RCA
Solid State
Division

Power Transistors
Application Note
AN-3065

Silicon Transistors for High-Voltage Application

by

D. T. DeFino

This note discusses several new applications for RCA high-voltage silicon transistors (2N3583, 2N3584, 2N3585, 2N3439 and 2N3440). These devices are triple-diffused n-p-n types featuring high frequency response, fast switching speeds, and low cost. Electrical characteristics are listed in Table I.

The advent of these types has made possible many new applications for transistors. Among these applications are circuits in which, until now, the use of transistors was restricted because of high operating voltages (horizontal-deflection circuits, for example). Other applications include those in which the use of a higher supply voltage can enhance circuit design, performance, and economy. High supply voltages reduce the cost of line-operated amplifiers, and improve the efficiency of inverters. Several other important applications are illustrated.

Series Voltage Regulator

A voltage regulator provides a constant output voltage when the input voltage and/or output current is varied over a limited range. As shown in Fig. 1, the pass transistor, acting on a signal from the control circuit, prevents the output voltage V_{out} from varying. The control circuit receives a sample of the output voltage, compares it with a reference voltage, and amplifies the difference. The resulting error signal corrects the collector current I_C of the pass transistor so that the collector-to-emitter voltage V_{CE} is always

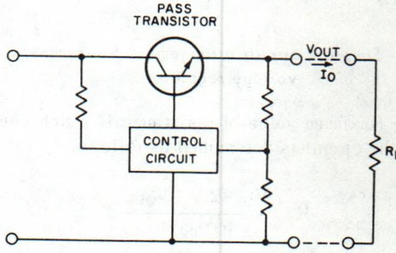


Fig. 1 - Basic form of a transistorized series voltage regulator.

Maximum Ratings, *Absolute-Maximum Values:*

	2N3583	2N3584	2N3585	2N3439	2N3440	
COLLECTOR-TO-BASE VOLTAGE, V_{CBO}	250	375	500	450	300	Volts
COLLECTOR-TO-EMITTER VOLTAGE, $V_{CEO}(sus)$	175	250	300	350	250	Volts
EMITTER-TO-BASE VOLTAGE, V_{EBO}	6	6	6	7	7	Volts
CONTINUOUS COLLECTOR CURRENT, I_C	2	2	2	1	1	Amp
PEAK COLLECTOR CURRENT	5	5	5	-	-	Amp
BASE CURRENT, I_B	1	1	1	0.5	0.5	Amp
TRANSISTOR DISSIPATION, P_T	35	35	35	5	5	Watts

Table I - Electrical characteristics of RCA high-voltage silicon transistors.

the difference between the input voltage V_{in} and the desired output voltage.

The simplest circuit arrangement for a transistor voltage regulator is shown in Fig.2. The circuit consists of a transistor, a resistor, and a zener diode. Because the zener diode maintains the base of the transistor at a constant voltage, changes in output can result only from variations in the base-to-emitter voltage V_{BE} with current and temperature. A zener diode having a high current rating is required if large currents are drawn from the transistor.

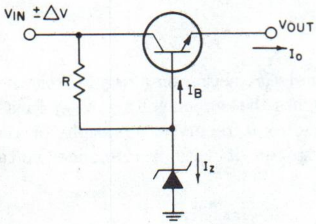


Fig.2 - Simplest circuit arrangement for a transistor voltage regulator.

The maximum value of resistance R which can be used in the circuit is determined as follows:

$$R = \frac{V_{in} - \Delta V - V_{out}}{I_B\,(max)}$$

Because the maximum base current $I_B(max)$ is equal to $I_o(max)/h_{FE}(min)$, where I_o is the output current and h_{FE} is the dc forward-current transfer ratio, the resistance equation can be rewritten as follows:

$$R = \frac{V_{in} - \Delta V - V_{out}}{I_o\,(max)} \times h_{FE}\,(min)$$

The zener diode must be capable of handling a peak current I_Z given by

$$I_Z = \frac{V_{in} + \Delta V - V_{out}}{R} = \frac{[V_{in} + \Delta V - V_{out}]\,[I_o(max)]}{[V_{in} - \Delta V - V_{out}]\,[h_{FE}(min)]}$$

In the series regulator, the pass transistor must remain always in the active region. For this reason, the pass transistor must be chosen carefully to avoid dc forward-bias second breakdown. As shown in Fig.3, under the worst-case condition $I_o(max)$, $V_{in}(min)$, the bias point of the transistor must be within the dc forward-bias second-breakdown rating $P_{s/b}$, or the dc power-dissipation rating P_{dc}, whichever is the limiting factor. From the equations given above, it is obvious that near the operating point h_{FE} should be as high as possible. In general, leakage current and saturation voltage are not important.

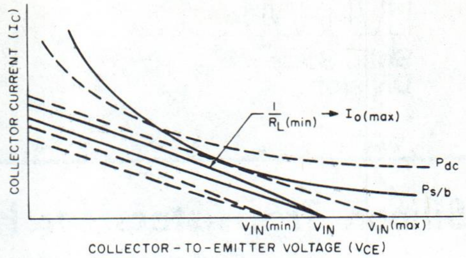


Fig.3 - Transistor load line.

Design Example

The following conditions are specified for a series voltage regulator:

$$V_{out} = 100\text{ V}$$
$$I_o(max) = 400\text{ mA}$$
$$V_{in} = 135 \pm 15\text{ V}$$
$$h_{FE}(min) = 20$$

Circuit values are then determined as follows:

$$R = \frac{(135 - 15 - 100)\,20}{0.4} = \frac{400}{0.4} = 1\text{ k}\Omega \text{ at } 2.5\text{ W}$$

$$I_B(max) = \frac{0.4}{20} = 20\text{ mA}$$

$$I_Z = \frac{135 + 15 - 100}{1000} = \frac{50}{1000} = 50\text{ mA}$$

Therefore, the zener-diode requirements are $V_Z = 100$ V, $I_Z = 50$ mA, $P_Z = 5$ W. Under worst-case conditions, the transistor must be capable of handling 400 milliamperes at 50 volts, or a dissipation of 20 watts. In addition, the point 50 V and 400 mA must be within the dc second-breakdown rating of the transistor. Fig.4 shows the circuit values for this regulator.

The power-dissipation rating of the resistor and zener diode can be reduced by addition of another transistor (usually much smaller in dissipation) in a configuration such as that shown in Fig.5. This arrangement effectively increases the over-all minimum gain. The two transistors can be regarded as one in which the effective h_{FE} (approximately the product of the gain of the two transistors) can be substituted for h_{FE} in the previous equations. Because the 2N3440 has a minimum gain of 40 at 20 mA, the minimum effective gain is $(40)(20) = 800$. From this value, the new resistor and zener diode requirements can be calculated as follows:

$$R = \frac{(135 - 15 - 100)\,800}{0.4} = 40\text{ k}\Omega \text{ at } 0.062\text{ W}$$

$$I_Z = \frac{135 + 15 - 100}{40000} = \frac{50}{40000} = 1.25\text{ mA}$$

$$P_Z = 125\text{ mW}$$

The maximum power dissipated by the 2N3440 transistor in this circuit is (20 mA)(50 V) = 1 W.

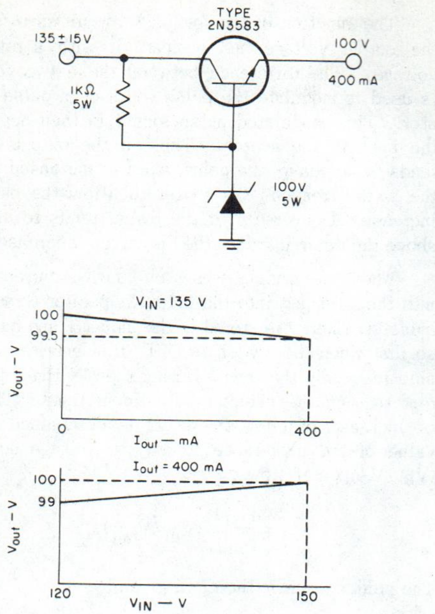


Fig.4 - Schematic diagram of a simple transistor voltage regulator.

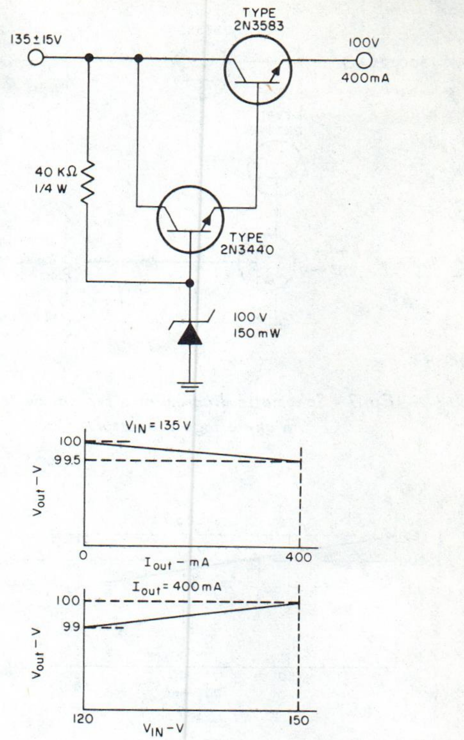


Fig.5 - Schematic diagram of a series voltage regulator using darlington driver.

The disadvantage of the circuit of Fig.5 as compared with that of Fig.4 is that voltage regulation is less sensitive because there are two junctions to create V_{BE} variations with current and voltage changes.

Fig.6 shows a feedback arrangement designed to improve regulation. In this circuit, the output is sampled and compared with a very stable reference voltage. The resulting error signal is used to adjust the bias on the pass transistor. The requirements for Q_3 are determined in the same manner as those for the zener diode in the preceding circuits. The zener-diode current $I_Z(max)$ is equal to the collector current $I_C(max)$ of Q_3 divided by the minimum gain of Q_3 at $I_C(max)$.

In general, the full load voltage need not be fed back. Instead, a voltage divider can be used to reduce the voltage requirement on the zener diode. Although the voltage divider also degrades the performance, this method must be used if a variable output voltage is required. Fig.7 shows a typical high-voltage regulator that provides an output variable from 175 to 225 volts and delivers up to 150 mA. Performance curves for this circuit are shown in Fig.8.

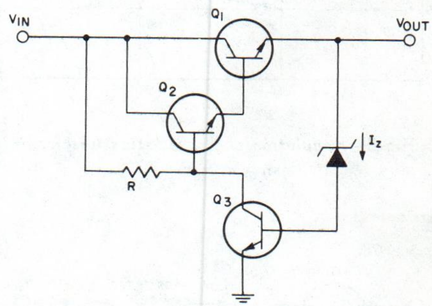


Fig.6 - Schematic diagram of a series voltage regulator employing feedback amplifier.

Switching Regulator

The advantage of a transistorized switching regulator, such as that shown in Fig.9, is its extremely high efficiency. It does not, however, provide the excellent regulation obtainable from a series-type regulator. For this reason, a switching regulator is normally used as a coarse or pre-regulator preceding a series regulator. The switching regulator is highly efficient because the transistor switch is either saturated or cut off. Because both of these conditions are states of low dissipation, very little power is lost in the transistor.

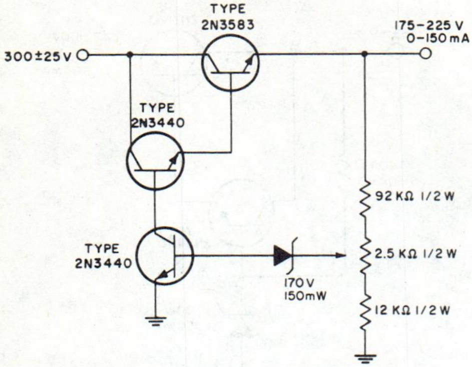


Fig.7 - Schematic diagram of a typical series high-voltage regulator.

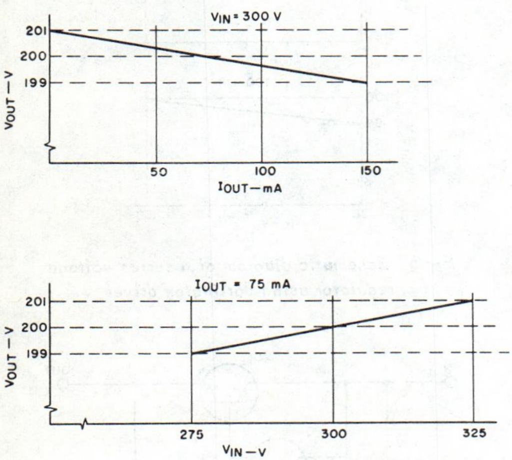


Fig.8 - Regulation characteristics for circuit shown in Fig.7.

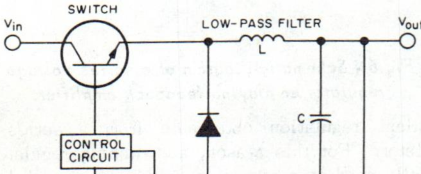


Fig.9 - Simplest form of a transistor switching regulator.

The function of the feedback circuit is to sample the output voltage and compare it with a reference voltage. The difference between these two voltages is used to modulate the pulse width of a pulse generator. This modulated pulse signal is then applied to the base of the switch. Thus, if the output voltage tends to decrease, the pulse width is increased so that the switch remains ON longer to allow the output to increase. Conversely, if the output tends to increase above the desired value, the duty cycle decreases.

When the transistor switch is ON, current flows into the load and into the output capacitor through the inductor. Energy is stored in the inductor and capacitor so that when the switch is OFF, this energy is available to supply the load. During the ON time, the current through the inductor is a linear ramp. The rate of increase of current ($\Delta I/\Delta t$) is determined by the value of the inductance L and the voltage across it ($V_{in} - V_{out}$) as follows:

$$\frac{\Delta I}{\Delta t} = \frac{1}{L}(V_{in} - V_{out})$$

The peak current is therefore given by

$$I_p = \frac{V_{in} - V_{out}}{L}(t_{on})$$

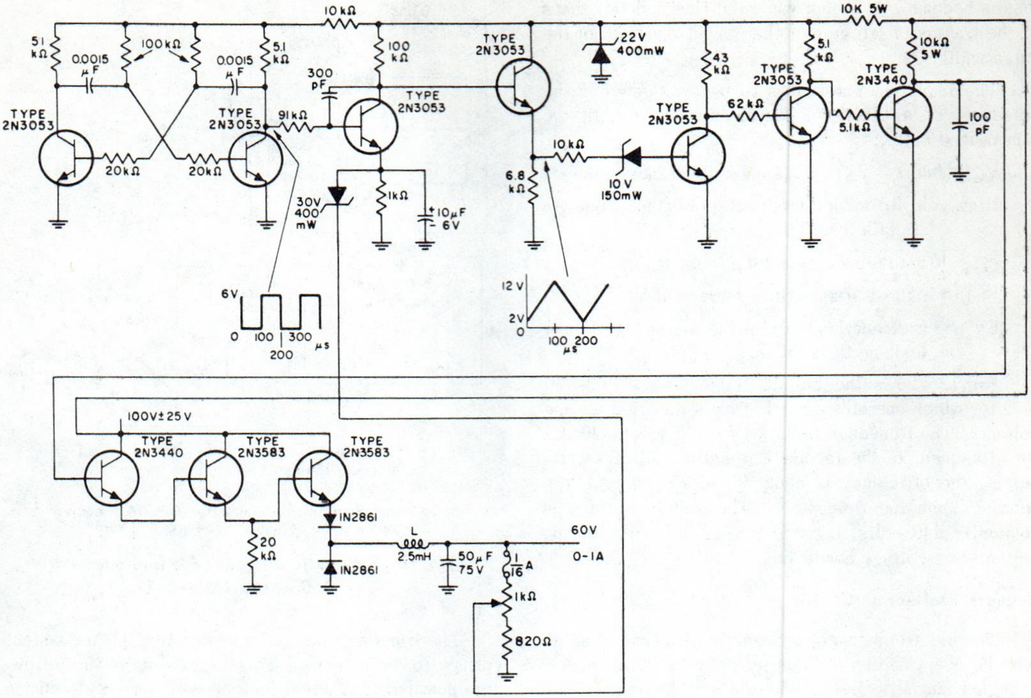
The transistor chosen for this application must provide sufficiently fast switching times, i.e., rise time t_r and fall time t_f. For good regulation over a wide range of input voltage and output current, the duty cycle must be variable from 10 to 90 per cent. Consequently, the minimum pulse width should be one-tenth of the period (1/10f). For low switching losses, the rise and fall times should be about one-fifth of the minimum pulse width, or one-fiftieth of the frequency of the pulse generator (1/50f).

A switching regulator can also be used as a dc step-down transformer. In this application, the regulator provides a very efficient method of obtaining low dc voltage directly from a high-voltage ac line. Fig.10 shows a typical step-down switching regulator which utilizes the dc voltage obtained by rectification of a 117-volt ac line source to provide a regulated 60-volt supply. Performance characteristics for the circuit are shown in Fig.11.

Inverters

An inverter is used to transform dc power to ac power. If the ac output is rectified and filtered to provide dc again, the over-all circuit is referred to as a converter. A converter is normally employed to change the magnitude of an available dc supply.

A transistorized inverter can be made very light in weight and small in size. It is a highly efficient circuit and, unlike its mechanical counterpart, has no



L = 60-turns # 18 wire,
core: Carpenter 49 or equiv., 21 E I 0.014-in. laminations not interleaved. Use 0.015-in. air gap.

All resistors 1/2-watt unless specified otherwise.

Fig.10 - Schematic diagram of a typical step-down switching regulator.

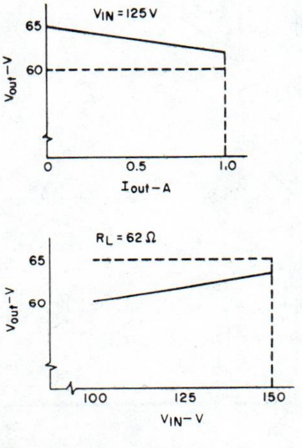


Fig.11 - Performance curves for circuit shown in Fig.10.

moving components. The output from the inverter can be used to drive any equipment which requires an ac supply (motors, ac radios, television receivers, fluorescent lights, and the like). Another very important application of an inverter is in driving the electro-mechanical transducers used in ultrasonic equipment (such as ultrasonic cleaners and sonar detection devices).

The operating frequency of an inverter is usually fixed between 60 Hz and 100 kHz, depending upon the application. For applications in which the operating frequency can be chosen by the designer, the highest possible frequency should be selected.

In general, the size and weight of the inverter can be decreased as the supply voltage and frequency are increased. This relation results mainly from the decreasing size of the transformer needed. The upper frequency and supply voltage are limited by the transistors used. The collector-to-emitter breakdown voltage, for example, must be greater than twice the supply voltage, and the gain-bandwidth product f_T of the device should be greater than ten times the operating frequency. The latter requirement is necessary because switching losses become significant when the rise and fall times of the transistor are greater than about one-fifth of the pulse width.

The important parameters to be considered in the selection of a transistor for an inverter circuit are summarized below:

$V_{CER(sus)} \geq 2V_{CC}$ + leakage reactance spikes

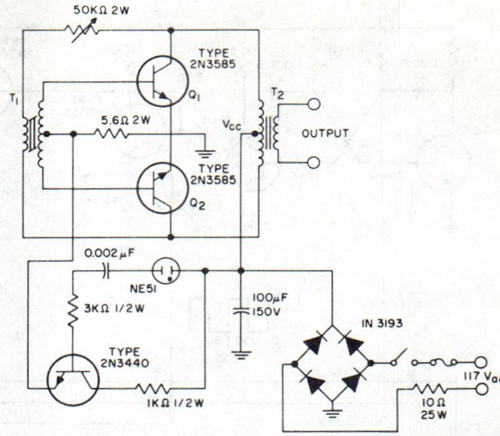
High gain (to reduce feedback power and increase efficiency)

$f_T \geq 10f$ (to reduce switching losses)

$I_{S/b} \geq$ highest starting bias current at V_{CC}

$E_{S/b} \geq$ max. energy stored in the output-transformer leakage inductance.

Fig.12 shows the circuit diagram for a 100-watt inverter which operates directly from a rectified ac-line voltage. The frequency is varied from 25 kHz to 40 kHz by adjustment of the feedback resistor. At 100 watts output, the efficiency is about 90 to 95 per cent, depending upon the frequency. The supply voltage is nominally 140 volts, but can rise to 155 volts during high ac-line-voltage conditions.



T_1 = Allen Bradley RO-3 (E I 102 H 142 A) or equiv. primary: 160-turn #32 wire; secondary: each 3-turns #32 wire.

T_2 = Indiana General C2 material (CF216) or equiv. primary and secondary: 80-turns #28 wire.

Fig.12 - Schematic diagram of a line-operated 100-watt inverter.

Magnetic Deflection Circuit

The electron beam of a magnetically driven display tube is swept across the face of the tube by a linearly changing magnetic field. This deflecting field is produced by a linear ramp of current through the deflection yoke which surrounds the neck of the tube. Fig.13 shows a transistorized magnetic deflection circuit and the corresponding current and voltage waveforms.

The transistor acts as a switch to apply a constant voltage to the inductor. Then, according to the following equation, the current increases linearly to I_p during one-half the sweep time t_s:

$$\frac{\Delta I}{\Delta t} = \frac{V}{L} \qquad \Delta I = \frac{V_{CC}}{L}\Delta t, \; I_p = \frac{V_{CC}}{L}\frac{t_s}{2}$$

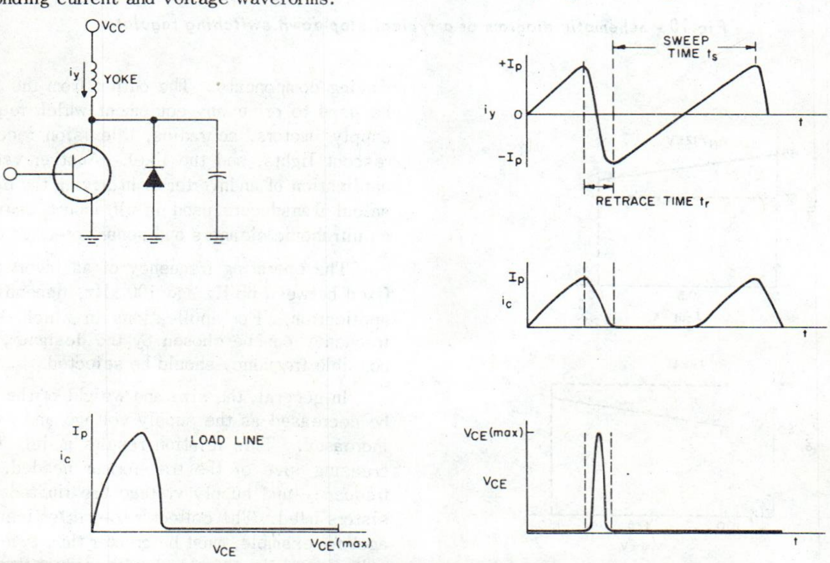


Fig.13 - Basic configuration for a transistor magnetic deflection circuit showing corresponding current and voltage waveforms.

When the transistor is turned off, LC forms a tuned circuit in which the yoke current decreases very rapidly (retrace time t_r) through zero to $-I_p$. At this point capacitor C has a negative voltage across it, the diode is forward-biased, and the yoke current begins to increase toward zero. At this point the cycle begins again.

During the retrace time, when the yoke current is decreasing from I_p to $-I_p$, the voltage across the transistor becomes quite high. The collector-to-emitter voltage is given by

$$V_{CE}(max) = V_{CC} + I_p \omega L$$

The term ω can be expressed as follows:

$$\omega = \frac{1}{\sqrt{LC}} = \frac{\pi}{t_r}$$

Therefore, the equation for $V_{CE}(max)$ may be rewritten as follows:

$$V_{CE}(max) = V_{CC} + \sqrt{\frac{L}{C}}\, I_p.$$

The energy E supplied to the yoke is given by

$$E = ½ L I_p^2$$

In the design of a deflection circuit, this required energy is fixed by the picture tube being used. The sweep time and retrace time are both fixed by the application. There are, therefore, only three parameters which can be varied by the designer: I_p, V_{CC}, and L. From the energy equation, it is evident that the value chosen for L determines I_p, and vice versa. However, the value of I_p is given by

$$I_p = \frac{V_{CC}}{L} \frac{t_s}{2}$$

Therefore, for a given value of I_p it is apparent that V_{CC} also becomes fixed. At this point, the peak voltage swing across the transistor can be calculated from the following equation:

$$V_{CE}(max) = V_{CC} + I_p \frac{\pi}{t_r} L$$

When these values have been determined, the designer must choose a transistor to meet the requirements imposed by the circuit.

The breakdown voltage (BV_{CEO}, BV_{CER}, BV_{CES}, BV_{CEX}, depending upon the drive-circuit impedance between the base to emitter of the output transistor), should be greater than 1.3 $V_{EE}(max)$, as determined above. This safety factor allows for stray inductance and transients.

A sustaining voltage rating is not required because the collector current drops to zero before the voltage swings out (as shown by the waveform in Fig.13) if the transistor turn-off time is less than half the retrace time. However, if the turn-off is greater than one-half the retrace time, a sustaining voltage rating should be used. In addition, the transistor not only must be able to handle the peak collector current, but should also have usable current gain at this level ($I_c = I_p$). At the same time, the $V_{CE}(sat)$ of the transistor at I_p should be as low as possible to minimize the power dissipation. In practice, both of these requirements are guaranteed by a specification such as:

$$V_{CE}(sat) \ (\text{at } I_C = I_p,\ I_B = \frac{I_p}{15}) = 1.5 \text{ V max.}$$

Another important parameter of the output transistor is switching speed. For good linearity, the turn-on time of the transistor should be less than one-tenth of the total on-time of the device (approximately half the sweep time). The turn-off time, meanwhile, should be at least one-quarter of the retrace time to reduce the high-energy dissipation, which could cause reverse-biased second-breakdown problems.

Design Example

The object of this example is to illustrate the design of a magnetic deflection circuit for a specific yoke. The yoke, Celco HD 428-S560 or equivalent, is used to drive a cathode-ray tube for an alpha-numeric display with a 36-degree full-deflection angle and a 12-kilovolt acceleration potential. The yoke inductance is 250 microhenries and the energy required is 225 microjoules. The sweep time is 50 microseconds and the retrace time 10 microseconds.

From this information, the peak collector current I_p of the deflection-circuit transistor is calculated as follows:

$$I_p = \sqrt{\frac{2\,(225)\,10^{-6}}{250 \cdot 10^{-6}}} = 1.35 \text{ A}$$

The supply voltage V_{CC} required is given by

$$V_{CC} = \frac{2\,L\,I_p}{t_s} = \frac{2\,(250 \cdot 10^{-6})\,(1.35)}{50 \cdot 10^{-6}} = 13.5 \text{ V}$$

The tuning-capacitor value C is given by

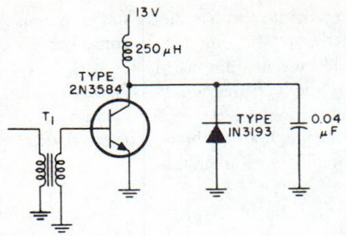
$$C = \left(\frac{t_r}{\pi}\right)^2 \left(\frac{1}{L}\right) = \frac{100 \cdot 10^{-12}}{(\pi)^2\, 250 \cdot 10^{-6}} = .040\ \mu F$$

Finally, the maximum collector voltage V_{CE} is given by

$$V_{CE} = 13.5 + (1.35) \frac{\pi}{(10) \cdot 10^{-6}} 250 \cdot 10^{-6} = 118 \text{ V}$$

The breakdown voltage, therefore, must be greater than (118) (1.3) = 155 V.

The 2N3584 meets all of the requirements for this application. The transistor switching times are short, its gain is 25 minimum at 1 ampere, and its voltage ratings are well above the required minimum. The circuit diagram and waveforms are shown in Figs.14 and 15, respectively.



T1 = C.P. ELECTRONICS X-9370 OR EQUIV.

Fig.14 - Schematic diagram of a typical transistor magnetic deflection circuit.

Line-Operated Audio Amplifier

Fig.16 illustrates how high-voltage silicon transistors can be used to produce a compact, low-cost, high-quality audio-power amplifier. This particular circuit shows a class A, 5-watt, line-operated unit. The line voltage is rectified and filtered directly to provide the required dc supply voltage. This method reduces considerably the size, weight, and cost of the circuit by eliminating the need for a power-supply transformer. Negative feedback from the output transformer produces a linear output and good frequency response. Operation is relatively unaffected by normal line variations between 105 and 135 volts, and by temperatures up to 257° F. Amplifier performance curves are shown in Figs.17, 18, and 19. A summary of the amplifier characteristics is listed below:*

Frequency Response: -3 dB from 35 Hz to 35 kHz

Total Harmonic Distortion:
0.6% at 400 Hz and 4 W output
1.5% at 400 Hz and 5 W output

Hum and Noise: 65 dB below 4 W

Input Impedance: 300 ohms

Input Voltage: 0.6 V for power output of 4 W

The 2N3584 transistor used in the output stage satisfies three very important requirements for the successful operation of this amplifier: (1) a high value of voltage breakdown V_{CER}; (2) good gain linearity; (3) a high gain-bandwidth product.

Because the dc supply voltage conceivably can reach 140 volts, the sustaining-voltage rating V_{CER} for the output transistor, at R_{BE} = 500 ohms, must be greater than 280 volts. Circuits designed to permit the use of a transistor having a lower V_{CER} generally compromise performance and should be avoided. For example, one method of reducing this rating involves decreasing the supply voltage by increasing the size of the current-limiting resistors in the power supply. This procedure, however, not only requires the use of expensive power resistors, but also creates high dissipation losses and reduces the power output of the amplifier.

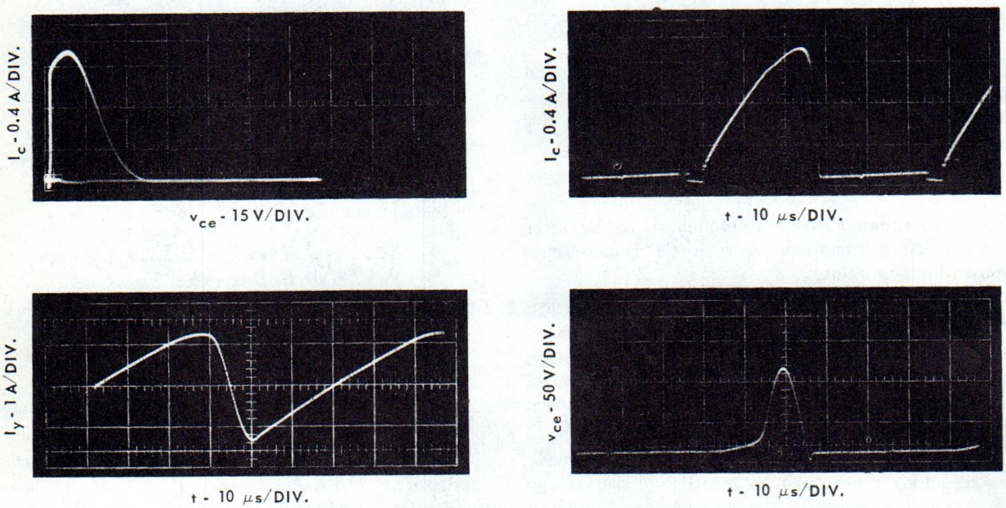


Fig.15 - Current and voltage waveforms produced by circuit shown in Fig.14.

* Additional information concerning this amplifier circuit is given in RCA publication ATC-402.

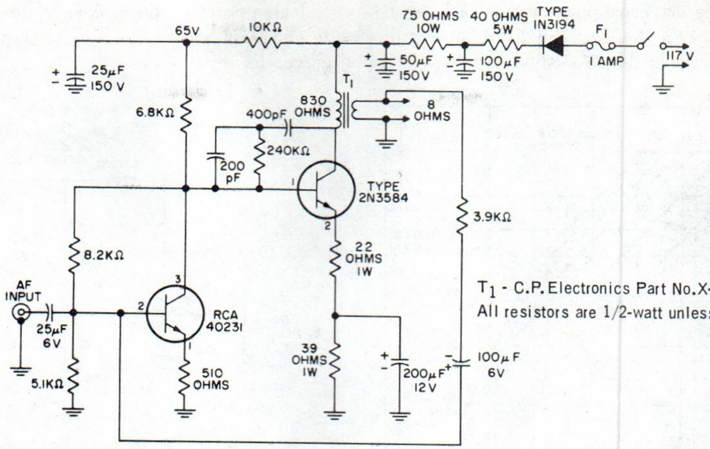


Fig.16 - Schematic diagram of a line-operated, class A, 5-watt audio amplifier.

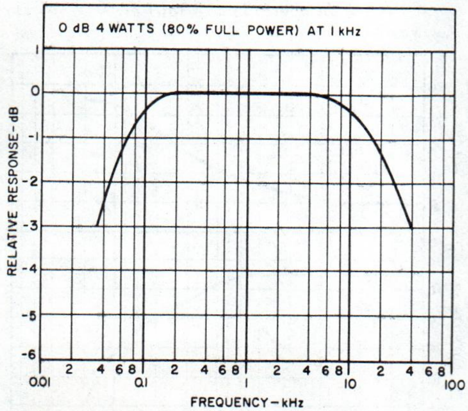


Fig.17 - Response curve for circuit shown in Fig.16.

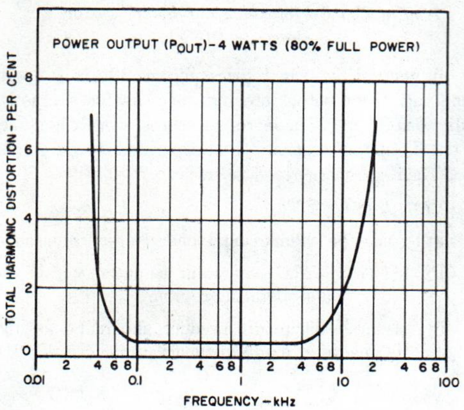


Fig.18 - Total harmonic distortion as a function of frequency for circuit shown in Fig.16.

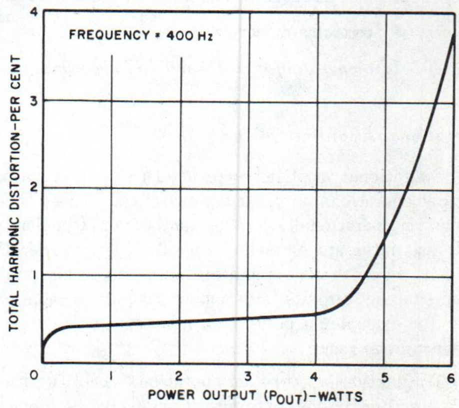


Fig.19 - Harmonic distortion as a function of power output for circuit shown in Fig.16.

Changing the design of the circuit may change the conditions on the required breakdown voltage. For example, if the circuit is altered so that the impedance presented to the base-emitter junction is increased to 1000 ohms and the maximum supply voltage is limited to 130 volts, the designer must choose a transistor that has a V_{CER}(sus) rating (R_{BE} = 1000 ohms) of greater than 260 volts.

The excellent gain linearity of the 2N3584 (±10%) from 10 to 300 milliamperes keeps distortion at a very low level. Moreover, the high gain-bandwidth product (1 MHz) provides wide frequency response, and also permits the use of a large negative feedback without affecting circuit stability.

One final consideration is the safe operating area. Under high line voltages and worst-case temperature conditions, the dc bias point for the output transistor must be within the maximum power rating and second-breakdown rating of the device. Fig.20 illustrates this safe-operating region for the 2N3584.

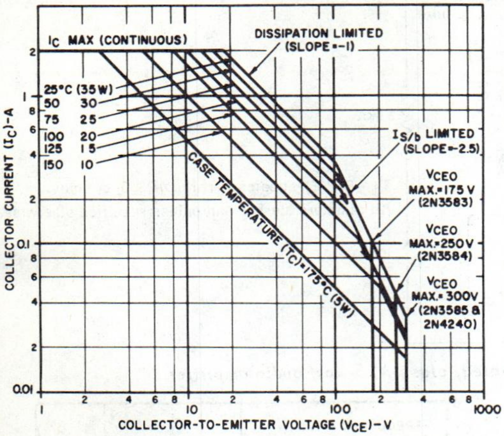


Fig.20 - Safe operating area for the 2N3584 transistor.

Operational Amplifier

Operational amplifiers are used to perform mathematical operations on voltage waveforms. Among other things, an operational amplifier can be used to multiply, add, and integrate electrical signals. It is generally used in one of these capacities in an analog computer. Wave-shaping circuits are another important application; for example, a pulse can be integrated to form a linear voltage ramp.

To function properly, an operational amplifier must have very high open-loop gain. It must also be capable of amplification over a wide passband extending from dc to perhaps 50 kHz. Its phase-shift characteristics must be such that a large negative feedback can be applied without causing oscillations. DC drift must be very low. In addition, the amplifier should have very high input impedance and low output impedance, or vice versa. Generally, the high-input-impedance type is used.

To meet all of these requirements, an operational amplifier normally utilizes a chopper amplifier and other stabilizing circuits. This portion of the amplifier can be designed to operate at low supply voltages. The final stage, however, requires a high supply voltage because it must provide a large voltage swing to drive the high input impedance of the next operational amplifier. A typical final stage that meets this requirement and also provides the necessary low output impedance is shown in Figure 21. Fig.22 shows the performance curves for this circuit.

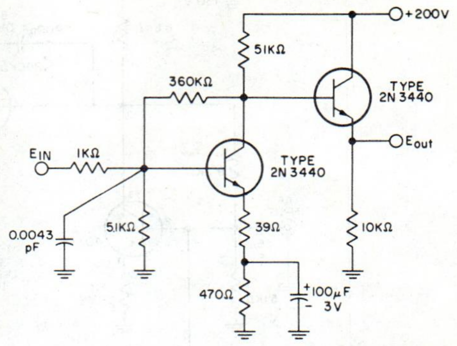


Fig.21 - Schematic diagram of a typical final stage of an operational amplifier.

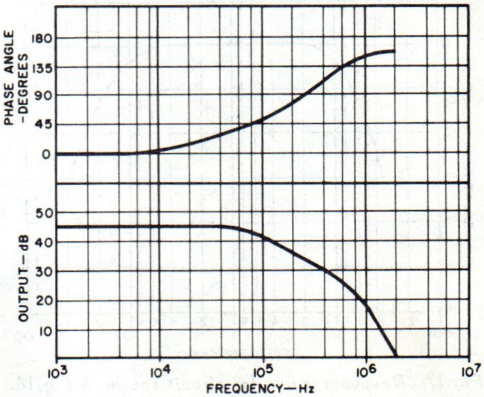


Fig.22 - Performance curves for circuit shown in Fig.21.

In general the transistor requirements for an operational amplifier output are the same as for a class A audio amplifier. These requirements were discussed in detail in the section "Line-Operated Audio Amplifier," and are summarized below:

$V_{CER}(sus) > 2\,V_{CC}$

h_{FE}: must be linear over the operating-current range.

$P_{S/b}/P_D$: the dc bias point must be within the safe operating region.

f_T: the gain-bandwidth product should be as high as possible; a rule-of-thumb minimum is 10 MHz.