NEGATIVE RESISTANCE CURVE TRACER

PART II: MANUAL

by

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Abstract

This manual is a sequel to the paper "Negative Resistance Curve Tracer." The specifications of the curve tracer and its principles of operation are presented in this manual. In addition several photographs of different parts of the tracer are shown.

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1. Introduction

The negative resistance curve tracer described in [1] is used to trace both i-v curves of a 2-terminal and 6 standard representations, as listed in Table 1, of the family of characteristics of a 3-terminal or 2-port device. As the tracer signals, there is a voltage source and a current source with sine-wave, positive half sine-wave and negative half sine-wave available. So, the characteristics of both voltage-controlled (type N) and current-controlled (type S) devices can be traced. To trace the family of characteristics of a 3-terminal or 2-port device, there is a staircase voltage source and a current source with positive or negative steps, too. The input signal for the curve tracer is from an external signal generator. The output signals, which may be voltage across or current through the associated terminals of the device being traced, of the vertical channel and horizontal channel of the curve tracer are connected to the vertical and horizontal terminals of an oscilloscope, respectively. The positions of the switches on the tracer panel are all calibrated, so that it is possible by just considering their settings, and the oscilloscope amplifier gains, to determine the appropriate vertical and horizontal axis calibrations for the oscilloscope.

Table 1. Equations for the six representations of a 3-terminal or 2-port device

voltage-controlled representation	current-controlled representation
$i_1 = \hat{i}_1(v_1,v_2)$	$v_1 = \hat{v}_1(i_1,i_2)$
$i_2 = \hat{i}_2(v_1,v_2)$	$v_2 = \hat{v}_2(i_1,i_2)$
hybrid-1 representation	**hybrid-2 representation**
$i_1 = \hat{i}_1(v_1,i_2)$	$v_1 = \hat{v}_1(i_1,v_2)$
$v_2 = \hat{v}_2(v_1,i_2)$	$i_2 = \hat{i}_2(i_1,v_2)$
transmission-1 representation	**transmission-2 representation**
$v_2 = \hat{v}_2(v_1,i_1)$	$v_1 = \hat{v}_1(v_2,-i_2)$
$-i_2 = \hat{i}_2(v_1,i_1)$	$i_1 = \hat{i}_1(v_2,-i_2)$

To simplify the circuitry in the curve tracer, there is no power supply with the tracer. So, to operate the curve tracer, an external DC power supply is necessary. Moreover, as mentioned above, the curve tracer requires an external signal generator and an oscilloscope.

Fig. 1 shows an outline photo of the curve tracer. Fig. 2 shows an internal view of the tracer. Figs. 3(a) and 4(a) show the circuit boards. The former includes the tracer signal generator circuit, and the latter includes the staircase signal generator (located on the left hand side) and vertical and horizontal channel measurement circuit (located on the right hand side). Fig. 3(b) shows a simplified layout diagram of tracer signal generator and ± 15 volts power supply circuit. Fig. 4(b) shows a simplified layout diagram of staircase signal generator along with vertical and horizontal measurement channel circuit.

2. Specifications of the Curve Tracer

Power supply voltage: ± 40 volts and ± 15 volts.

Available tracer signal sources: a voltage source and a current source with sinusoidal wave, positive half sine-wave and negative half sine-wave.

Maximum output voltage of the tracer voltage source at tracing terminals: 76 volts peak to peak when sinusoidal wave; ± 38 volts peak value when positive and negative half sine-wave.

Maximum output current of the tracer voltage source at tracing terminals: 500 mA r.m.s.

Maximum output current of the tracer current source at tracing terminals: 50 mA peak value.

Available staircase signal source: a staircase voltage source and a staircase current source with positive steps and negative steps.

Step increment of the staircase voltage source: 1, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01 and 0.005 volts.

Step increment of the staircase current source: 1, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01 and 0.005 mA.

Operating mode: v-i characteristic of both voltage-controlled (type N) and current-controlled (type s) 2-terminal device; 6 standard representations characterizing a 3-terminal or 2-port device.

Sensitivity of sensing current: 1 mA/volt, 2 mA/volt, 10 mA/volt and

100 mA/volt.

Attenuation factor of voltage divider: x1, x $\frac{1}{2}$, x $\frac{1}{5}$, x $\frac{1}{10}$.

External equipments required: sinusoidal signal generator, oscilloscope, ± 40 volt DC power supply.

3. Principles of Operation

The curve tracer consists of three main blocks: a tracer signal generator, a staircase signal generator, and a vertical and horizongal channel measurement circuit as shown in Fig. 5. The input signals of the tracer signal generator and staircase signal generator are from an external signal generator (which is usually a low frequency sinusoidal signal generator). The output signals of the vertical and horizontal channel measurement circuit are connected to the associated terminals of an oscilloscope to display the characteristic of the device being traced.

Fig. 6 shows the tracer signal generator which consists of a full-wave rectifier, an amplifier, a voltage source, and a current source. Push-pull transformer T_1 is used to apply the signal from the external signal generator to full-wave rectifier which is formed by four diodes D_1, D_2, D_3 and D_4. Capacitors C_1 and C_2 are used to avoid the potential parasitic oscillations. The load of the full-wave rectifier is a voltage amplifier IC_1 which has different gain for different waveforms so that the amplitude of its output voltage is basically the same when the input voltage of the push-pull transformer T_1 is constant. The output stage IC_2 is a buffer. Potentiometer R_6 is used to adjust the amplitude of the input signal of the voltage source and the current source, i.e., adjust the amplitude of the voltage across or the current through the associated terminals of the device being traced, respectively.

High voltage op amp IC_3, transistors Q_1 and Q_2 and the associated resistors form the tracer current source. The signal from potentiometer R_6 is applied to the non-inverting input of IC_3 via switch SW_2. The output voltage of IC_3 is applied to transistors Q_1 and Q_2. Q_1 will conduct when the input voltage of IC_3 is negative, and Q_2 will conduct when the input voltage of IC_3 is positive, respectively. The feedback of IC_3 is from the output current of the vertical channel measurement circuit in Fig. 8 via resistor R_9. The output current of the current source is connected to the associated positions of switch SW_2 in Fig. 8.

The tracer voltage source is formed by high voltage op amp IC_4, transistors Q_3, Q_4, Q_5 and Q_6, diodes D_5 - D_{12} and the associated resistors. The input signal from potentiometer R_6 is applied to the inverting input of IC_4. Meanwhile, SW_2 will ground the input terminal of IC_3 so that the current source will not interfere with other circuits. The signal amplified by IC_4 is applied to the driver stages which are formed by transistors Q_3 and Q_5. Transistors Q_4 and Q_6 are the power output stages of the voltage source. Q_3 and Q_4 will conduct when the input signal of IC_4 is negative, and Q_5 and Q_6 will conduct when the input signal of IC_4 is positive, respectively. Diodes D_5, D_6, D_9 and D_{10} provide biasing for the output stages, and D_7, D_8, D_{11} and D_{12} are used as overload protection. Resistors R_{24} and R_{25}, connected to the emitters of Q_4 and Q_6, respectively, are current-limiting resistors. The output of the voltage source is connected to the associated positions of SW_2 in Fig. 8.

The circuit diagram of the staircase signal generator is shown in Fig. 7. The generator consists of three parts, that is, staircase voltage generator, staircase voltage source and staircase current source. IC_6, IC_7, IC_8 and IC_9 form the staircase voltage generator. Op amp IC_6 is used as a zero-cross detector. The input signal of IC_6 is from the same external signal generator as transformer T_1 in tracer signal generator shown in Fig. 6 so that the staircase signal will be synchronous with the tracer signal. The output pulses of the zero-cross detector are used as the triggers of monostable multivibrators IC_7 and IC_8. The negative output pulses of IC_6 will be clipped by diode D_{13}. IC_5 is a +5 volt regulator that is used as a DC power supply for monostable multivibrators IC_7 and IC_8. The output (positive) pulses of IC_7 charge capacitor C_{10} of the integrator which is formed by IC_9, resistor R_{34} and capacitor C_{10} to generate a staircase voltage between the output terminals of IC_9. The output (positive) pulses of IC_8 will discharge the integrator so that a periodic staircase voltage will be obtained. The step increment is changed by adjusting the width of the output signal of IC_7 which itself is adjusted through potentiometer R_{27}. The number of steps will be changed when the width of the output pulses of IC_8 is adjusted (by adjusting potentiometer R_{29}). Diode D_{14} is used to avoid discharge of capacitor C_{10} curing the period of generating the step voltage. The network formed by resistor R_{35} and potentiometer R_{36} is used to adjust the zero step of the output staircase voltage of the integrator. Op amps IC_{10} and IC_{11} form a voltage source with positive or negative output voltage. In fact, IC_{10} serves as a phase inverter and IC_{11}

is a voltage follower. There is a voltage divider between IC_{10} and IC_{11} to change the step increment. The positive step voltage from the integrator is fed to the inverting input or non-inverting input of IC_{10} by switch SW_1 so that positive and negative staircase voltages can be obtained. Op amp IC_{12} and transistor Q_7 with the associated resistors form a positive staircase current source to which the positive staircase voltage from IC_{11} is applied by SW_1. Potentiometer R_{56} is used to adjust the zero step of the positive staircase current signal. Op amp IC_{13} and transistor Q_8 with the associated resistors form a negative staircase current source to which the negative staircase voltage from IC_{11} is applied by SW_1. Diode D_{15} and potentiometer R_{66} are used to adjust the zero step of the negative staircase current signal.

Fig. 8 shows the circuit diagram of vertical and horizontal channel measurement circuit of the curve tracer. Summarily speaking, the function of the measurement circuit is to apply a pertinent tracer signal to the associated terminsla of the device being traced and measure the voltage across or the current through the associated terminals of the device being traced. Switch SW_2 is actually a controller by which a pertinent tracer signal (and a staircase signal when tracing a 3-terminal device) is applied to the associated terminals of the device being traced. Resistors R_{71}-R_{74}, R_{75}-R_{78} and R_{79}-R_{82}, op amps IC_{14}-IC_{18} and the associated resistors form the horizontal channel measurement circuit. Resistors R_{91}-R_{94}, R_{95}-R_{98} and R_{99}-R_{102}, op amps IC_{19}-IC_{23} and the associated resistors form the vertical channel measurement circuit. R_{71}-R_{74} and R_{91}-R_{94} are current sensing resistors which are used to sense the current through the device being traced. Switches SW_7 and SW_8 are used to change the sensitivities of sensing currents. Switch SW_9 and resistors R_{75}-R_{78}, R_{79}-R_{82}, switch SW_{10} and resistors R_{95}-R_{98}, R_{99}-R_{102} form a voltage attenuator, respectively, so that op amps IC_{14}, IC_{15}, IC_{19} and IC_{20} will not get saturated. To improve the precision of the measurement circuit, we use JFET input quad op amps as the input stages and large enough resistance for the voltage attenuator so that the current through the current sensing resistor is almost the same as that through the associated terminals of the device being traced. Op amp IC_{16} (or IC_{21}) works as a differential amplifier when switch SW_{11} (or SW_{12}) is on the position "i" in wihch case the current through the device being traced is being measured. To measure the voltage across the device being traced, SW_{11} (or SW_{12}) should be on the position "v," then the op amp IC_{16} (or IC_{21}) is working as a normal amplifier.

Note that when tracing the i-v characteristic of a 2-terminal device or the first 4 representations (refer to Table 1) of a 3--erminal device, the vertical channel is assigned to measure the current, and the horizontal channel is assigned to measure the voltage, i.e. SW_{12} should be on positions "i" and SW_{11} should be on position "v." Switches SW_{13} and SW_{14} are used to change the polarities of the output signals whenever it is desirable.

To trace the transmission characteristics of a 3-terminal device, a tracer signal and a staircase signal must be applied simultaneously and independently to the same associated terminals of the device. Applying a nullator† and a norator†† will make that to be possible. When SW_2 switches on position "5" or "6," IC_{24} acts as a nullator and a norator.

Switch SW_4 is used to apply a tracer signal or a tracer signal and a staircase signal to the associated terminals of a 2-terminal device or a 3-terminal device. For example, when SW_4 switches on position "2-term.," a tracer signal is applied to the two terminals of a 2-terminal device. However, when SW_4 switches on position "1st" or "2nd," a tracer signal is applied between the first and the third terminals and a staircase signal is applied between the second and the third terminals of a 3-terminal device, or vice versa.

Both potentiometer R_{68} connected in parallel with the tracer current source and one of inductors L_1-L_6 connected in series with the device being traced, are used to quench the oscillation when tracing a current-controlled device. Similarly, both potentiometer R_{111} connected in series and one of capacitors C_{11}-C_{16} connected in parallel with the device being traced are used to quench the oscillation when tracing a voltage-controlled device. For convenience in choosing any inductance and capacitance value, external inductor and capacitor terminals are available. Figure 9 shows the circuit for a ± 15 volt power supply.

4. Operating Instructions

Before operating the curve tracer, the user should read the preceding section to gain some understanding of how the curve tracer works. The user should also read this entire section on operating instructions before attempting

†The nullator is a singular circuit element defined by a single point at the origin, namely, v = 0, i = 0 [2-3].

††A norator is a singular circuit element defined by all points in the v-i plane [2-3].

to use the instrument.

(1) The following equipment is required for oeprating the curve tracer:

(a) A low frequency sine-wave signal generator.

(b) An oscilloscope with identical vertical and horizontal amplifiers. Both amplifiers must be calibrated in range from 10 mv/division to 10 v/division. (In writing this manual we used a 7633 tektronix).

(c) A dc power supply with ± 40 volt 1 ampere output.

(2) To set up the curve tracer do the following:

(a) Connect the dc power supply to the binding posts on the rear of the curve tracer. Note that there is no power switch on the curve tracer. Therefore, <u>do not</u> turn the dc power supplies on before the set up has been completed.

(b) Connect the vertical and horizontal output BNC terminals to the appropriate oscilloscope terminals. Sheilded calbe should be used. Turn the oscilloscope on and adjust it for proper operation.

(c) Connect the output terminals of the sine-wave signal generator to the "ext. signal" terminals of the curve tracer. Select an output signal frequency between 40 Hz and 120 Hz. Adjust the amplitude of the output signal to about 3 volts peak to peak.

(d) Set the controls of the curve tracer on the following settings:

- "voltage attenuat." (SW_9 and SW_{10} in Fig. 8) on "X.1";
- "sensing current" (SW_7 and SW_8 in Fig. 8) on "1";
- "tracer signal amplitude" (R_6 in Fig. 6) on its extreme counterclockwise position;
- "shunt resist." (R_{68} in Fig. 8) on its extreme clockwise position;
- "parallel capacit." (SW_6 in Fig. 8) on "0" position;
- "series induct." (SW_5 in Fig. 8) on its extreme counterclockwise
- "series resist." (R_{111} in Fig. 8) on its extreme counterclockwise position;
- polarity switches (SW_{13} and SW_{14} in Fig. 8) on "norm." positions;
- vertical channel measurement switch (SW_{12} in Fig. 8) on "i" (when tracing i-v characteristics of a 2-terminal device or one of the first 4 standard representations of a 3-terminal device); on "i" or "v" depending on which parameter is being measured when tracing the transmission characteristics of a 3-terminal device;
- "no. of steps" (R_{29} in Fig. 7) on its extreme counterclockwise

position;

- "step increment" (SW_3 in Fig. 7) on its smallest position;
- "waveform select" switch (SW_1 in Fig. 6 and Fig. 7) is used to select the waveforms of the tracer signal and the staircase signal. For example, the first position from left hand side indicates negative half sine-wave tracer signal and negative staircase signal are available. Hence, the position of this switch depends on the desired measurement.
- "representation select" switch (SW_2 in Fig. 6 and Fig. 8) is used to select the type of the tracer signal and the staircase signal. The left and right symbols around the hyphen on each position indicate the type of the tracer signal and the staircase signal, respectively. For example, if the switch is on position "1," tracer voltage source and staircase voltage source are available. On the other hand, the signals from tracer voltage source and staircase current source are available when the switch is on position "3." Position "1" is used when tracing a voltage-controlled (type N) 2-terminal device; position "2" is used when tracing a current-controlled (type S) 2-terminal device. Turn the switch to the associated position with the desirable representation when tracing a 3-terminal device. In fact, the 6 positions of the switch correspond to the 6 standard representations of a 3-terminal device listed in Table 1.

(e) To complete the setting up procedure, do the following in the order listed:

- Turn on ± 40 volts dc power supply;
- Turn on the external signal generator.

The curve tracer is now ready to be used.

(3) To trace a 2-terminal device, connect the two terminals of the device to red (positive) and black (negative) terminals on the tracer panel, and turn "device select" switch (SW_4 in Fig. 8) to "2 term." position. Slowly increase the amplitude of the tracer signal using the "tracer signal amplitude" control (potentiometer R_6 in Fig. 6), until a desirable tracing appears on the scope. For example, to trace the one-port shown in Fig. 10(a), connect the positive terminal of the one-port to the red terminal and the negative terminal of the one-port to the black terminal on the

tracer panel. Put the associated controls on the following settings:

- both "voltage attenuat." in vertical and horizontal channels on position "X.1."
- "sensing current" in vertical channel on position "2";
- "waveform select" control on the third position from left;
- "representation select" control on position "1";
- "type of device" control on position "2-term.";
- the vertical amplifier gain of 7633 Tektronix scope on position "50 mv/div";
- the horizontal amplifier gain of 7633 Tektronix scope on position "1 v/div";

After slowly increasing the tracer signal amplitude, the characteristic shown in Fig. 10(b) should appear on the scope.

(4) To trace a 3-terminal device, connect the 1st terminal to "1st" (red) binding post, the 2nd terminal to "2nd" (white) binding post, and the 3rd terminal to "3rd" (black) binding post. Turn "device select" switch to "1st" or "2nd" position. Slowly increase the amplitude of the tracer signal until a desirable tracing appears. Next, slowly adjust "No. of steps" control (R_{29} in Fig. 7) until a family of characteristics appears. The "step increment" switch (SW_3 in Fig. 7) can then be used to obtain a desirable spacing between two adjacent curves.

For example, to trace the 2-port device shown in Fig. 11(a), connect the positive terminal of the first port of the device to the 1st terminal on the curve tracer panel, the positive terminal of the second port of the device to the 2nd terminal on the tracer panel, and the common terminal of the 2-port to the 3rd terminal on the tracer panel, respectively. Put the associated controls on the following settings:

- both "voltage attenuat." in vertical and horizontal channels on position "X0.1";
- "sensing current" in vertical channel on position "100";
- "step increment" control on position "1";
- "waveform select." control on the second position from left;
- "representation select." control on position "3";
- "type of device" control on position "1st";
- the vertical amplifier gain of 7633 Tektronix scope on position "50 mv/div";

- the horizontal amplifier gain of 7633 Tektronix scope on position "0.5 v/div."

After slowly increasing the tracer signal the tracing shown in Fig. 11(b) will appear on the scope.

(5) To scale the readings on the scope, the user should combine the scale on the tracer and the sacel on the scope. For example, when the reading on the scope is .5 volt per division and the voltage attenuation on the tracer is on position "X.1," then the actual reading is 5 volts per division. Similarly, if the reading is the current through the device being traced, and the "sensing current" control is on position "1 mA/v," then the actual reading is 5 mA per division. It should be pointed out that the calibration of the amplifier in the 7633 Tektronix scope, when working as a horizontal channel amplifier, is one fifth of that listed on the panel which corresponds to when it is working as a normal vertical channel amplifier. For example, if the gain control on the scope is on 2 volts/div, then the actual calibration should be .4 volt/div for the horizontal channel.

(6) When the slope of the negative resistance region in the i-v characteristic of a voltage-controlled device is steep, it would be better to use a high sensing current position to avoid a jump within the negative resistance region of the curve. This is because the sensing current resistor is in series with the tracer voltage source and is equivalent to an internal resistance of the tracer voltage source. For example, if the "sensing current" control of vertical channel in (3) is moved to position "1," a jump appears in the negative resistance region of Fig. 10(b).

(7) If there are oscillations within the negative resistance region of a voltage-controlled device, "series resistance" or "parallel capacitance" control (R_{111} or SW_6 in Fig. 8) should be utilized to quench the oscillations. Similarly, if there are oscillations within the negative resistance region of a current-controlled device, "shunt resistance" or "series inductance" control (R_{68} or SW_5 in Fig. 8) should be used to quench the oscillations. If it is not possible to get a suitable parallel capacitance or series inductance value; turn "parallel capacit." or "series induct." control to "ext." position and connect a desirable capacitor or inductor between "ext. capacitor" or "ext. inductor" terminals.

5. Trouble Shooting

In this section we present some guidelines on how to go about trouble shooting in the curve tracer. It should be noted that, in our opinion, this instrument is very robust and if operated according to the instructions in this manual, should not present any problems to the user. We hope that the user would never have to consult this section.

(1) Tracer signal generator

- If the current source is being used and there is no positive (negative) half sine-wave output, then check transistor $Q_1(Q_2)$ in Fig. 6.
- If the voltage source is being used and there is no positive (negative) half sine-wave output, then check Q_3 and Q_4 (Q_5 and Q_6) in Fig. 6.
- If there is a half sine-wave output but no full sine-wave output, then check diodes D_1-D_4 in Fig. 6.

(2) Staircase signal generator

- If the zero step of the staircase voltage source is not equal to zero, then check potentiometer R_{36} in Fig. 7.
- If the zero step of the positive (negative) staircase current source is not equal to zero, check potentiometer R_{66} (R_{56}) in Fig. 7.
- If the step size is not calibrated, check potentiometer R_{27} in Fig. 7.
- If the number of steps is not calibrated, check potentiometer R_{24} in Fig. 7.

(3) Vertical and horizontal channel measurement circuit

- In tracing transmission representation of a 3-terminal device if oscillations are observed, check the wires in the circuit (Fig. 8). Some wires may be worn out because of the large number of switches in this circuit.

References

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Appendix A: The Catalog of Components

Part No.	Model Description	Part No.	Model Description
R_1	10 KΩ ± 10% 1/4 W	R_{33}	3 KΩ ± 10% 1/4 W
R_2	10 KΩ ± 10% 1/4 W	R_{34}	30 KΩ ± 10% 1/4 W
R_3	62 KΩ ± 10% 1/4 W	R_{35}	2.2 KΩ ± 10% 1/4 W
R_4	330 KΩ ± 10% 1/4 W	R_{36}	10 KΩ potentiometer
R_5	20 KΩ ± 10% 1/4 W	R_{37}	100 KΩ ± 10% 1/4 W
R_6	10 KΩ potentiometer	R_{38}	100 KΩ ± 10% 1/4 W
R_7	10 KΩ ± 10% 1/4 W	R_{39}	100 KΩ ± 10% 1/4 W
R_8	10 KΩ ± 10% 1/4 W	R_{40}	100 KΩ ± 10% 1/4 W
R_9	100 KΩ ± 10% 1/4 W	R_{41}	500 KΩ ± 1% 1/4 W
R_{10}	3.9 KΩ ± 10% 1/4 W	R_{42}	300 KΩ ± 1% 1/4 W
R_{11}	22 KΩ ± 10% 1/4 W	R_{43}	100 KΩ ± 1% 1/4 W
R_{12}	680 Ω ± 10% 1/2 W	R_{44}	50 KΩ ± 1% 1/4 W
R_{13}	10 KΩ ± 10% 1/4 W	R_{45}	30 KΩ ± 1% 1/4 W
R_{14}	22 KΩ ± 10% 1/4 W	R_{46}	10 KΩ ± 1% 1/4 W
R_{15}	3.9 KΩ ± 10% 1/4 W	R_{47}	5 KΩ ± 1% 1/4 W
R_{16}	680 Ω ± 10% 1/2 W	R_{48}	5 KΩ ± 1% 1/4 W
R_{17}	10 KΩ ± 10% 1/4 W	R_{49}	20 KΩ ± 10% 1/4 W
R_{18}	2.2 KΩ ± 10% 1/2 W	R_{50}	1 MΩ ± 10% 1/4 W
R_{19}	22 KΩ ± 10% 1/2 W	R_{51}	100 KΩ ± 10% 1/4 W
R_{20}	100 Ω ± 10% 1/2 W	R_{52}	1 MΩ ± 10% 1/4 W
R_{21}	100 Ω ± 10% 1/2 W	R_{53}	20 KΩ ± 10% 1/4 W
R_{22}	2.2 KΩ ± 10% 1/2 W	R_{54}	1 KΩ + 10% 1/4 W
R_{23}	22 KΩ ± 10% 1/2 W	R_{55}	91 KΩ ± 10% 1/4 W
R_{24}	1 Ω ± 10% 1 W	R_{56}	10 KΩ potentiometer
R_{25}	1 Ω ± 10% 1 W	R_{57}	1 MΩ ± 10% 1/4 W
R_{26}	20 KΩ ± 10% 1/4 W	R_{58}	20 KΩ ± 10% 1/4 W
R_{27}	10 KΩ trimpot	R_{59}	1 MΩ ± 10% 1/4 W
R_{28}	100 Ω ± 10% 1/4 W	R_{60}	100 KΩ ± 10% 1/4 W
R_{29}	50 KΩ trimpot	R_{61}	1 MΩ ± 10% 1/4 W
R_{30}	1 KΩ ± 10% 1/4 W	R_{62}	20 KΩ ± 10% 1/4 W
R_{31}	10 KΩ ± 10% 1/4 W	R_{63}	1 KΩ ± 10% 1/4 W
R_{32}	5.6 KΩ ± 10% 1/4 W	R_{64}	1 MΩ ± 10% 1/4 W

Part No.	Model Description
R_{65}	91 KΩ ± 10% 1/4 W
R_{66}	10 KΩ potentiometer
R_{67}	20 KΩ ± 10% 1/4 W
R_{68}	1 MΩ potentiometer
R_{69}	30 KΩ ± 10% 1/4 W
R_{70}	30 KΩ ± 10% 1/4 W
R_{71}	1 KΩ ± 1% 1/2 W
R_{72}	500 Ω ± 1% 1/4 W
R_{73}	100 Ω ± 1% 1/4 W
R_{74}	10 Ω ± 1% 1/4 W
R_{75}, R_{79}, R_{95}, R_{99}	5 MΩ ± 1% 1/4 W
R_{76}, R_{80}, R_{96}, R_{100}	3 MΩ ± 1% 1/4 W
R_{77}, R_{81}, R_{97}, R_{101}	1 MΩ ± 1% 1/4 W
R_{78}, R_{82}, R_{98}, R_{102}	1 MΩ ± 1% 1/4 W
R_{83}, R_{84}	30 KΩ ± 1% 1/4 W
R_{85}	30 KΩ ± 1% 1/4 W
R_{86}	30 KΩ ± 1% 1/4 W
R_{87}, R_{88}	30 KΩ ± 1% 1/4 W
R_{89}, R_{90}	30 KΩ ± 1% 1/4 W
R_{91}	1 KΩ ± 1% 1/2 W
R_{92}	500 Ω ± 1% 1/4 W
R_{93}	100 Ω ± 1% 1/4 W
R_{94}	10 Ω ± 1% 1/4 W
R_{103}	30 KΩ ± 1% 1/4 W
R_{104}	30 KΩ ± 1% 1/4 W
R_{105}	30 KΩ ± 1% 1/4 W
R_{106}	30 KΩ ± 1% 1/4 W

Part No.	Model Description
R_{107}	30 KΩ ± 1% 1/4 W
R_{108}	30 KΩ ± 1% 1/4 W
R_{109}	30 KΩ ± 1% 1/4 W
R_{110}	30 KΩ ± 1% 1/4 W
R_{111}	1 KΩ precision potentiometer
R_{112}	2 KΩ trimpot
R_{113}	120 Ω ± 10% 1/4 W
R_{114}	3.9 KΩ ± 10% 1/4 W
R_{115}	10 KΩ trimpot
R_{116}	6.8 KΩ ± 10% 1/4 W
C_1	0.1 μF 100V DC ceramic
C_2	0.1 μF 100V DC ceramic
C_3	0.1 μF 100V DC ceramic
C_4	0.1 μF 100V DC ceramic
C_5	0.01 μF 100V DC ceramic
C_6	0.2 μF 100V DC ceramic
C_7	0.1 μF 100V DC ceramic
C_8	0.01 F 100V DC ceramic
C_9	10 μF 20V DC tantalum
C_{10}	0.01 μF 100V DC ceramic
C_{11}	0.01 μF 100V DC ceramic
C_{12}	0.05 μF 100V DC ceramic
C_{13}	0.1 μF 100V DC ceramic
C_{14}	0.56 μF 100V DC orange drop
C_{15}	1 μF 100V DC orange drop
C_{16}	2.2 μF 50V DC tantalum
C_{17}	Two 2.2 μF 50V tantalum in series
C_{18}	1 μF 35V tantalum
C_{19}	100 pF ceramic
L_1	0.01 mH fixed inductor
L_2	0.1 mH fixed inductor
L_3	0.47 mH fixed inductor

Part No.	Model Description	Part No.	Model Description
L_4	1 mH fixed inductor	IC_6	LM741C
L_5	2.2 mH fixed inductor	IC_7	74121 monostable
L_6	10 mH fixed inductor	IC_8	74121 multivibrator
T_1	1 : 1 push-pull transformer	IC_9	1/4 LM2900n quad amp.
D_1-D_4	1N4448 100 mA 75 volt diode	IC_{10}	LM741C
D_5-D_{12}	1N4003 1A 200 volt diode	IC_{11}	LM741C
D_{13}	1N34a germanium diode	IC_{12}	1/4 LM 2900n quad amp.
D_{14}	1N4448 100 mA 75 volt	IC_{13}	LM741C
D_{15}	1N4448 100 mA 75 volt	IC_{14}	1/4 TL074C quad amp.
Q_1	2N4888 Si pnp transistor	IC_{15}	1/4 TL074C
Q_2	F2N5831 Si npn transistor	IC_{16}	1/4 TL074C
Q_3	2N3666 Si npn transistor	IC_{17}	1/4 TL074C
Q_4	2N5979 Si npn transistor	IC_{18}	1/4 TL074C
Q_5	2N4033 Si pnp transistor	IC_{19}	1/4 TL074C
Q_6	2N5976 Si pnp transistor	IC_{20}	1/4 TL074C
Q_7	2N4249 Si pnp transistor	IC_{21}	1/4 TL074C
Q_8	F2N5831 Si npn transistor	IC_{22}	1/4 TL074C
IC_1	LM741C general purpose	IC_{23}	1/4 TL074C
IC_2	LM741C op amp	IC_{24}	LM143H
IC_3	LM143H high voltage op amp	IC_{25}	LM337T voltage regulator
IC_4	LM143H	IC_{26}	LM723N voltage regulator
IC_5	LM340-5 + 5V regulator		

Figure Captions

Fig. 1. Outline photograph of the curve tracer.

Fig. 2. Internal view of the curve tracer.

Fig. 3. (a) Circuit board for tracer signal generator.

(b) Simplified layout diagram of tracer signal generator and ± 15 volt power supply circuit.

Fig. 4. (a) Circuit board for staircase signal generator and vertical and horizontal channel measurement circuit.

(b) Simplified layout diagram of staircase signal generator, vertical and horizontal measurement channel circuit.

Fig. 5. Block diagram of the curve tracer.

Fig. 6. Tracer signal generator circuit.

Fig. 7. Staircase signal generator circuit.

Fig. 8. Vertical and horizontal channel measurement circuit.

Fig. 9. ± 15 volt power supply.

Fig. 10. (a) A 2-terminal negative resistance device mode of a 741 op amp with saturation voltage E_s = 15 v and resistors.

(b) v-i characteristic of the device in (a). Horizontal scale: 2 volts/div. Vertical scale: 1 mA/div.

Fig. 11. (a) 2-port negative resistance device made of 2 n-channel JFETS, one npn transistor and one pnp transistor.

(b) The tracing of the 2-port deivce shown in (a). Horizontal scale: 2 volts/div. Vertical scale: 20 mA/div, current step: + 1 mA.

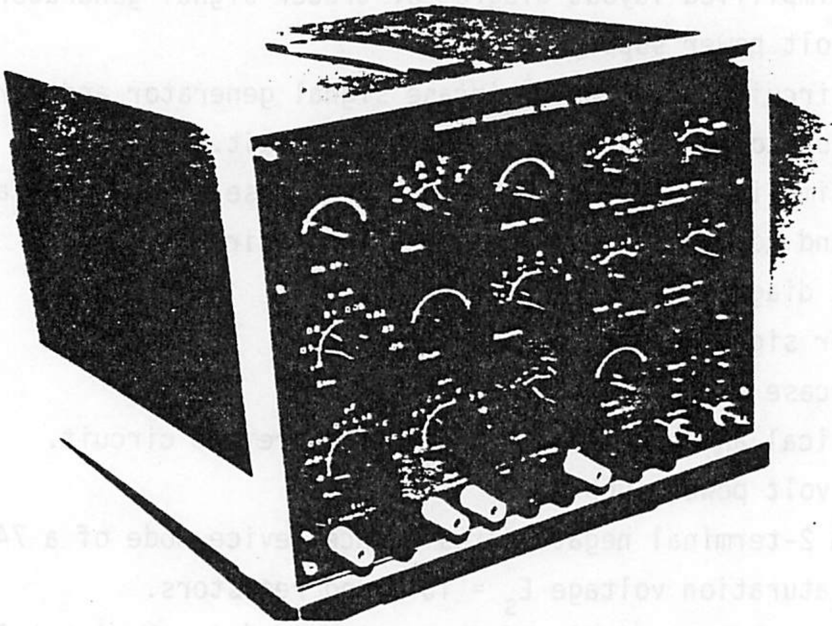


Fig. 1

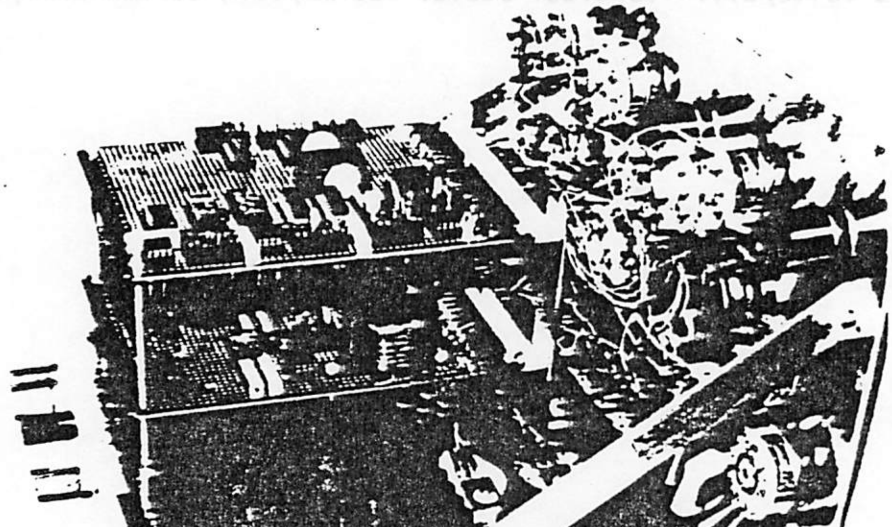


Fig. 2

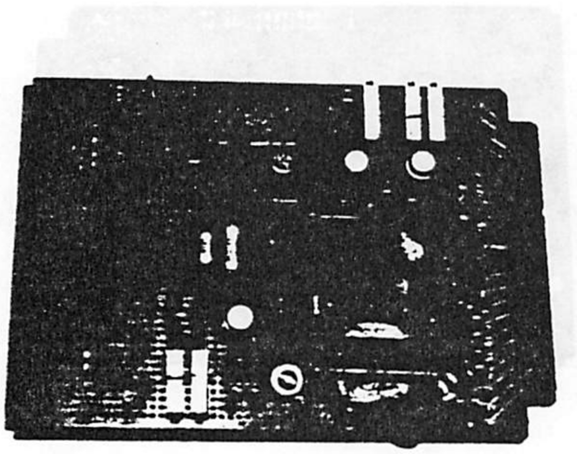


Fig. 3(a)

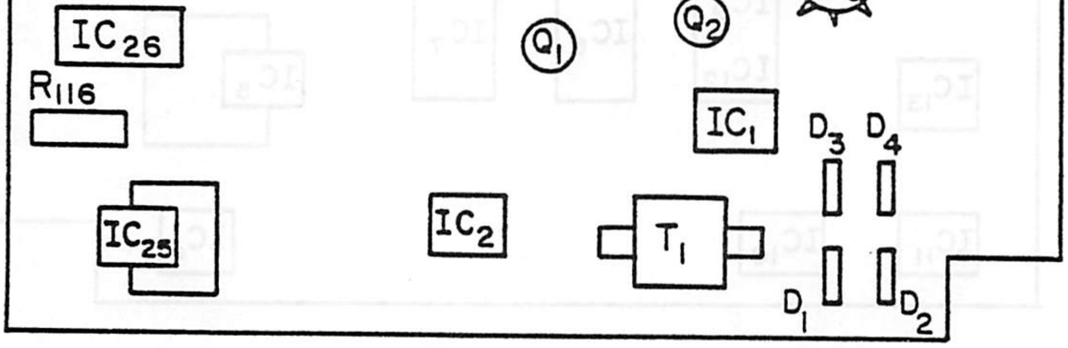

D10 D9 D11 D12 D8 D7 D6 D5
R115
Q5
Q3
IC4
IC24
IC3
IC26
Q1
Q2
R116
IC1
D3 D4
IC25
IC2
T1
D1 D2

Fig. 3(b)

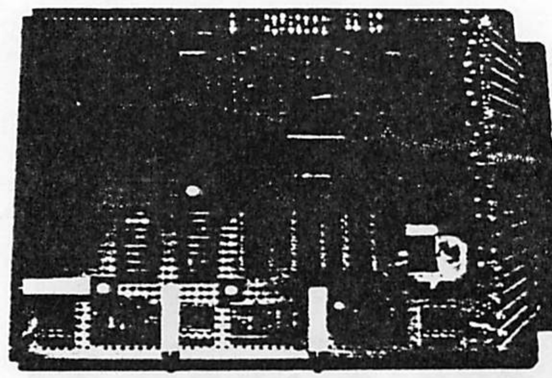
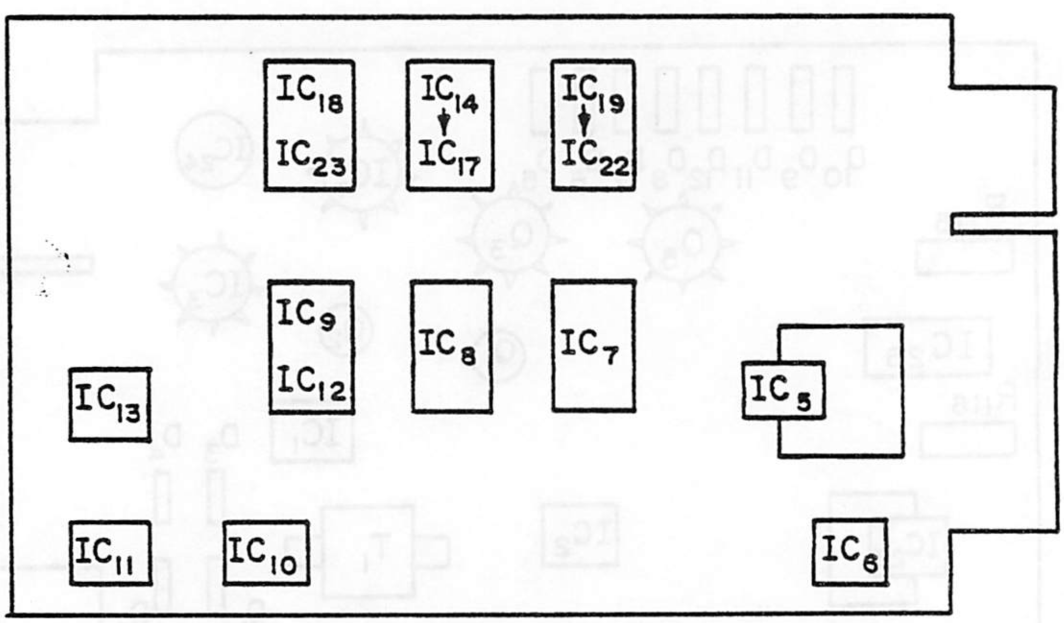


Fig. 4(a)



IC18
IC23
IC14
IC17
IC19
IC22
IC9
IC12
IC8
IC7
IC5
IC13
IC11
IC10
IC6

Fig. 4 (b)

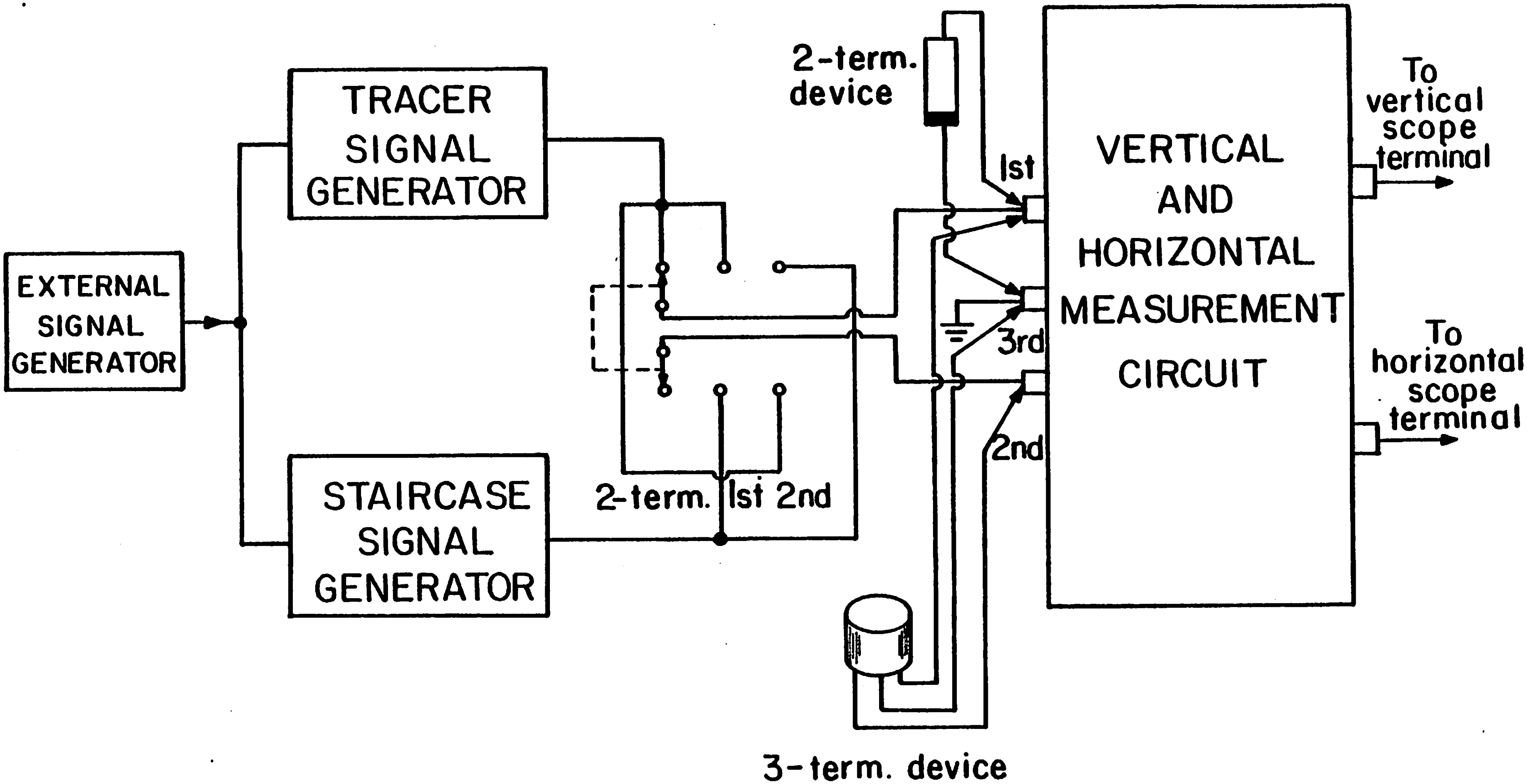
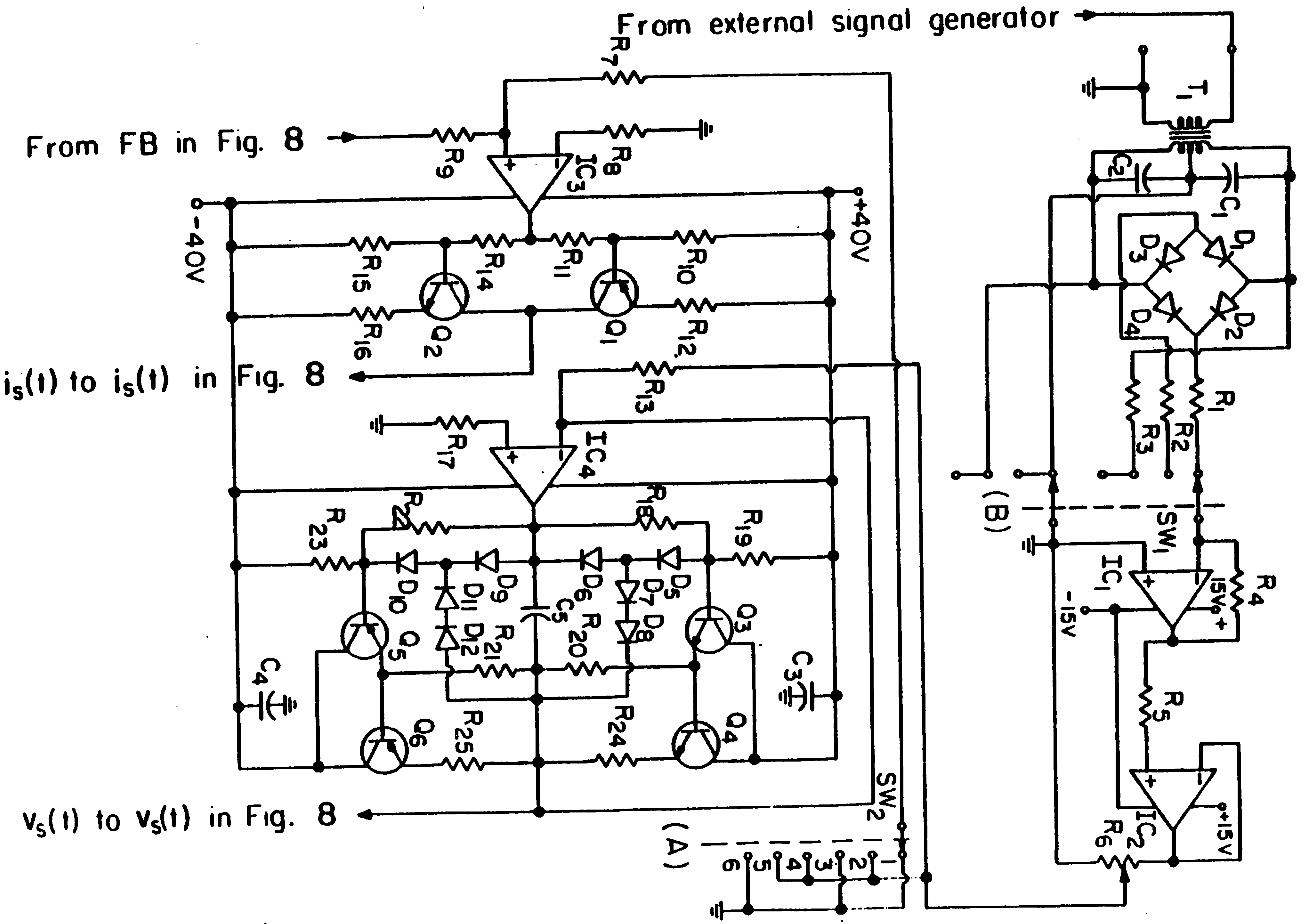
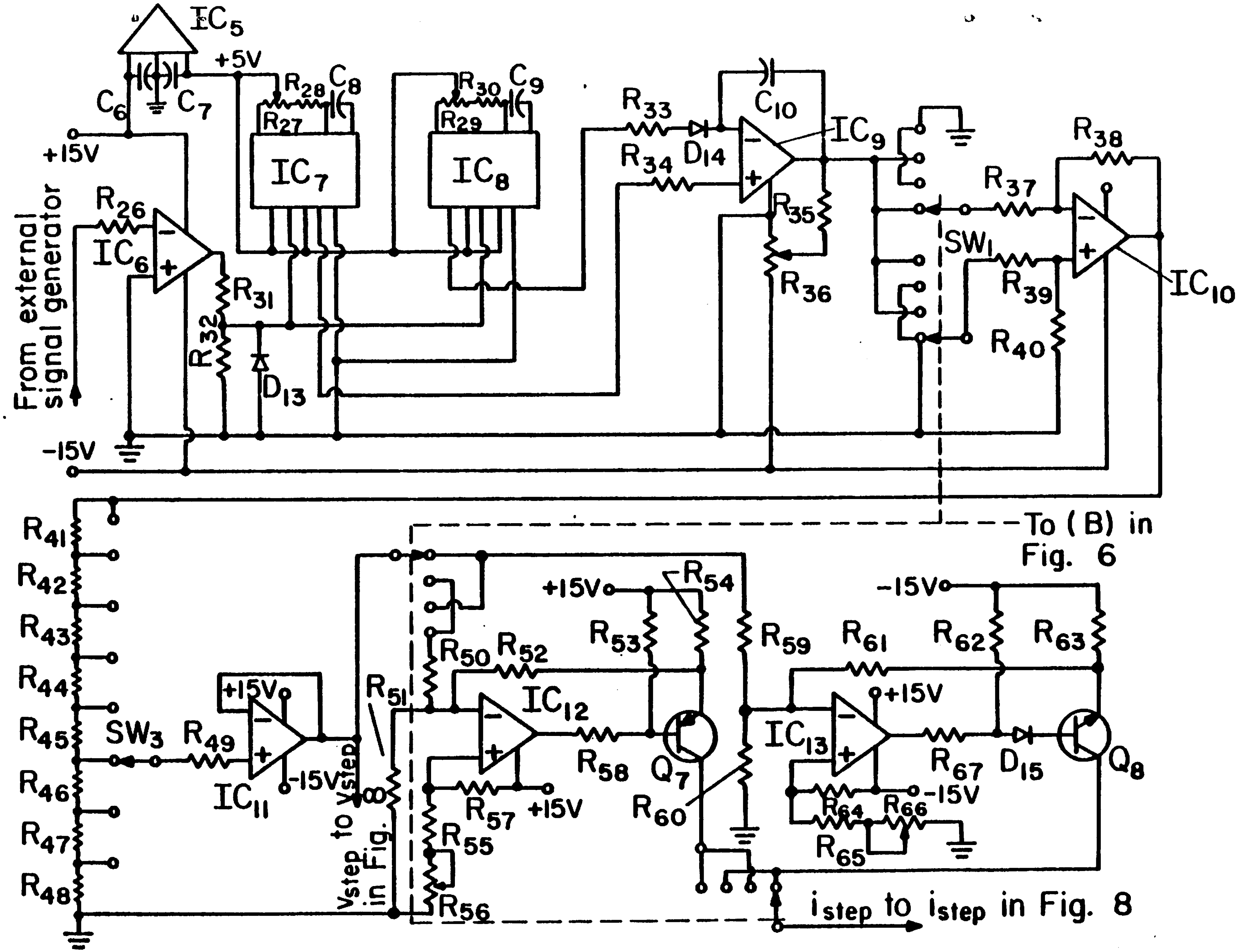

EXTERNAL SIGNAL GENERATOR
TRACER SIGNAL GENERATOR
STAIRCASE SIGNAL GENERATOR
2-term.
Ist
2nd
2-term. device
Ist
3rd
2nd
VERTICAL AND HORIZONTAL MEASUREMENT CIRCUIT
To vertical scope terminal
To horizontal scope terminal
3-term. device

Fig. 5



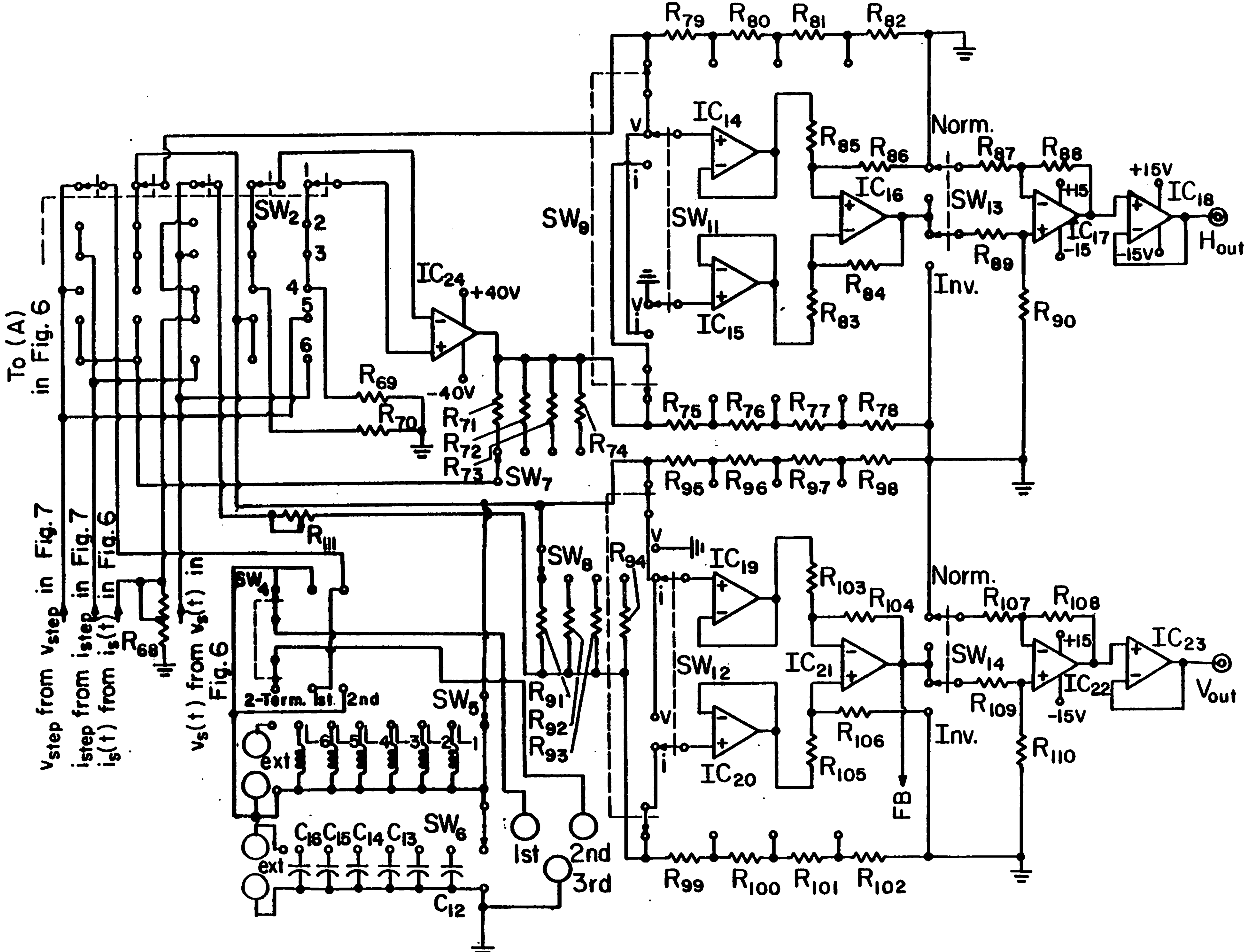
From external signal generator
From FB in Fig. 8
$i_s(t)$ to $i_s(t)$ in Fig. 8
$v_s(t)$ to $v_s(t)$ in Fig. 8
-40V
+40V
+15V
-15V
15V
R_1 R_2 R_3 R_4 R_5 R_6 R_7 R_8 R_9 R_{10} R_{11} R_{12} R_{13} R_{14} R_{15} R_{16} R_{17} R_{18} R_{19} R_{20} R_{21} R_{22} R_{23} R_{24} R_{25}
IC_1 IC_2 IC_3 IC_4
Q_1 Q_2 Q_3 Q_4 Q_5 Q_6
D_1 D_2 D_3 D_4 D_5 D_6 D_7 D_8 D_9 D_{10} D_{11} D_{12}
C_1 C_2 C_3 C_4 C_5
T_1
SW_1 SW_2
(A)
(B)
1 2 3 4 5 6

Fig. 6



IC5
+5V
C6
C7
R28
C8
R27
IC7
R30
C9
R29
IC8
R33
C10
IC9
R34
D14
R38
+15V
R37
R26
IC6
R35
SW1
R36
IC10
R31
R39
R40
From external signal generator
R32
D13
-15V
R41
To (B) in Fig. 6
R42
R43
R44
R45
SW3
R49
+15V
-15V
IC11
R51
R50
R52
IC12
R53
R54
+15V
R59
-15V
R61
R62
R63
IC13
+15V
R58
Q7
R57
+15V
R55
R56
R60
R67
D15
Q8
-15V
R64
R66
R65
R46
R47
R48
Vstep to Vstep in Fig.
istep to istep in Fig. 8

Fig. 7



To (A) in Fig. 6
v_{step} from v_{step} in Fig. 7
i_{step} from i_{step} in Fig. 7
$i_s(t)$ from $i_s(t)$ in Fig. 6
$v_s(t)$ from $v_s(t)$ in Fig. 6
SW2
IC24
+40V
-40V
R68
R69
R70
R71
R72
R73
R74
SW7
R111
SW4
2-Term. 1st 2nd
SW5
ext
L6 L5 L4 L3 L2 L1
C16 C15 C14 C13
SW6
C12
1st
2nd
3rd
SW8
R91
R92
R93
R94
SW9
R79 R80 R81 R82
IC14
IC15
IC16
SW11
R83
R84
R85
R86
R75 R76 R77 R78
Norm.
Inv.
SW13
R87 R88
R89
R90
IC17
IC18
+15V
-15V
Hout
R95 R96 R97 R98
IC19
IC20
IC21
SW12
R103
R104
R105
R106
FB
R99 R100 R101 R102
SW14
R107 R108
R109
R110
IC22
IC23
Vout

Fig. 8

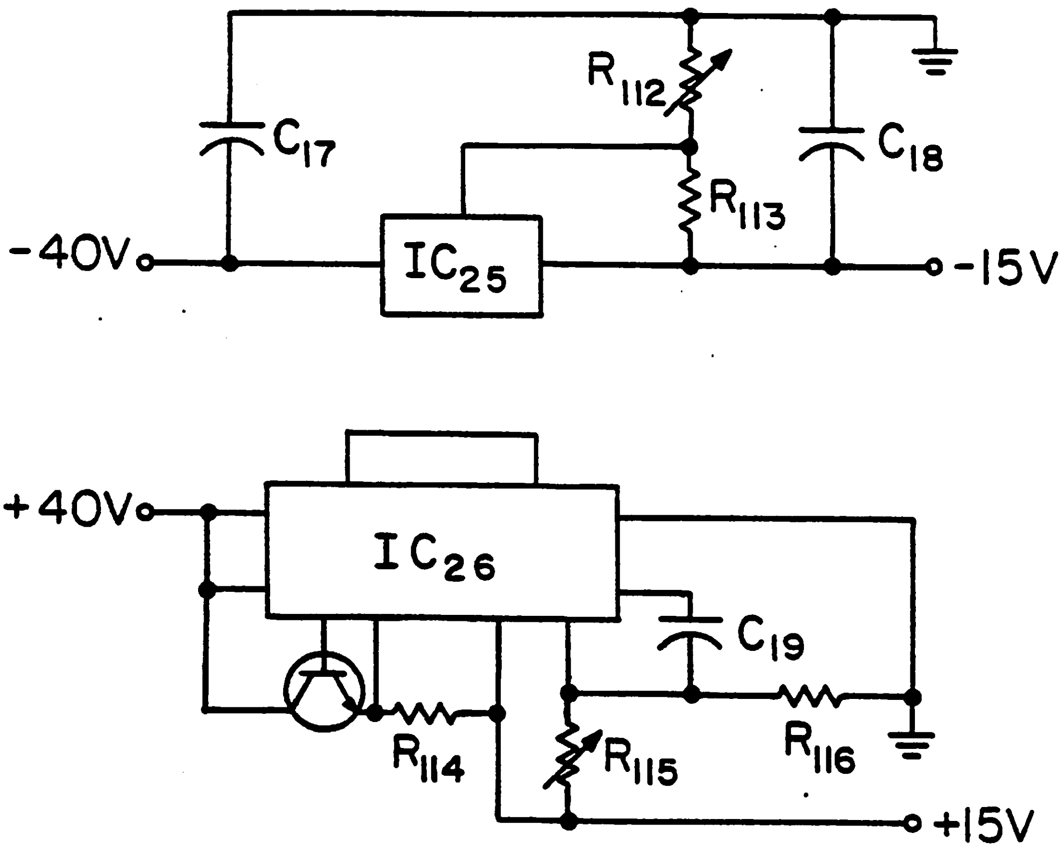
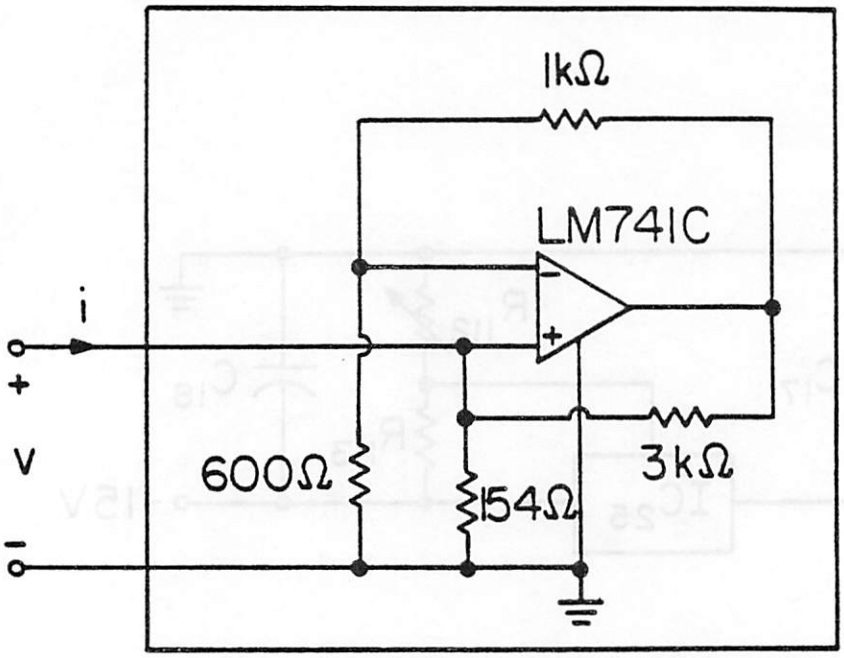
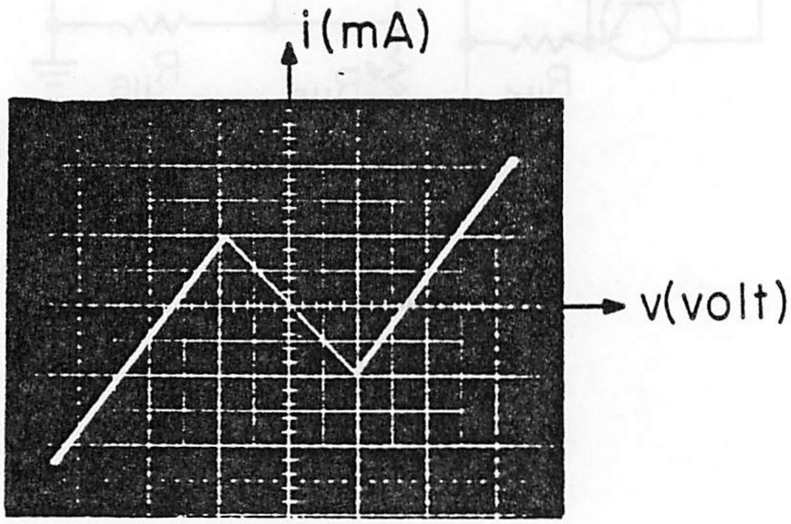


Fig. 9

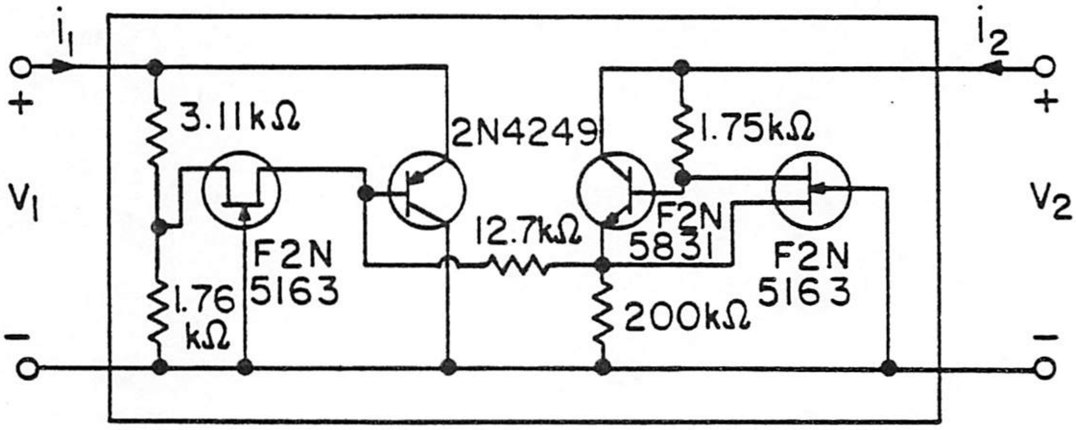


(a)

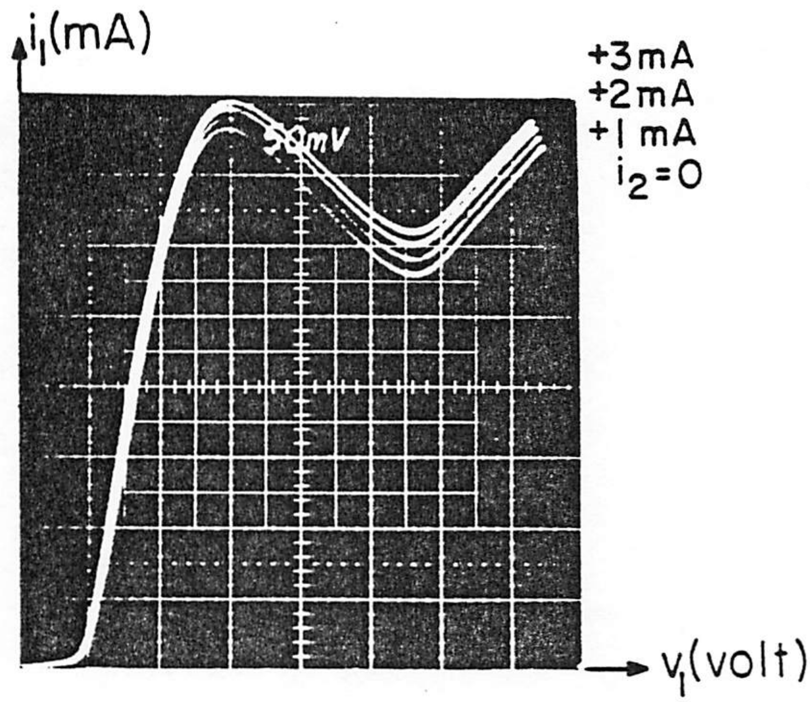


(b)

Fig. 10


i1
i2
+
+
V1
V2
3.11kΩ
2N4249
1.75kΩ
F2N
5831
12.7kΩ
F2N
5163
F2N
5163
1.76
kΩ
200kΩ
−
−

(a)


i1(mA)
50mV
+3mA
+2mA
+1 mA
i2=0
v1(volt)

(b)

Fig. 11