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## A PRACTICAL APPROACH TO TRANSISTOR AND VACUUM TUBE AMPLIFIERS

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BY F. J. BECKETT

TEKTRONIX, INC.

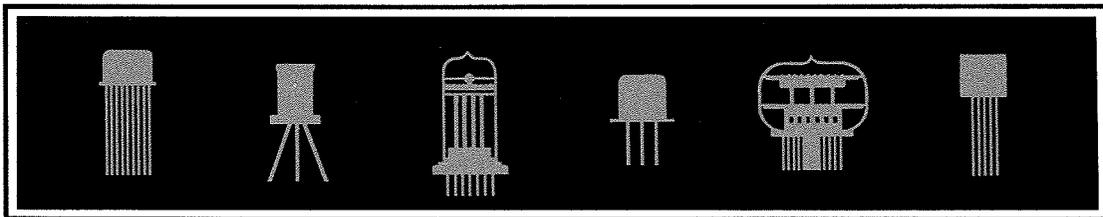
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### PART 3

A DC ANALYSIS OF A TYPICAL  
TEKTRONIX HYBRID CIRCUIT



This is the third in a series of three articles offering a new approach to transistor and vacuum-tube amplifiers. This new approach is based on a simple DC analysis that incorporates the concepts of "trans-resistance" and the principles of Thévenin's Theorem.

In this article, conclusions reached in Part 1, "The Transistor Amplifier" (Service Scope #42, February 1967) and Part 2, "The Vacuum Tube Amplifier" (Service Scope #43, April 1967) form the basis for a DC analysis of a typical Tektronix, Inc. hybrid-amplifier circuit.

As a typical example of a Tektronix, Inc. hybrid circuit on which to demonstrate our DC analysis, we have chosen the vertical amplifier of a Type 545B Oscilloscope. This circuit is representative of the hybrid circuit one encounters so often in electronic instrumentation today.

The Type 545B vertical amplifier is a hybrid push-pull amplifier operating in a class A mode. It incorporates a few extra circuits such as trigger pick-off amplifiers necessary to accomplish its function, but, basically it is a hybrid push-pull amplifier.

To begin our analysis of the amplifier, the first thing we must do is select a portion of the amplifier circuit which will give us the information necessary for us to make our first calculation. We are going to analyze the whole circuit so we can choose our point of entry. The input circuit is as good a point as any. Bear in mind that, for our purpose, this is not the only point of entry. Any point on the circuit which will give us useful information would do.

A quiescent DC voltage of +67 volts is the nominal voltage at the output of the plug-in amplifiers used in the Type 545B oscilloscope. This voltage appears at terminals 1 and 3 of J11 in Figure 17, and thus, at the grids of V494A and V494B, a 6DJ8 dual triode. The input cathode follower (V494 A & B) has a bias of about 4 volts; therefore, both cathodes will be at +71 volts. The base voltage of Q514 and Q524 is then fixed at 71 volts. This sets the emitter voltages of Q514 and Q524 at one junction drop more negative (they are both NPN transistors) than the base. Therefore, the voltage at the emitter of Q514 and Q524 is 70.5 volts. T500 is a small toroidal transformer used for high-frequency common-mode rejection. The DC BALANCE Control, R495, sets the quiescent condition. We mean by this that the trace is centered.

We have made certain assumptions about the bias of a vacuum tube and the base-to-emitter voltage drop of a transistor. This is quite justifiable since we know what function the device performs. One helpful hint about transistors is that you can expect a base-to-emitter voltage drop of about 0.5 to 0.6 volts for a silicon transistor and about 0.2 volts for a germanium transistor.

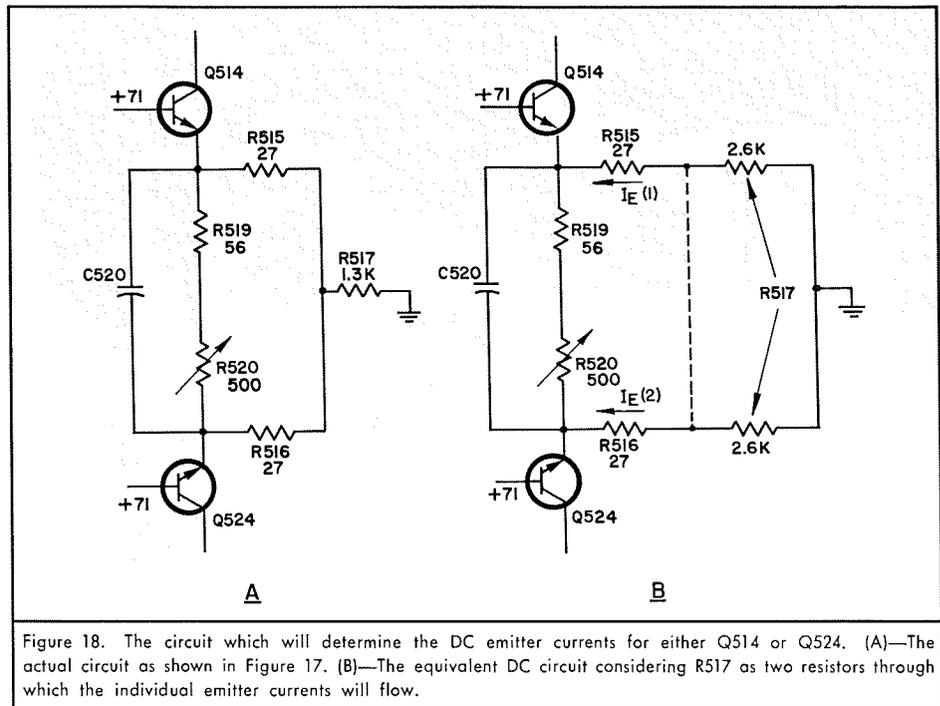


Figure 18. The circuit which will determine the DC emitter currents for either Q514 or Q524. (A)—The actual circuit as shown in Figure 17. (B)—The equivalent DC circuit considering R517 as two resistors through which the individual emitter currents will flow.

We are now able to calculate the emitter current of either Q514 or Q524. The DC-emitter current will flow through R515 or R516 and into R517 to ground. Since the emitter currents of Q514 and Q524 both pass through R517, we may think of R517 being made up of two resistors, each of 2.6 kΩ in value, in which the individual emitter currents will flow, refer to Figure 18: Therefore,

$$I_E (1) \text{ or } (2) = \frac{70.5 \times 10^3}{2.627 \times 10^3} \text{ mA}$$

$$= 27 \text{ mA}$$

We can now calculate the value of  $r_e$ , the dynamic-emitter resistance,

$$r_e = \frac{26}{I_E} = \frac{26}{27}$$

$$= 0.96 \Omega$$

to this we can add our constant,  $R_r$ , of say, 4Ω. We recall that:

$$R_t = r_e + R_r \quad (9)$$

therefore:

$$R_t = 0.96 + 4 = 4.96 \Omega$$

or approximately 5Ω. We have now established the value of the emitter current and the value of  $R_t$  for Q514 and Q524.

Our next step is to find the value of  $R_E$ . We must know this value in order to calculate gain. You will recall that  $R_E$  will be that impedance through which the signal current will flow to the AC ground. Let us take another look at the resistive network between the emitters of Q514 and Q524. The signal currents flowing in this circuit will be equal and opposite at two points, refer to Figure 19. These points are virtual AC-ground points; therefore, the impedance seen by the signal current from the emitters of Q514 or Q524 will be the parallel combination of 153Ω and 27Ω or approximately 23Ω to the AC ground points. Hence,  $R_E$  for Q514 or Q524 will be 23Ω.

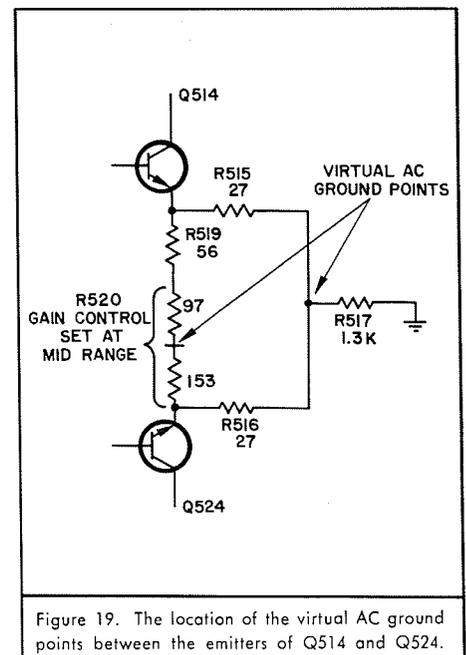


Figure 19. The location of the virtual AC ground points between the emitters of Q514 and Q524.

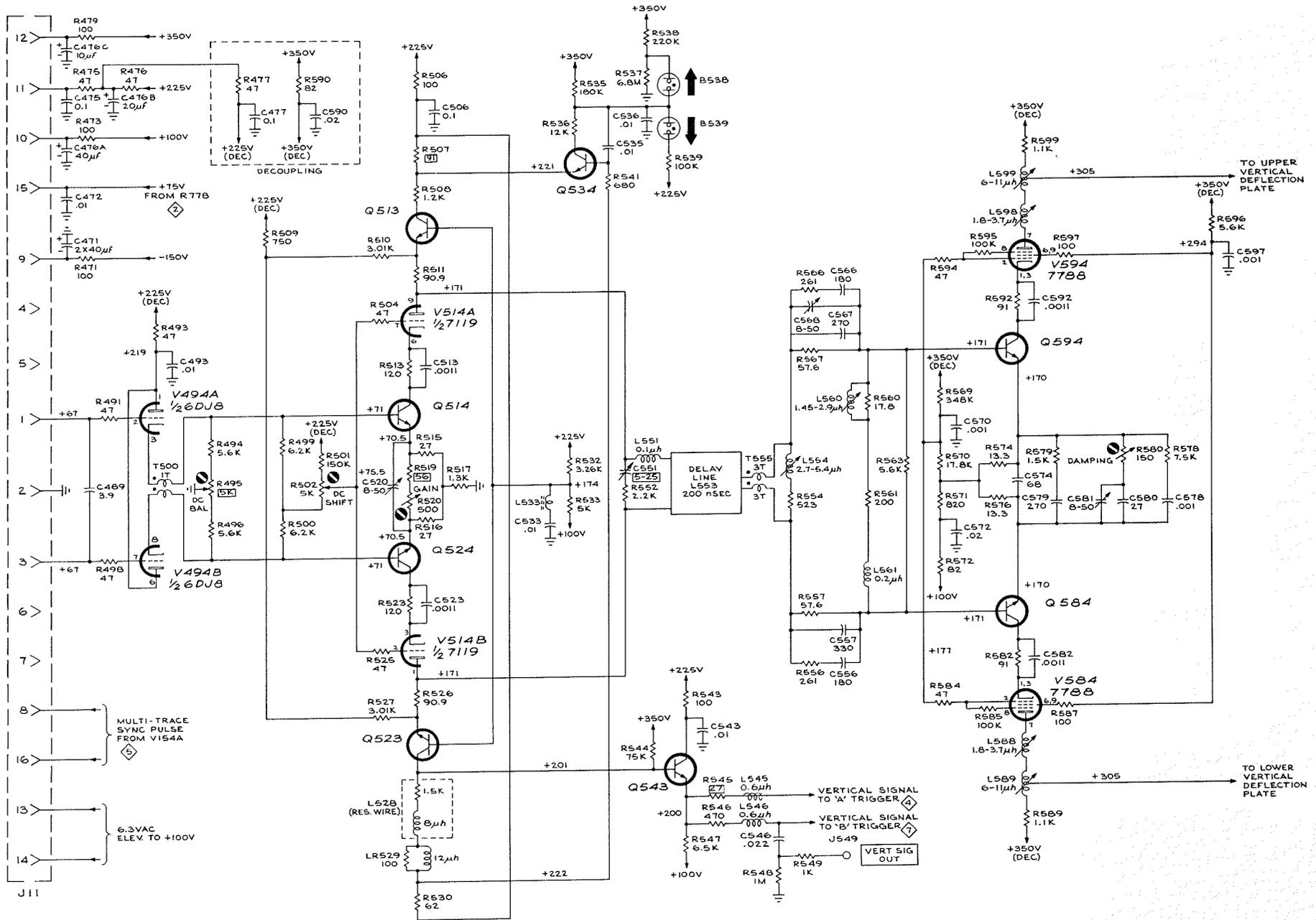


Figure 17.

TYPE S45B OSCILLOSCOPE

VERTICAL AMPLIFIER

We have now calculated from this part of the circuit all of the information we need to progress further into the circuit. Let us turn our attention to the circuit around Q513 and Q523. The first thing we notice is that the base of Q513 and Q523 are tied together at an AC-ground point. You will recall that the impedance we see looking into the emitter of the common-base configuration is  $R_t$ . In order to calculate  $R_t$  we must, of course, calculate  $r_e$  and add our constant for  $R_r$  of  $4\Omega$ ;  $r_e$  will be a function of the actual value of current flowing into the emitter. 27 milliamps has been set in the emitter circuit of Q514 and Q524; but not all of this current will flow into the

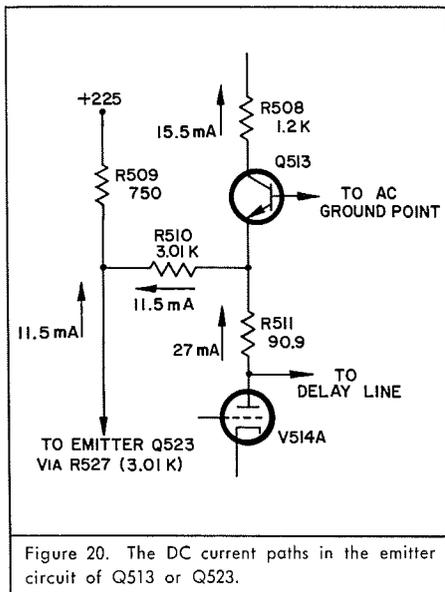


Figure 20. The DC current paths in the emitter circuit of Q513 or Q523.

emitter of Q513 and Q523. 11.5 milliamps will flow through R510 and R527, refer to Figure 20. The actual value of current into Q513 or Q523 will be 15.5 milliamps. Therefore, the impedance ( $R_t$ ) we see looking into the emitter of Q513 and Q523 will be

$$R_t = r_e + R_r \quad (9)$$

$$= \frac{26}{15.5} + 4\Omega$$

$$= 5.68\Omega$$

This impedance of  $5.68\Omega$  plus R511 or R526 ( $90.9\Omega$ ) constitutes part of the load impedance of the hybrid cascode amplifier Q514, V514A or Q524, V514B and the necessary matching impedance for the delay line.

There is one point we should make clear here. We have assumed a value of  $4\Omega$  for  $R_r$  which you will recall is equal to  $\frac{R_b}{\beta}$ .  $R_r$  can vary from between  $2\Omega$  to  $24\Omega$  depending upon the type of transistor (refer to Part 1, "The Transistor Amplifier" SERVICE SCOPE #42, February 1967). This is one of those few times we should be really a bit more specific about assuming a value of  $R_r$ . The sum of the impedances  $5.68\Omega$  and  $90.9\Omega$  should be equal to  $93\Omega$  since our delay line is a  $186\Omega$  balanced line. Therefore, we have a difference of  $3.58\Omega$  between the theoretical value and the calculated value, or an error of approximately 3.7%. This error has been due in part to our presupposed value of  $R_r$  to be  $4\Omega$ . Such an error could not be tolerated in design work but it is acceptable here for our purpose of DC analysis. Bear this limitation in mind when you apply this analysis.

There is another point we must clear up. What is the load impedance of the hybrid cascode amplifier Q514, V514A or Q524, V514B? Clearly it will be that impedance or impedances connected from the plate of V514A or V514B to the AC ground. We are using a balanced delay line of  $186\Omega$ , ( $93\Omega$  to a side), referenced to the AC ground. Therefore, the delay line impedance ( $93\Omega$ ) must shunt R511 in series with  $R_t$  (or R526 in series with  $R_t$ ) making an effective load impedance of approximately  $47\Omega$  in the plate circuit of V514A or V514B. We now have all the necessary information to calculate the gain to this point.

$$A_{(v)} = \frac{R_{L(1)} + R_{L(2)}}{R_{E(1)} + R_{E(2)} + R_{t(1)} + R_{t(2)}}$$

$$= \frac{47 + 47}{23 + 23 + 5 + 5}$$

$$= \frac{94}{56}$$

$$A_{(v)} = 1.68$$

Q523 is the trigger pick-off amplifier and Q543 is an emitter follower providing isolation between the vertical amplifier and the trigger circuits.

The trigger pick-off amplifier Q523 is one part of a transistor cascode amplifier. The input stage is Q514 and Q524. Normally, the gain of a transistor cascode amplifier is the ratio of  $R_L$  to  $R_E + R_t$ . The gain in this case must be multiplied by 0.5 for the following reason. The signal current is equally divided at the plate of V514B, half of the signal current will flow through the delay line impedance ( $93\Omega$ ) and the other half through R526 and finally through the load impedance of Q523. The load impedance will be that impedance which is connected to the AC ground. The collector of Q523 is connected to the base of Q543. The impedance we see looking into the base of Q543 is

$$R_{in} = \beta (R_E + R_t) \quad (10)$$

If we choose to neglect the input circuit of the trigger amplifier we see that  $R_E$  in this case is R547  $6.5k\Omega$ . A beta of 50 is a close figure to use for Q543, and since  $R_E \gg R_t$  then,

$$R_{in} = \beta R_E$$

$$= 50 \times 6500\Omega$$

$$= 325k\Omega$$

This impedance shunts R544 ( $75k\Omega$ ) and L528 a  $1.5k\Omega$  wire-wound resistor. We may then, for all practical purposes, consider L528 the collector load resistance ( $R_L$ ); therefore,

$$A_{(v)} = 0.5 \left[ \frac{R_L}{R_{E(1)} + R_{E(2)} + R_{t(1)} + R_{t(2)}} \right]$$

$$= 0.5 \left[ \frac{1500}{23 + 23 + 5 + 5} \right]$$

$$= 13.3$$

Q534 is the beam-indicator amplifier. Its function is to drive two neon lamps situated above the CRT on the front panel of the oscilloscope. These neons indicate the position of the trace in a vertical direction. In the quiescent condition the voltage at the junction of R535 and R536 is 287 volts. Both indicator neons, B538 and B539, have 62 volts across them, not enough voltage to strike either neon. (This type of neon has a striking voltage in excess of 68 volts.)

When we apply a negative signal to the vertical input of the oscilloscope, the base of Q524 is driven negative and the base of Q514 moves in a positive direction by a similar amount. Therefore, the current through R530 decreases and the current through R507 increases. The voltage at the emitter of Q534 increases and the voltage at the base of Q534 decreases. As a result, the base-to-emitter junction of Q534 becomes reverse biased and Q534 ceases to conduct.

Therefore, the voltage at the junction of R535 and R536 rises towards 350 volts striking neon B539 which indicates trace has shifted down.

R513 and R523 and the DC SHIFT control R502 are thermal-compensation networks. The thermal time constants are long and the visible result appears on the CRT display as a DC shift in trace position after a step function. The DC SHIFT con-

trol is adjusted for the best dynamic thermal compensation, typically about 1% tilt.

We will now analyze the output circuits to the right of the delay line, refer to Figure 17. The first thing we must do is to calculate the voltage at the base of Q594 or Q584. The voltage at the junction of R532 and R533 (174 volts) will set the base voltage of Q513 and Q523. Assuming a junction drop of 0.5 volt the voltage at the emitter of Q513 and Q523 will be 173.5 volts. The current through R511 and R526 is 27 milliamps, hence the voltage drop across these resistors will be

$$\frac{90.9 \times 27}{1000}$$

$$\approx 2.5 \text{ volts}$$

therefore, the voltage at the plate of V514A and V514B is

$$173.5 - 2.5 = 171 \text{ volts.}$$

This 171 volts is directly coupled to the base of Q594 and Q584 via the delay line. The voltage at the emitter of both Q594 and Q584 is then 170.5 volts. We will now calculate the current flowing into the emitter of Q594 or Q584. Figure 21 shows a step-by-step approach in solving this problem. The simplest approach is to use Thévenin's Theorem to simplify the resistive network R569, R570, R571 and R572. The result is we have a  $V_{oc}$  of +100 volts and a  $Z_{th}$  of 900  $\Omega$  to the junction of R574 and R576. Therefore, looking from the emitter of either Q594 or Q584 we see an impedance of 13.3  $\Omega$  in series with 1800  $\Omega$  to +100 volts.

$$I_E = \frac{(170.5 - 100)10^3}{1.8 \times 10^3} \text{ mA}$$

$$= \frac{70.5}{1.8}$$

$$= 39 \text{ mA}$$

we now calculate  $r_e$

$$r_e = \frac{26}{I_E} = \frac{26}{39}$$

$$\approx 0.7 \Omega$$

and to this we add our constant  $R_r$  of 4  $\Omega$ ; therefore,

$$R_t = r_e + R_r \quad (9)$$

$$= 0.7 + 4.0$$

$$= 4.7 \Omega's$$

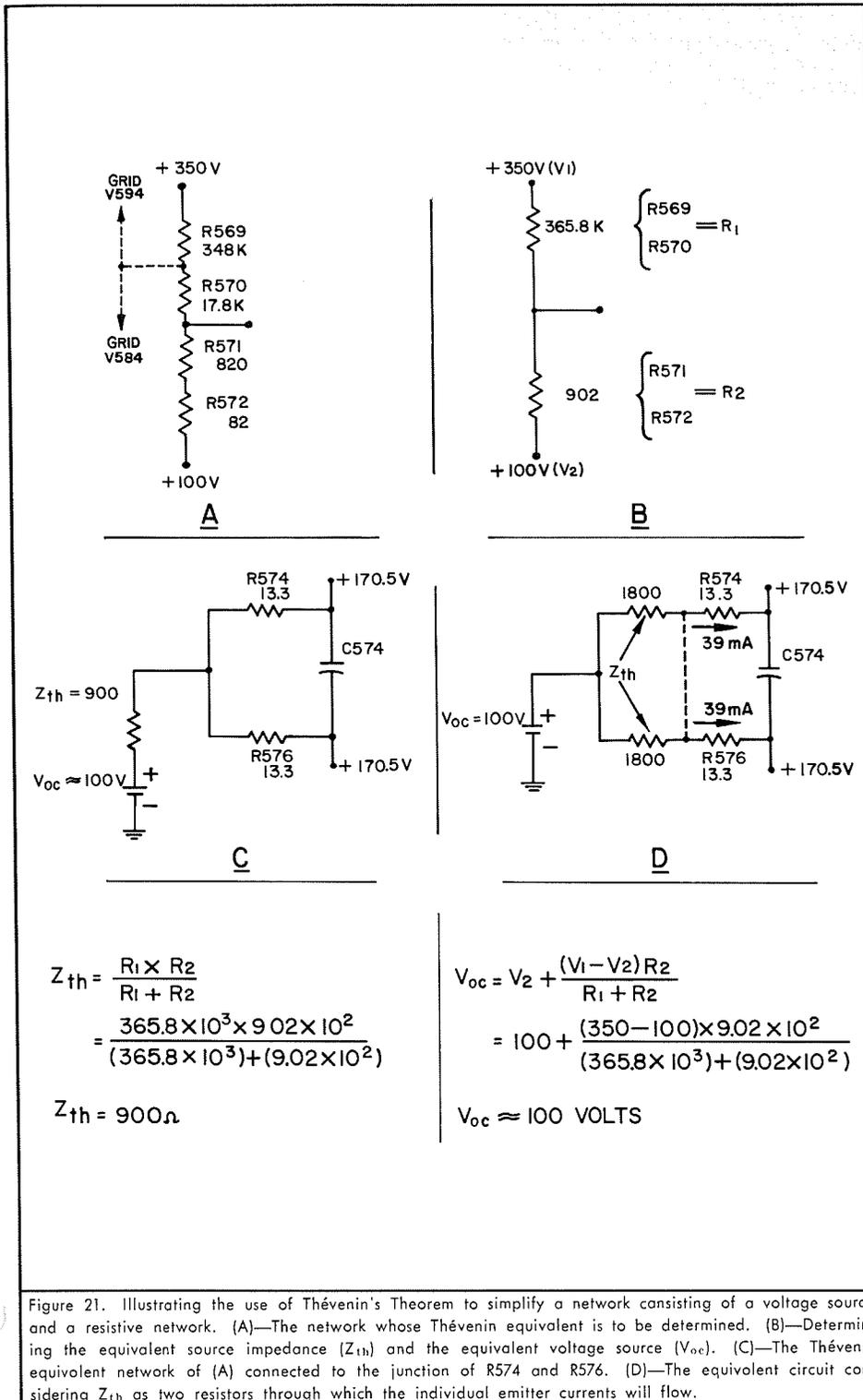


Figure 21. Illustrating the use of Thévenin's Theorem to simplify a network consisting of a voltage source and a resistive network. (A)—The network whose Thévenin equivalent is to be determined. (B)—Determining the equivalent source impedance ( $Z_{th}$ ) and the equivalent voltage source ( $V_{oc}$ ). (C)—The Thévenin equivalent network of (A) connected to the junction of R574 and R576. (D)—The equivalent circuit considering  $Z_{th}$  as two resistors through which the individual emitter currents will flow.

We have only one point in this circuit (a virtual AC ground point) at which the signal currents will be equal and opposite. That point is the junction of R574 and R576 (13.3Ω resistors). This fact sets  $R_E$  at 13.3Ω. The purpose of the RC network to the right of R574, R576 is to compensate the high frequencies.

The input impedance we see looking into the base of Q594 or Q584 is

$$R_{in} = \beta (R_E + R_t) \quad (10)$$

A beta of 75 for this type of transistor is a close figure to use for practical purposes. Therefore,

$$\begin{aligned} R_{in} &= 75 (13.3 + 4.7) \Omega's \\ &= 1350 \Omega \end{aligned}$$

The value of  $R_{in}$  is part of a resistive network which will terminate the delay line in its correct impedance. Therefore, before we leave this section we must check to see if our

value of  $R_{in}$  is within practical limits. Figure 22 shows a progressive breakdown of this network.

This network will induce a loss between the two stages. The signal is reduced in amplitude by a factor of 0.64 because of the voltage divider network consisting of 57.6Ω and the parallel combination of 100Ω, 2800Ω, and the input impedance into Q594 or Q584.

The gain of the output stage is

$$\begin{aligned} A_{(v)} &= \left[ \frac{R_{L(1)} + R_{L(2)}}{R_{E(1)} + R_{E(2)} + R_{t(1)} + R_{t(2)}} \right] \eta \\ &= \left[ \frac{1100 + 1100}{13.3 + 13.3 + 4.7 + 4.7} \right] \eta \\ &= \left[ \frac{2200}{36} \right] \eta \\ &= 61 \eta \end{aligned}$$

You recall that the gain equation of a hybrid cascode amplifier (refer part 2, "The Vacuum Tube Amplifier," Service Scope #43, April 1967) must be multiplied by the plate efficiency factor ( $\eta$ ) if the vacuum tube is not a triode. The plate efficiency factor ( $\eta$ ) normally varies from between 0.7 to 0.9. In this case ( $\eta$ ) is approximately 0.9 - 0.88 to be exact. So finally,

$$\begin{aligned} A_{(v)} &= 61 \times \frac{9}{10} \\ &= 54.9 \end{aligned}$$

The gain of the complete Type 545B vertical amplifier is

$$\begin{aligned} A_{(v)} \text{ (total)} &= 54.9 \times 1.68 \times 0.64 \\ &= 59 \end{aligned}$$

#### Summary

This brings to a close this series of three articles dealing with a practical approach to transistor and vacuum-tube amplifiers. This approach has been offered as a direct method of trouble shooting and understanding circuits. There are limitations as to its application as we have seen. However, these limitations do not impair the practical approach we must apply to our everyday maintenance and trouble shooting problems.

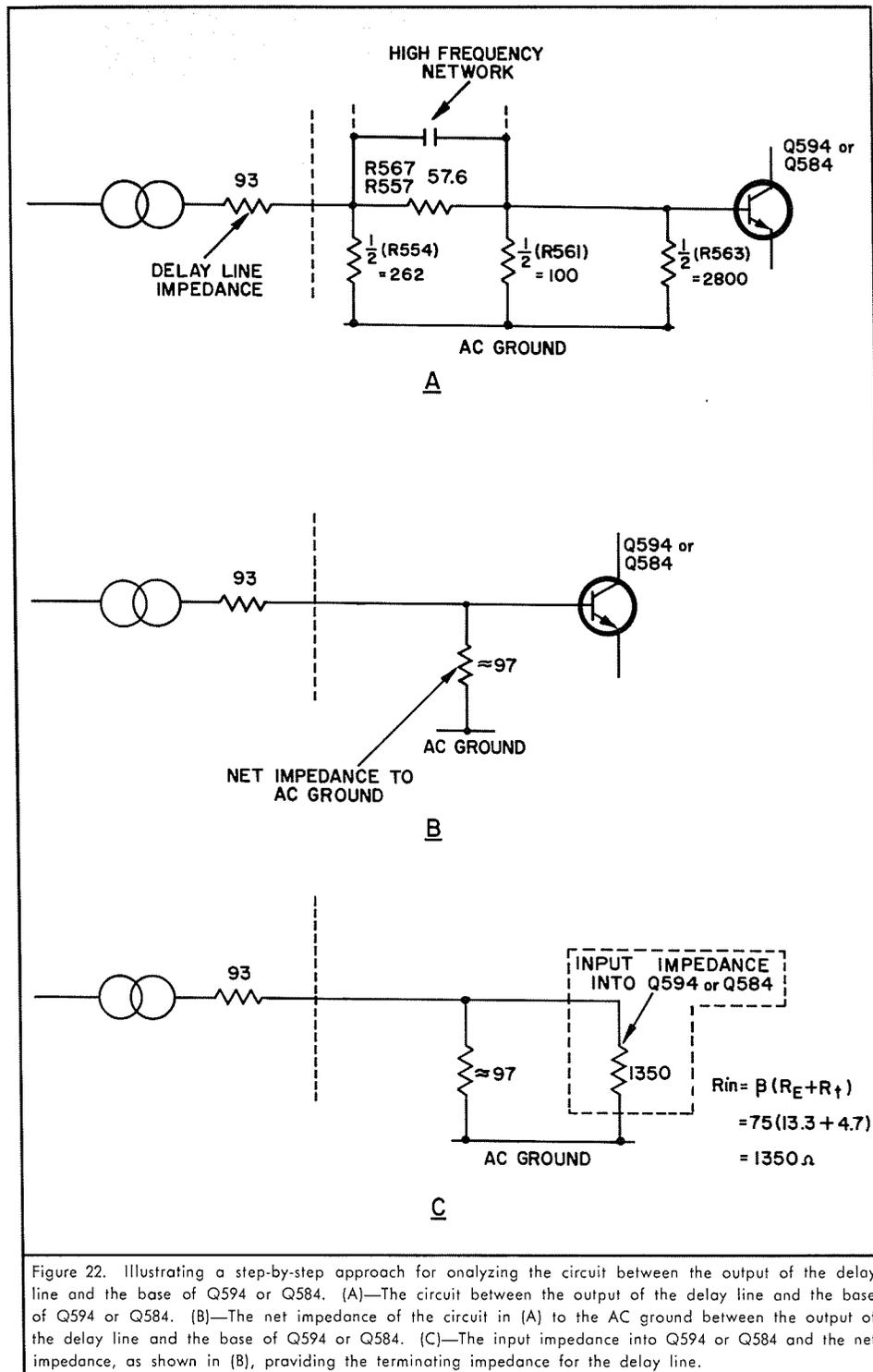
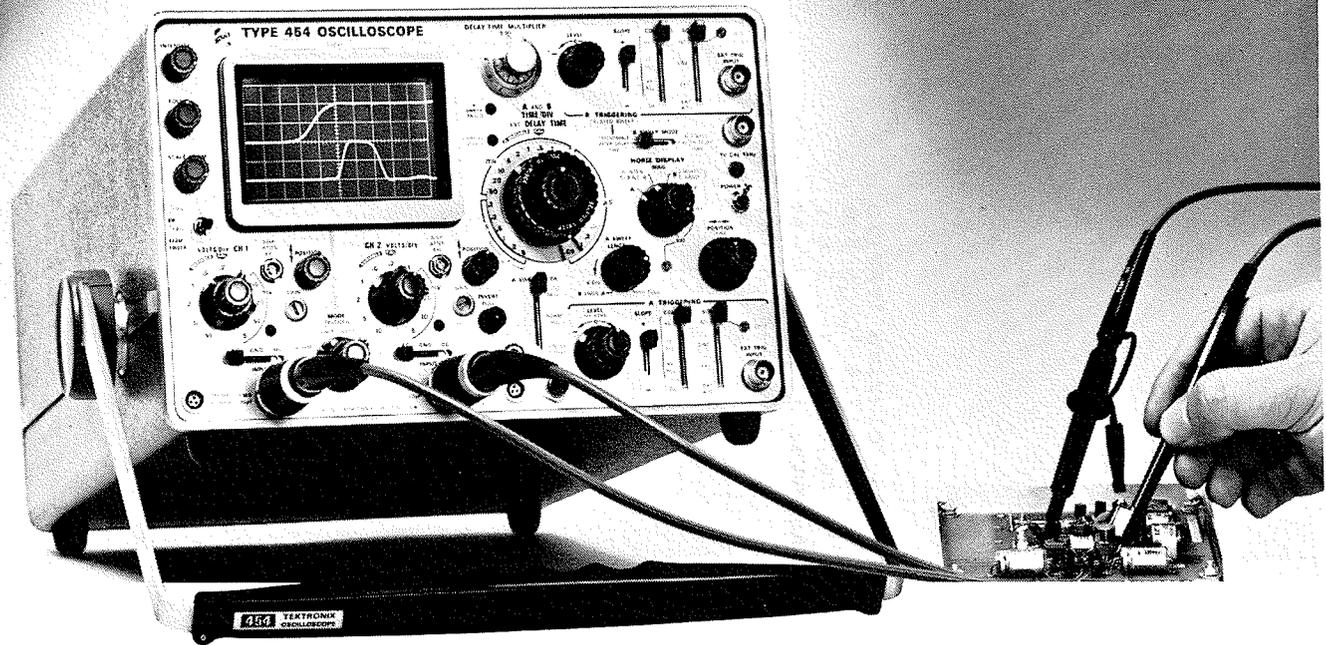


Figure 22. Illustrating a step-by-step approach for analyzing the circuit between the output of the delay line and the base of Q594 or Q584. (A)—The circuit between the output of the delay line and the base of Q594 or Q584. (B)—The net impedance of the circuit in (A) to the AC ground between the output of the delay line and the base of Q594 or Q584. (C)—The input impedance into Q594 or Q584 and the net impedance, as shown in (B), providing the terminating impedance for the delay line.

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10 mV/div	3.5 ns	DC to 100 MHz
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\*Front panel reading. Deflection factor with P6047 is 10X panel reading.

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P.O. Box 500  
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FRANK GREENWOOD  
DEPARTMENT OF TRANSPORT  
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BOX 4028, STATION E  
OTTAWA, ONTARIO, CANADA

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