# A Power Curve Tracer At Surplus Prices
*by Dennis L. Feucht*

Curve tracers draw a graph of current versus voltage of electronic devices. They are usually used to plot the characteristic curves of transistors (see Fig. 1a), but can also display diode curves (see Fig. 1b), and the *v-i* characteristics of other two and three-terminal devices. A *family* of curves is drawn, each curve differing from the next by a change in a controlling quantity (or *parameter*), such as base current or gate voltage. A curve tracer not only can do pass/fail tests but the mode of failure can also often be determined.
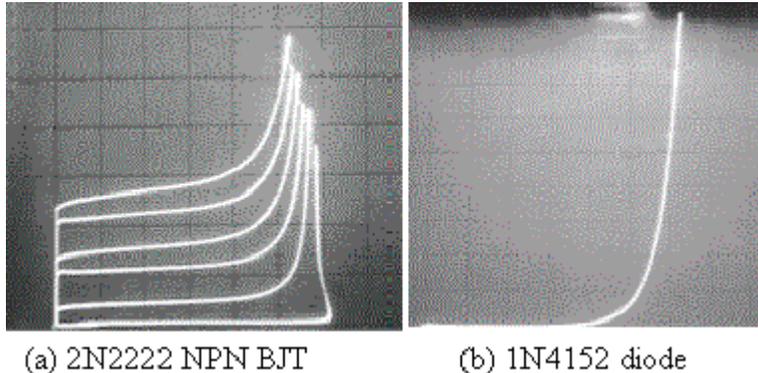


(a) 2N2222 NPN BJT          (b) 1N4152 diode

**Fig. 1: Curves Of (a) npn Bipolar Junction Transistor (BJT), (b) Diode**

The problem in equipping cost-sensitive electronics labs with a curve tracer is simple: They cost too much! A Tektronix CT, such as the 576, can run into thousands of dollars, even as used equipment. But there is one vacuum-tube era CT, the Tek 575, on the surplus market for under $300. (For instance, see www.electronicsurplus.com in Cleveland, where the author found two good 575s languishing on the warehouse shelf.) The 575 has a full-scale voltage of 200 V at up to 1 A and a 20 V range that can supply up to 20 A. That's 400 W of power -- well-suited for testing power Darlingtons, diodes, MOSFETs, and IGBTs.

**How the 575 Works**

A block diagram of the 575 is shown in Fig. 2. A collector supply connects to the collector in series with a selectable current-limiting resistor. The emitter current flows through the sense resistor and back to the collector supply. Although the emitter is grounded, the collector supply return terminal is not. This causes the voltage on the supply end of the sense resistor to be negative (for a positive collector supply voltage). The voltage dropped across the switch-selected sense resistor is the input to the vertical amplifier, which scales the current according to its gain. For pnp (negative collector voltage) transistors, the floating collector supply terminals are swapped with a front-panel switch labeled collector sweep POLARITY.

The horizontal amplifier input is the collector (to emitter) voltage, which is amplified by the selected gain corresponding to the scale factor shown by the front-panel VOLTS/DIV knob. The horizontal amplifier in the 575 is identical in design to the vertical. Identical amplifiers simplify repair and minimize the number of different replacement parts required. Each amplifier has a differential output which drives its pair of CRT deflection plates.
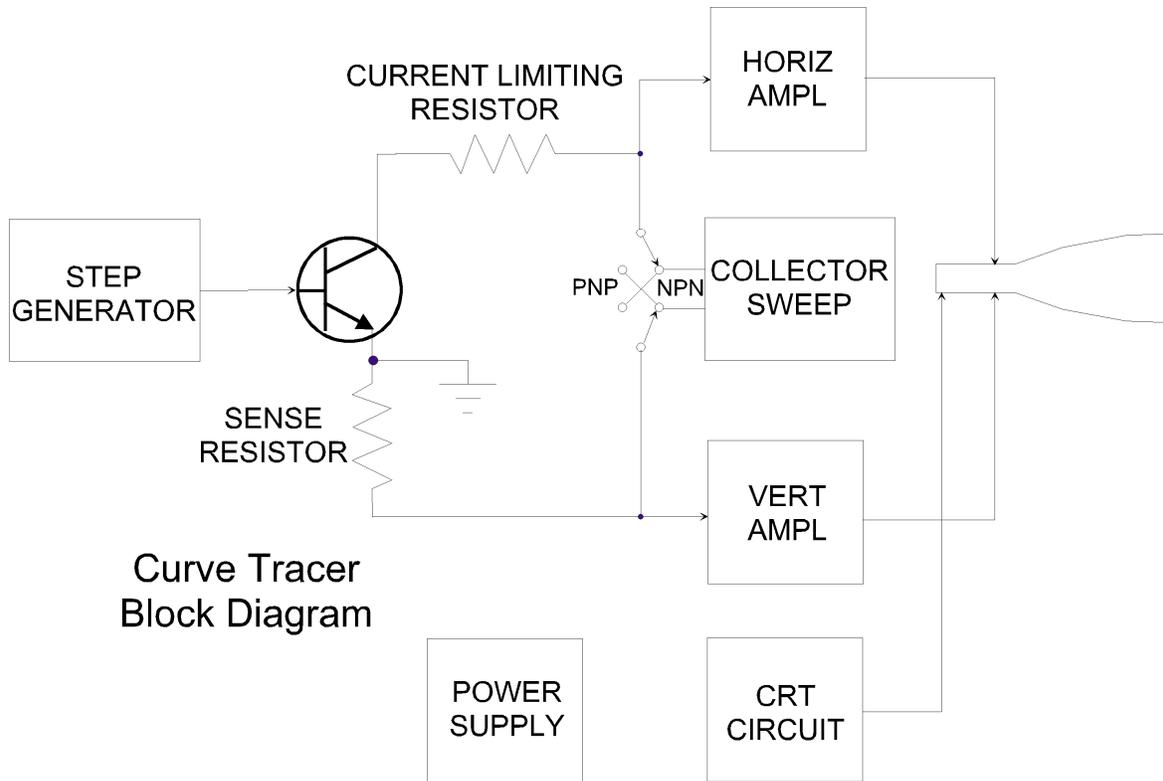
**CURRENT LIMITING RESISTOR**

**HORIZ AMPL**

**STEP GENERATOR**

**PNP** **NPN**

**COLLECTOR SWEEP**

**SENSE RESISTOR**

Curve Tracer
Block Diagram

**VERT AMPL**

**POWER SUPPLY**

**CRT CIRCUIT**

**Fig. 2: Block Diagram Of The 575 Curve Tracer**

The transistor is stepped through a series of curves by a step generator. Each curve is "swept" by varying the collector supply voltage from zero to a maximum value and back to zero. Each base-current step is synchronized to occur at the zero-crossing of the collector sweep, while the CRT spot is at the origin of the curves. Each one of the collector sweeps draws the current-voltage function for the constant value of base current, set for a given step. For 12 steps, 12 sweeps are required to draw the complete family of curves.

**Some 575 Circuit Details**

To repair, refurbish, and maintain a 575, some knowledge of its vacuum-tube-era circuitry is required. A "walk-through" of one subsystem, the step generator, will provide some familiarity by explaining detailed circuit operation.

The collector sweep circuit varies the collector voltage from zero to a PEAK VOLTS value set by a front-panel variac knob. A Variac is a variable autotransformer: It varies the voltage supplied by a winding on the power-supply transformer from zero to its peak value by changing the turns ratio as the user turns the variac shaft. The Variac sinewave voltage is rectified by a full-wave diode bridge, resulting in a 120 Hz pulsating dc waveform. The bridge output can be switched (see Fig. 2, again) for either polarity. The rectified sinewave sweeps the collector voltage 120 times per second for a 60 Hz power line. Each half-cycle produces one curve on the display.

The step generator generates a stairstep of either current or voltage and applies it to the base of the transistor under test. The polarity can be selected for n- or p-type devices, and the current (or voltage) per step is selectable along with number of steps. The circuit diagram is shown in Fig. 3, as drawn in the Tektronix 575 instruction manual. One oddity of the schematic for younger readers is the vacuum-tube symbols. (See the "Vacuum Tube Basics" box for details.)

Preceding the step generator is signal conditioning of the sine-magnitude waveforms used to trigger the step generator. The power-supply winding of the collector supply is sensed through two phase-adjust circuits, and trim-pots are set so that B lags A by 90°. The resulting waveforms from the two phase-shifted circuits are applied to a logic-NOR circuit. The output, at the grid of V143A, is a 240 Hz sequence of negative-going pulses corresponding to the 90° points of the collector-sweep sinewave. V143A is a cathode-follower (like an emitter-follower), which provides a voltage-source drive.
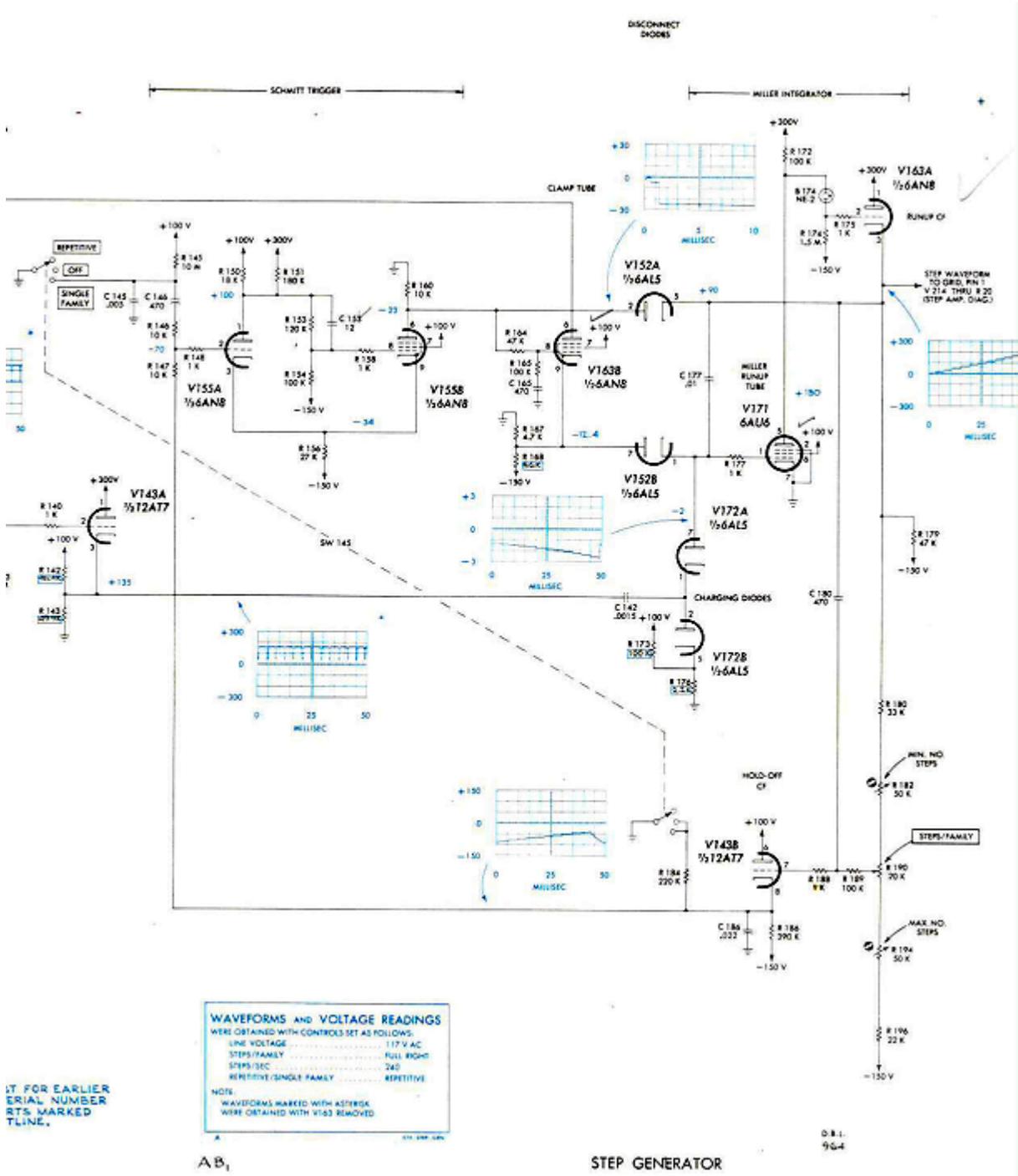
**Fig. 3: The Tek 575 Step Generator Circuit Diagram**

The pulses at the cathode of V143A have a high level determined by the supply connections of the NOR circuit -- about 150 V. The low level is set (when V143A cuts off) by resistive divider R142, R143 at 50 V. When this node goes high, C142 is charged to about 150 V through clamp diode V172B. Then when it goes low diode V172A conducts, transferring the charge of C142 to the non-inverting input of an op-amp integrator circuit. The op-amp consists of V171 and V163A. V171 is an inverting, high-gain stage followed by cathode-follower V163A, which provides a voltage-source output. B174 is a neon bulb.

It has a constant voltage drop of about 60 V and is a voltage translator, shifting the dc voltage down to give the V163A some "headroom" from the +300 V supply.

C177 is the integration capacitor from op-amp output to inverting input -- the grid of V171. Negative current pulses conducted through diode V172A cause a positive output step at the cathode of V163A. The time it takes to transfer the charge of C142 to C177 is small and occurs at the sine half-cycle zero-crossings. The stairstep voltage is fed back via a divider (from R190, adjusted for a maximum 12 steps of stairstep amplitude) via V143B, a unity-gain buffer (another cathode-follower) which drives a flip-flop, V155 (in the form of an emitter-coupled MMV). When the grid voltage of V155A increases past the flop threshold, it conducts, causing the voltage on the V155B cathode to rise while its grid voltage falls, driving it into cutoff. V155B plate voltage then increases to ground (through R160), allowing diode V152A to conduct and clamp the integrator output to near-zero volts. But what causes clamping is the turn-on of V163B, which conducts through V152B, discharging C177. The reset stairstep then resets the flop through the V143B loop.

The stairstep waveform is input to the step amplifier, which (like the collector supply) is a floating, polarity-switchable, current or voltage source with selectable gain for setting the current (or voltage) per step.


**Vacuum Tube Basics**

Vacuum tubes were the predecessors of transistors and they have similarities, allowing the transistor to be a basis for explanation. The simplest vacuum tube device is a triode (schematic symbol shown in diagram). The plate is like the drain of a FET and cathode like the source. The grid corresponds to the gate. When the grid-to-cathode voltage is less negative than the grid cutoff voltage, the tube conducts. The operating $V_{GK}$ is usually around -15 V to 0 V, somewhat more than depletion-mode FET voltages, but comparable.
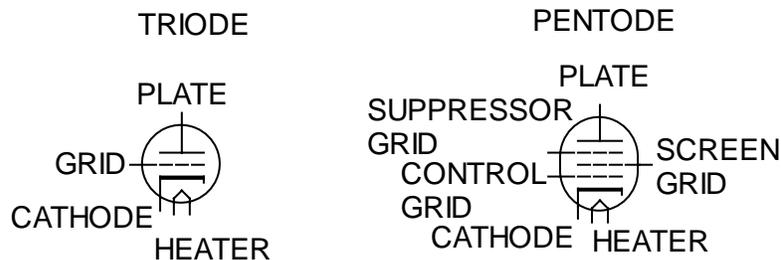


**Fig. 4: Schematics Used For Triode And Pentode With Connections**


The plate-to-cathode voltage of a triode has a significant effect on current. This is characterized by the *plate resistance*, $r_p$, which is typically around 10 kΩ, lower than the $r_o$ of a FET. Grid current is insignificant for linear amplifier stages.

The tube parameter corresponding to BJT β is μ (mu), but instead of being a current gain, it is the grid-to-plate voltage gain. Typical values of μ are 20 to 100. The dynamic cathode resistance, $r_k$, corresponds to dynamic emitter resistance, $r_e$ ($= 26$ mV$/I_E$). These tube parameters are related through the formula:

$$r_p = \mu \cdot r_k$$

One complication of tubes is that their cathodes must be heated in order to emit electrons. Heaters typically require about 250 mA at 6.3 V and contribute substantially to the power dissipation of tubes.

To increase the plate resistance to that comparable to a BJT (where collector voltage changes do not cause appreciable current changes), an additional *screen* grid is inserted between the control grid and plate. This grid is set at a constant voltage and looks like a virtual plate from the cathode. Current flowing through the screen goes to the plate, and plate-voltage variation is no longer "seen" by the cathode. One complication introduced by the screen grid is that electrons bouncing off the plate are attracted to it, causing appreciable loss in plate current. To remedy this, a *suppressor* grid is placed between plate and screen grid. It is connected to a negative voltage relative to the screen and plate (usually the cathode), and it repels electrons bouncing off the plate back to the plate. Pentodes have flat collector curves (as displayed on a vacuum-tube CT such as the old Tek 570) and are like BJT curves. Consequently, pentodes can have high gain and be used as single-stage op-amp integrators.

A vacuum-tube diode consists of plate (anode) and cathode. Unfortunately, there is only one polarity of tube, and it corresponds to npn BJTs and n-channel MOSFETs. A single polarity limits the kind of circuits possible with tubes.

Tubes also have three basic configurations corresponding to transistors: common-cathode (corresponding to common-emitter), common-grid (common-base), and common-plate or cathode-follower (common-collector or emitter-follower). Each configuration has properties similar to its transistor counterpart.


**Adapting for MOSFETs and IGBTs**

The 575 was designed for BJTs but MOSFETs, IGBTs, and JFETs are easily adapted by attaching a precision resistor between the base and emitter terminals. For a 1.00 kΩ, 1 % resistor, the base current is interpreted as a volt per mA. (The 575 has base voltage step selections, but the voltage is a maximum of only 0.2 V/step, insufficient to drive most FETs.) Power MOSFETs and IGBTs usually require about 10 to 15 V of gate drive. At 2 V per step, three or four curves typically are displayed. The base-current STEP ZERO control can then be used to vary the gate-voltage offset, which moves the curves slightly.

Not only is a gate-source resistor needed for gate drive but the terminals often will not correspond to those of a BJT on the test fixture. For TO-220 MOSFETs, a TO-220 socket can be wired, using large-diameter wire, and held in place with the screw terminals on the front-panel test-fixture porch. For power testing, a heat sink should be attached to the TO-220 package. Be sure to *not* use a TO-3 fixture made for power BJTs with MOSFETs; the terminals may not correspond, though the packages are the same.

## Transistor Parameters

The newer, expensive curve tracers acquire what for a 575 is displayed data and then calculate (with an embedded microcomputer) parameters such as "beta":

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

The $\Delta I_B$ are the steps of the base current and $\Delta I_C$ is the resulting (vertical) change in collector current. In collector-current saturation, BJT curves are nearly horizontal (corresponding to MOSFETs in voltage saturation) and the displayed vertical difference can be read off the graticule. Divide this current difference by the current/step setting of the STEP SELECTOR control and the result is $\beta$.

The change in $\beta$ with collector current can also be noted by the change in spacing of the curves. Typically, $\beta$ falls off at low currents and the curves are compressed near the bottom of the display. This data can be useful in choosing a collector-current operating point for a BJT circuit. The minimum current that provides adequate $\beta$ can be determined from the characteristic curves.

For power transistors, the saturation voltage is important in determining conduction loss when used as a switch. In Fig. 1a, note that at the left side of the curves (at low collector voltage), the curves are vertical. If the horizontal VOLTS/DIV is turned CW, the curve around zero voltage is expanded, and the voltage at the collector or drain current of interest can be measured. These saturation curves are also useful in determining the base current (or gate voltage for FETs) adequate to drive the transistor fully "on."

## Transistor Failures

If a transistor shows only a horizontal line at zero current, the collector or drain is open. This failure is due to fusing, whereby the semiconductor crystalline structure or a bonding wire overheats and melts, opening the circuit. Excessive power (and junction temperature) or current will cause a transistor to open.

If the displayed curves are vertical at near-zero voltage, the transistor is shorted. This is often due to collector or drain overvoltage, which causes a strong electric field to produce the avalanche effect. Electrons are accelerated by the field to a high speed and when they collide with other electrons, they knock them out of their atomic orbits. These electrons are also accelerated, causing an "avalanche" of current. In Fig. 1(a), avalanche breakdown is evident to the right, where at the collector breakdown voltage, the curves become vertical and the current depends mainly on collector voltage instead of base current. Limited avalanche current need not be catastrophic.

Sometimes a fairly straight line, neither horizontal nor vertical, will be displayed. This indicates that the transistor is behaving as a resistance and can be caused by a shorted gate (due to insulation breakdown) or a channel that has not opened fully. This suggests that the failure event was not as extreme as it could have been, which results in open transistors.

Similar results apply to diodes. Even capacitors and inductors can be tested on a CT for shorts and opens, and the 120 Hz resistance of an inductor can be measured on a power CT

such as the 575. Large capacitors that appear as shorts at 120 Hz will sweep out a loop on the display due to phase shifting.

**Closure**

The other low-cost and surplus-available CT is a Tek 5CT1N plug-in for a 5000 series scope. (There is also a TM500 version of this instrument which connects to an oscilloscope.) But it has low power capability and has limited voltage and current ranges.

A low-cost CT with some power, useful for power electronics, is the Tek 575, a vacuum-tube instrument that portrays the historic tradition of craftsmanship and elegant design of Tektronix products generally. On a limited budget, a power electronics laboratory can have CT capability for about $400 and a willingness to possibly expend a little do-it-yourself refurbishing and maintenance effort.