector sweep voltage can be adjusted by the variac which is an external, panel adjustment. Various units will be tested. Therefore, to provide a wide amount of flexibility, the Collector Voltage High-Low switch has been used. With this switch, two ranges of output voltage are available. On the high voltage range, the primary to secondary turns ratio is one-half the value it is on the low voltage range. By using the switch and the variac, a continuous range of from zero to approximately 71 volts (peak) may be obtained from the secondary of the transformer.

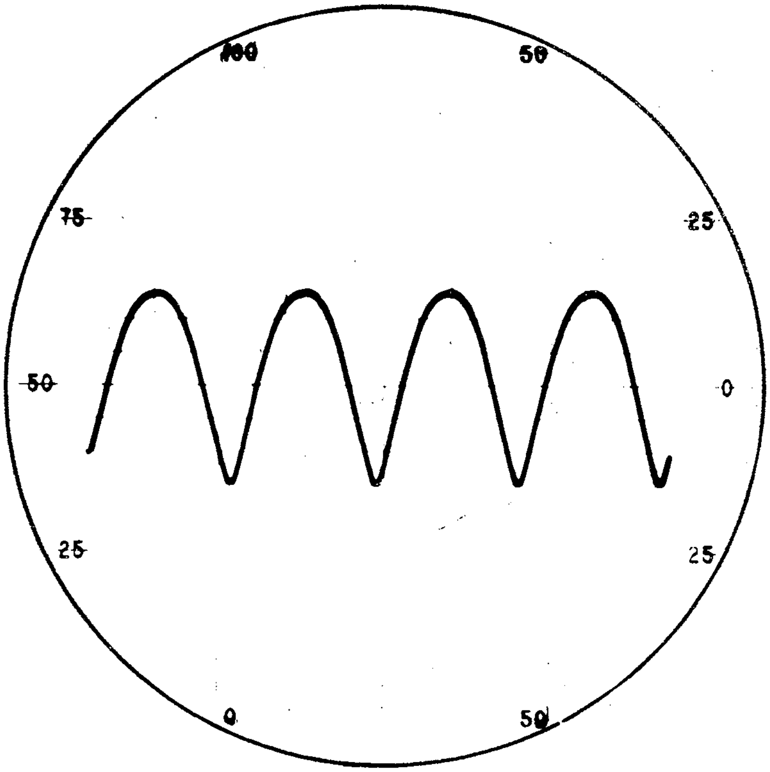
The transformer is center-tapped so that full-wave rectification may take place. Since the collector sweep voltage must go through its complete range for each step function which is applied to the base, it must go through its complete range eight times in 1/30 of a second; this is the repetition rate of each step. In other words, the collector sweep voltage must vary from zero to maximum or maximum to zero 240 times per second. It must also be in proper synchronization with the step functions. As was explained in Chapter IV, the synchronization is adjusted by using the R-C phase shifting circuit.

The full-wave rectification of the 60 c.p.s. sine wave, which has been provided for, will supply 120 positive sine functions per second. Since the sine function goes from zero to maximum and then back to zero, two complete sweeps have been provided by each positive sine function. The result is that the collector sweep voltage goes through its complete range 240 times per second. This satisfies the requirements for the collector sweep voltage. It should be noted that half of the times the collector voltage will be sweeping from zero to maximum and the other half of the times the collector voltage will be sweeping from maximum to zero. However, this is not objectionable because it satisfies the requirements of continuously sweeping through the whole range while I_B is held constant. For one value of I_B, V_C varies from zero to the maximum value, then at the maximum value of V_C, the step function shifts and I_B changes to a new, constant value. V_C then sweeps from the maximum value to zero. The sequence is then continued.

Plate V shows the actual output of the Collector Sweep Voltage Circuit. The four positive sine functions represent the sweep voltage for the eight steps. Naturally, the peak value of the sine function can be varied and its value will be determined by the unit under test.

Plate V

Actual Output of The Collector
Sweep Voltage Circuit



CHAPTER VIII

COMPLEMENTARY CIRCUITS AND CONCLUSIONS

Complementary Circuits

This work has presented the basic, essential circuits which are necessary to present the static output characteristics of a transistor. The only external piece of equipment, that is necessary, is a cathode-ray-oscilloscope to visually display these characteristics. However, there are certain refinements and complementary circuits which are necessary to make this equipment a finished, versatile product.

There are many different types of transistors being manufactured today. The majority of them are of the junction or alloyed type. All of these fall into one of two categories; that is, they have either the NPN or PNP type of structure. With the NPN structure, the electron or negatively charged particle is the majority carrier. With the PNP structure, the hole or positively charged particle is the majority carrier. Each type of transistor operates in a similar fashion except that the bias polarities are reversed in each case. The circuits in this equipment were designed to produce the static output characteristics of a transistor which is in the NPN category. To be useful for all types, the equipment should be able to handle NPN or PNP transistors. This is one refinement which should be added to the equipment. As stated previously, only the bias voltages need to be reversed on the base and collector terminals of the unit under test. The polarity of the collector may easily be reversed by using a reversing switch to give the desired change in polarity on the output of the full-wave rectifier which is used as the collector sweep voltage. Reversing the polarity of the base bias is a much more difficult task. The step functions applied to the base of the unit under test in this equipment are positive in nature. For a PNP unit, the steps must be negative. An inverter circuit might be a possible solution to this problem.

All transistors do not have the same current and voltage ratings. Therefore, to be able to test the various units, the collector and base bias voltage magnitudes must be variable. The variac and "High-Low" switch, in the collector sweep voltage supply, provide an excellent means for controlling the collector bias. The base bias, which is controlled by resistors in series with the three multivibrators and the adder circuits, must be preset in order to eliminate the tedious alignment procedure which would be necessary for each change in transistor current and voltage rating. By using an external selector switch and various series resistors for adjusting the base biases, a number of desired step values, which are to be applied to the unit under test, may be preset and chosen when they are desired by merely rotating the ganged selector switch. These refinements would provide a rapid means of testing transistors with different current and voltage ratings.

The presentation on the oscilloscope, of the static output characteristics, is not of much use unless the values of the various parameters are known. Therefore, the results must be calibrated.

The collector voltage, V_C, may be calibrated by using a voltage source as a standard. A constant voltage device, such as a mercury cell, could be used to provide a certain horizontal deflection. The V_C value can then be easily determined by connecting the collector and emitter leads across the horizontal input terminals of the oscilloscope. A mercury cell of approximately 10-20 volts would be suitable.

The collector current, I_C, may be calibrated in much the same way. The same mercury cell could produce a certain vertical deflection. Then, if the I_C is forced to pass through a <u>known</u> value of series resistance, the vertical deflection caused by this IR drop could easily be converted to current values.

The base current, I_B, of the unit under test, is preset and the step values may be printed right on the I_B selector switch mentioned previously. The original, preset value of I_B may be adjusted to its desired value by inserting a microammeter or milliammeter in the base lead of the unit under test. By disconnecting the driver circuit, the steps may be presented one at a time by alternately connecting each base of the first multivibrator to the emitter.

This action will cause a shift from one state to another, by the multivibrator, at any rate desired. By switching the multivibrator manually eight times, the other two multivibrators will be triggered properly and the complete range of eight steps will be produced. This allows any amount of time which may be necessary to adjust the series resistors, and I_B, to the desired values.

These are the refinements and complementary circuits which are necessary to make the curve tracer a complete, versatile piece of test equipment.

Conclusions

The use of transistors in military and commercial equipment has increased greatly in the past few years. From all indications, it appears that their use will continue to increase in the future. Small size, low power consumption, non-microphonic, and long life are their main attributes.

In order to utilize transistors to their fullest extent, various parameters and characteristics must be determined. The static output characteristics of a particular type of unit will supply the information necessary to arrive at many of these values. Since the output characteristics are not always readily available, a device which will rapidly display these characteristics is a valuable aid to the design engineer and student.

This work has produced all the basic circuits which are necessary to furnish the static output characteristics which are desired. The complementary circuits which would increase the utility of the equipment are few in number and it is believed that the refinements suggested, when applied to the tester as presently developed, will produce a piece of test equipment suitable for use in most transistor applications.

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