Motor-driven version of curve tracer shown here connected to scope.

TRANSISTOR CURVE TRACER

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Design of a simple tester that will show the characteristics of junction and field-effect transistors on an oscilloscope.

WHEN transistors began replacing vacuum tubes in electronic circuits, designers and technicians all hoped that somehow transistors would be the panacea for all circuit problems. Besides lasting virtually forever, maybe they would simplify power-supply needs, ease circuit-design difficulties, and cure that blight on all circuit operation—*distortion*. But, alas, we couldn't have everything. Transistors *are* dependable, within reason; they *have* reduced power-supply needs; and they *have* made some circuits easier to design and lay out. But everyone soon found that distortion was still with us.

Stated briefly, *distortion* describes what happens when a signal of specific characteristics is fed into an amplifying stage and something different comes out. Carried further, the term also applies to signal-generating stages in which the output waveshape differs from what the circuit design would lead you to expect. Distortion, then, leads to undesirable and—what's worse—unpredictable circuit operation.

The three- or four-terminal simplicity of transistors offers an advantage that can be used to at least *reduce* the inconvenience that transistor distortion causes. A relatively simple tester can be built which enables the circuit designer to select junction and field-effect transistors that will work predictably in his latest brainchild, enables the service technician to choose from a batch of new transistors the one best suited for important or critical replacement situations, and enables the experimenter to pick out a transistor suitable for his purposes from among the hundreds of fractional-cost surplus transistors that are now available. A tester like this one can show up trouble spots at a glance and can help spot the cause of distortion in ordinary and field-effect transistors—even before the transistor is put into a circuit.

Ordinary transistor testers that simply measure gain or *beta* are all right for some purposes, but they don't tell the whole story. Graphs could be compiled from the measurements taken with such testers, but to put together a set of operating curves for a single transistor would take hours. More practical is an instrument that plots an entire group of operating-characteristics curves at once. A properly designed instrument can show quickly and graphically how a particular transistor would function under various operating voltages and current. An experienced operator of such an instrument can recognize the characteristics that cause a transistor to introduce distortion into its operating circuit. All the clues are included in the group of curves plotted by the instrument.

Transistor Curves

The transistor characteristics most useful for analyzing probability of distortion are based on curves of collector voltage *vs* collector current. If this curve can be plotted for several values of base bias, the resulting graph is a *family* of curves from which a great amount of information can be derived.

Fig. 1 is an example of such a graph. Collector current is plotted on the Y or vertical axis, with collector voltage on the X axis. Each curve shows the rate at which collector current increases as collector voltage goes up. By itself, this curve doesn't tell you much about the operation of a transistor in a circuit, but when a family of such curves is plotted, you can project a *load line* that represents what effect any changes in base bias will have. Each curve in the family represents the collector characteristic for one value of base bias. Six values are plotted in Fig. 1, representing bias from zero to 5 mA.

The *operating* load line is drawn in parallel with the test load line, which is along the right-hand edge of the family of curves. The operating load line begins on the bottom line of the graph, at the point of rated operating voltage for the transistor and continues upward through the various curves until it reaches a point of minimum collector volts (the left-hand knee of the curves in Fig. 1).

For analyzing the probability of distortion, it is *gain* or amplification along the load line that is most important. If gain is the same all the way up the load line, amplification is linear. You judge this from the spacing of the curves. The farther apart they are, the greater the change in collector current for a change in base bias—which means more gain or *beta*. If the transistor is perfectly linear, all six curves will be spaced equally along the operating load line. If the curves are spaced wide at the bottom and close to-

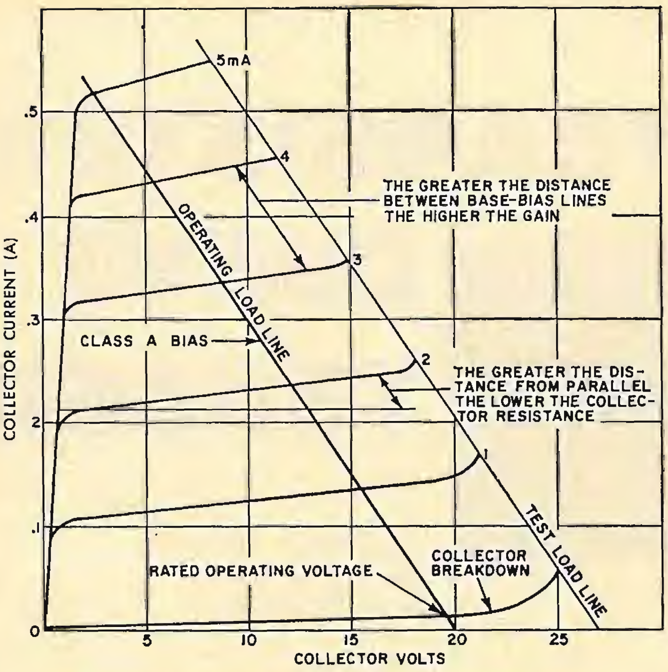


Fig. 1. Graph of voltage versus current curves for collector.

gether near the top of the load line, or *vice versa*, the amplification of the transistor is not linear and distortion can result.

There is more to be learned quickly about a transistor from the family of curves in Fig. 1. For example, you can gauge collector resistance. The more the collector current changes during a change in collector voltage, the greater the slope of the curve (more vertical). The less the change in collector current, the higher the collector resistance and the more nearly horizontal the curves appear. It is quite possible to have two transistors with the same gain but different collector resistances. In a class-B push-pull stage, this would result in imbalance between the two halves of the wave and thus create distortion.

The linearity and distortion problems that occur in ordinary transistors also apply to FET's. The FET gate is comparable to the transistor base, and gate voltage takes the place of base current. The FET drain and source compare with the transistor collector and emitter, respectively. Throughout our discussion of these operating curves, the principles will apply to FET's if the terminology is changed to conform.

What Curves Means

It will help you understand how much information you can get from a family of characteristic curves if you examine several. Since developing and plotting a family of curves is a time-consuming job if done with an ordinary tester, the faster way is with a curve tracer. This instrument can display the important parameters of a transistor in one quick view. An experienced operator can easily spot breakdown voltage, gain, linearity of amplification, collector resistance, and thermal runaway in a transistor or FET. A curve tracer also shows a great deal of useful information about zener and standard diodes.

Fig. 2 shows the first of several curve families, plotted on an oscilloscope with the curve tracer to be described later. They will familiarize you with how to interpret such displays. The display in Fig. 2 is a family of curves for a "textbook" transistor—a nearly perfect example of ideal characteristics in a transistor. This particular transistor happened to be an expensive one rescued from a piece of surplus equipment. The curves show that it would do quite well as a large-signal audio amplifier. Even with transistors as good as this, it must be remembered that when two transistors are used in class-B push-pull, both transistors must have the same gain or half of the output wave will be larger and the output distorted.

Notice how flat (horizontal) the curves are in Fig. 2. Since collector resistance equals the change in collector voltage divided by the change in collector current, a wide change of voltage without more than a small change in current means a transistor has high collector resistance. All the curves in Fig. 2 change very little in current (Y axis) over the entire range of collector voltage (X axis); therefore, you know this particular transistor has an extremely high collector resistance.

Notice also that the spacing of the curves is relatively constant. They spread only slightly farther apart up to the top pair. The transistor will be virtually linear in operation, then, until a very high value of base bias is reached. Also notice that the gain (*beta*) goes higher with an increase in base bias, which is usual with transistors.

The transistor whose curve family is shown in Fig. 3 would be good for use in a small-signal stage that is biased by automatic gain control. As greater amounts of bias are applied to this stage, the gain becomes less and less (the opposite of most transistors). However, the signal must be so small that it is always operating within an area of the same gain—between any two curves. If this transistor were used in the large-signal stages of an audio amplifier, the output would be distorted. The part of each cycle near zero bias would be greatly amplified (wide spacing at the bottom). The high-bias areas (top) have very low gain, and that part of the cycle would be compressed. The audio signal would have its shape altered drastically and sound terrible.

Fig. 4 shows a transistor with a low gain characteristic (narrow spacing) in the low-bias condition, and high gain in the high-bias condition. This transistor is either defective or made for special applications.

The curves in Fig. 5 are important to remember because they show collector breakdown. The upward hook at the extreme right of the base line is where the collector is drawing reverse current due to junction breakdown. Notice also that the other lines curve upward at their limit. This transistor is definitely operating beyond its rated maximum collector voltage. If the amount of voltage applied under operating conditions were the same as in this test situation, this transistor would cause distortion due to collector-voltage breakdown. Always operate well below breakdown voltage. You can estimate from these curves what that voltage is, at low bias values; just check the X-axis reading (calibration) at the point to the left of where the curves turn upward.

The transistor in Fig. 6 is also being driven beyond its maximum rated voltage at low bias values, note the hook at the right of the base line. This transistor is also a good example of one with low collector resistance. Notice how sharply upward each curve slopes.

Fig. 7 shows a transistor with considerable leakage between collector and emitter. Note that even with zero bias the collector is drawing high current. The first curve is well above zero. This transistor will amplify and will give an acceptable reading on most d.c.-type transistor testers, yet it will consume excessive current and run hot. The high operating current of this transistor could cause transformer saturation, power-supply problems, or short battery life.

In this display, although you can't see it in the still photo, the entire family of curves is slowly moving upward on the scope screen. When the pattern moves gradually upward with an *n-p-n* transistor (downward with a *p-n-p*), the transistor is generating heat within itself and changing characteristics. This condition is called thermal runaway and, if allowed to persist, will destroy the transistor. Lowering the transistor collector voltage or utilizing heat sinks will prevent this.

Figs. 8 and 9 are curves of two different zener diodes. The diode in Fig. 8 will immediately draw lots of current when its rated voltage is exceeded and will hold an applied voltage constant. The zener in Fig. 9 has a gradual curve at the right end of the line. The applied voltage will be allowed to shift along this curve, resulting in poor stability of the output voltage.

A Simple Curve Tracer

It isn't too difficult to build an instrument that will display the families of curves shown in Figs. 2 through 9. The schematic diagram of one built by the author is shown in Fig. 10. The instrument consists of two parts, a circuit to sweep the collector voltage and a stepper for the base current. Each of these units works independently of the other and are not synchronized.

The sweep voltage for the collector circuit comes from an adjustable full-wave unfiltered supply. This voltage sweeps the collector from zero to the calibrated voltage 60 times each second. The dial of adjustable transformer *T*3 is calibrated in peak volts so the operator can know at a glance the total length of his oscilloscope base line (X axis on the graph). A bridge rectifier (*D*5, *D*6, *D*7, *D*8) is connected in series with the transformer to prevent the incorrect half of the a.c. sine wave from being applied to the collector. Diode *D*9 and resistor *R*23 prevent transient responses from interfering with the zero base. Low and high scales (30 and 150 volts maximum) are controlled by switch *S*6. A 20-volt transformer (*T*2), connected ahead of the variable transformer, provides the low scale.

The base-current stepper circuit is fed by a 100-volt, 0.2-amp d.c. supply, consisting of *T*1, *D*1, *D*2, *D*3, and *D*4. This d.c. current is filtered through *CH*1, *C*1, and *C*2 and then applied to voltage dividers *R*1 through *R*5. A fast-turning rotary switch develops the sequential steps of voltage—or rather, current—that are applied to the transistor base. The sequence of steps is fed through one of the step-size resistors *R*6 through *R*16. The combination of the large supply voltage and the high values of the step-size resistances make this a constant-current supply. The variations in base resistance are small by comparison, and the base current is therefore determined mostly by the step-size resistor.

The taps between the step-sequence voltage-divider resistors are connected to a rotary switch which is driven either by a slow-speed motor or with a hand crank. The latter works quite well and allows the operator to stop at any desired base-bias step for detailed study of its curve.

To adapt the curve tracer for FET's, the step current must be changed into a step voltage, and the base-current supply (which becomes a gate-voltage supply) must be reversed in polarity. This is accomplished by switch *S*8 which grounds one end of the sequence-stepping divider. *S*8 also allows a choice between one step or no steps of reverse

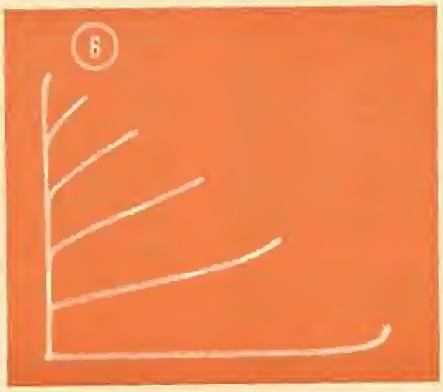
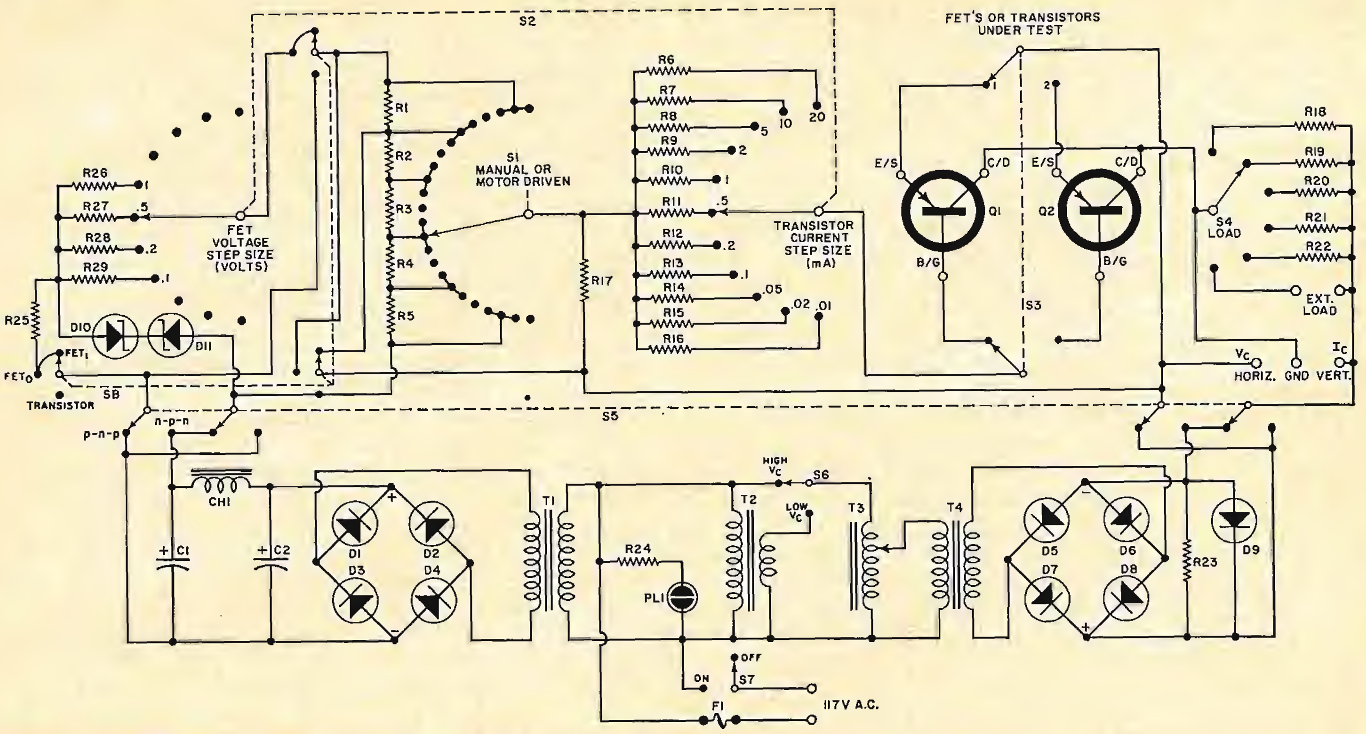


Fig. 2. Linear transistor. Note high collector resistance. Fig. 3. Non-linear gain characteristics; highest is near zero. Fig. 4. Non-linear, with the low-gain end near to zero bias. Fig. 5. Transistor being run at too high a collector voltage. Fig. 6. Upward slant is indicating low collector resistance. Fig. 7. This curve shows high leakage in collector junction. Fig. 8. Curve traced by good zener diode. Note sharp corner. Fig. 9. Round breakdown means zener won't be able to provide the proper regulation.



R1, R2, R3, R4, R5—100 ohm, 5 W wirewound res.
R6—1000 ohm, 2 W res. ± 5%
R7—2000 ohm, 2 W res. ± 5%
R8—3900 ohm, 1 W res. ± 5%
R9—10,000 ohm, ½ W res. ± 5%
R10—20,000 ohm, ½ W res. ± 5%
R11—39,000 ohm, ½ W res. ± 5%
R12—100,000 ohm, ½ W res. ± 5%
R13, R24—200,000 ohm, ½ W res. ± 5%
R14—390,000 ohm, ½ W res. ± 5%
R15—1 megohm, ½ W res. ± 5%
R16—2 megohm, ½ W res. ± 5%
R17—56,000 ohm, ½ W res. ± 10%
R18—1 ohm, 20 W wirewound res.
R19—10 ohm, 20 W wirewound res.
R20—100 ohm, 20 W wirewound res.
R21, R23—1000 ohm, 20 W wirewound res.
R22—10,000 ohm, 5 W wirewound res.
R25—10,000 ohm, 5 W wirewound res. ±10%
R26—1300 ohm, ½ W res. ± 5%
R27—3300 ohm, ½ W res. ± 5%
R28—9100 ohm, ½ W res. ± 5%
R29—18,000 ohm, ½ W res. ± 5%
C1—300 μF, 150 V elec. capacitor
C2—200 μF, 200 V elec. capacitor
S1—S.p. 24-pos. shorting rotary sw. Terminals are wired together in groups of three with one contact between each group. See text.
S2—D.p. 11-pos. non-shorting rotary sw.
S3—D.p. 2-pos. non-shorting lever sw.
S4—S.p. 6-pos. non-shorting rotary sw.
S5—4 p.d.t. non-shorting lever sw.
S6—S.p.d.t. toggle sw.
S7—S.p.s.t. toggle sw.
S8—3 p. 3-pos. non-shorting rotary sw.
F1—3 A fuse
PL1—NE51 neon pilot light
CH1—10 henry, 200 mA, 150 ohm choke (Triad C-16A)
T1, T4—Isolation trans., 115 V: 115 V, 0.3 A (Triad N-51X)
T2—Power trans. 115 V: 20 V @ 1.25 A (Chicago-Stancor RE-201)
T3—Variable trans. 0-120 V, .3 kVA (Superior 10B)
D1, D2, D3, D4, D5, D6, D7, D8, D9—1N4383 diode
D10, D11—1N3026 18 V, 1 W zener diode
Q1, Q2—Transistors or FET's under test

Fig. 10. Simple curve tracer that can be driven by hand to display entire families of transistor characteristic curves.

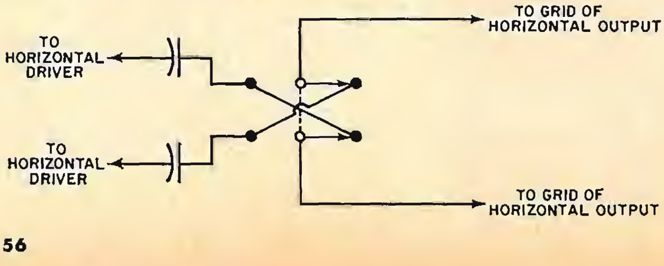
bias applied to the field-effect transistor being tested.

Zeners *D*10 and *D*11 regulate the voltage applied to the gate-voltage step-size switch. These two diodes are back to back so that the voltage will be a constant 18 volts regardless of polarity. The voltage is then dropped through *R*26 for 1-volt steps, *R*27 for 0.5-volt steps, *R*28 for 0.2-volt steps, or *R*29 for 0.1-volt steps. It is then applied to the sequencing divider. The voltage is commutated off through *S*1 to the gate of the FET. *FET's must not be tested with switch S8 in the transistor position* or the FET's will be permanently damaged.

The initial letter *p* or *n* on switch *S*5 represents the FET channel type. Thus, the *n-p-n* marking indicates the setting of *S*5 for testing an *n*-channel FET.

The collector is the common point for all measurements. Power-supply common is above ground, but no difficulty was encountered because most transformer insulation is thick enough to have no capacitive effect at the sweep frequency of 60 Hz. The scope actually looks at the emitter voltage, which is the reverse of the collector voltage. A polarity-reversing switch can be added to the oscilloscope horizontal-amplifier grids (see Fig. 11); otherwise curves will be reversed left-to-right.

Fig. 11. Polarity-reversal switch for scope horizontal amp.



Lever switch *S*3 permits a quick change from one transistor to another, for matching. When two transistors have the same spacing between curves, they have the same gain characteristic and are therefore a balanced pair.

Because a *p-n-p* transistor has negative collector voltage and current, the display of curves will be upside down. This image is mathematically correct. With a little experience, you can read these families of curves as easily as you can the *n-p-n* curves.

Construction

Subminiature transistor sockets accommodate the TO-5 or TO-40 case. Banana jacks and short clip leads are provided for eye-type terminals used on the TO-36 and TO-61. These short leads also allow reasonable connection to diodes or transistors. A TO-3 socket is mounted between the banana plugs in such a way that it can be plugged into the three banana jacks on the front panel.

The dial of the variable-voltage transformer is calibrated by connecting the vertical amplifier of an oscilloscope to the emitter terminal of one test socket and then grounding the scope to the collector or common terminal. There should be no transistor in the tester. The peak-to-peak readings indicated on the scope are recorded on the variable-voltage dial.

Load resistors are included, in values from 1 to 10,000 ohms. Any other size may be used by inserting it in the external terminals and turning

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switch S4 to "Ext. Load". The 1- and 10-ohm resistors are used for power transistors. These low values should not be used on low-power transistors because thermal runaway will cause permanent damage to the transistor. Instead, use 1000- or 10,000-ohm load.

The step generator that drives the transistor base produces five steps and a zero base line. For the author's unit, a motor-driven, shorting-type, 36-contact switch was obtained from surplus. The motor speed was about 300 r/min. Five consecutive contacts were tied together and used as one tap. One contact was left open between wired-together groups to prevent shorting.

A manually cranked switch can be used. The detent and stops are removed from a 24-position shorting-type switch. Terminals are tied together in groups of three with one open contact left between each group. A crank-type knob may be attached to this switch or a belt drive from a slow-speed motor.

How to Connect the Scope

The vertical and horizontal connections are standard. The oscilloscope is switched from internal sweep to "Ext. Horiz." The collector sweep of the tracer is adjusted to about 15 volts. The scope's horizontal gain is set so that the base-line voltage fills three-quarters of the scope screen. Select the 1000-ohm load resistor; it will give a reasonable current maximum at 15 volts. Throw the *n-p-n/p-n-p* switch to the correct type. Place a transistor in the socket and adjust the scope's vertical gain to give a display three-quarters of full height.

The vertical amplifier of the oscilloscope must be calibrated if you want to read current. Since the peak-to-peak voltage divided by the resistance equals the peak current, the voltage calibration may be divided into the 1000-ohm load resistance to obtain the value of maximum current.

Certain scopes show a tendency to make the vertical lines jitter. This is due to poor low-frequency response in the scope's horizontal amplifier. By increasing the coupling capacitance by ten times, the problem can be reduced.

Occasional faint lines will be seen between the curves, due to lack of synchronization between collector sweep and base-current steps. These lines can be disregarded. ▲

(Editor's Note: Readers who are interested in a somewhat more elaborate transistor curve tracer in which the stepping is performed completely automatically are referred to the article by Melvin Chan on p. 55 of our January issue.)