RCA
Solid State
Division

Power Transistors
Application Note
AN-4558

A 60-Watt, 20-Volt Regulated Power Supply Using a Single Pass Transistor

by D. Morris and R. H. Smith

This Note discusses a regulated constant-voltage power supply that uses RCA integrated circuits and a rugged RCA hometaxial transistor to attain high output-power capability. A 20-volt, 3-ampere supply that uses a single RCA-2N3055 pass transistor is described in detail; the discussion includes circuit descriptions, operating characteristics, component specifications, and suggestions for layout and construction. Thermal-fatigue effects and safe operating conditions for power transistors are considered. Finally, guidance is provided for those who may want to develop a similar circuit for their own needs.

DESCRIPTION OF CIRCUIT

Specifications for the 60-watt, 20-volt supply are listed in Table I, and a block diagram is shown in Fig. 1. The circuit uses an external pass transistor and driver to extend the current capability of the RCA-CA3055 integrated-circuit voltage regulator; the overload protection provided by a foldback current-limiting circuit permits operation of the transistor at a dissipation level close to its limit. This foldback circuit achieves high efficiency by use of an RCA-CA3030 integrated-circuit operational amplifier.

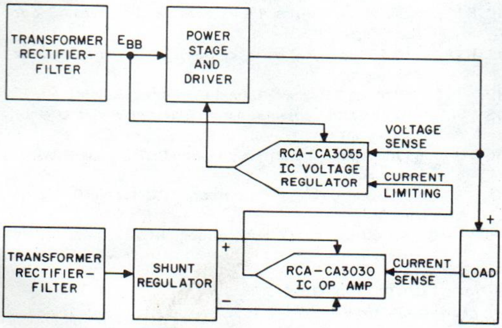
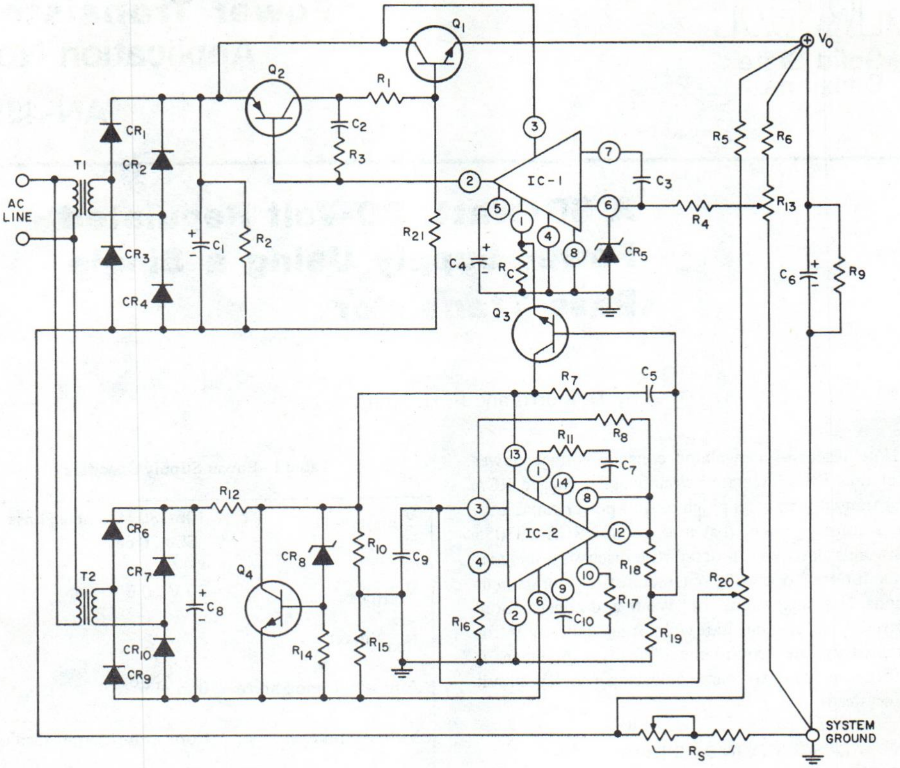


Fig. 1– Block diagram of regulated power supply with foldback current limiting.

Table I - Power-Supply Specifications

V_{input}	105-130 V, Single Phase 55-420 cps
V_{output}	20 V ±0.5 V
I_{load}(max)	3 A
Ambient Temperature	0 to +55°C
Voltage spikes	None at turn on or turn off
Regulation	Line: ±0.25%
	Load: ±0.25%
Ripple	33 mV pp; 9.5 mV rms
Transients:	
No load to full load:	100 mV, recovery within 50 μs
Full load to no load:	100 mV, recovery within 50 μs
Drift	20 mV in 8 hours of operation at constant ambient temperature
Short Circuit and overcurrent protection	Foldback technique

The over-all operation of the circuit can be understood with the aid of the schematic diagram shown in Fig. 2. Transformer T1 and its rectifiers supply the raw dc power that is regulated by pass transistor Q1; this pass transistor is driven by driver Q2, which is driven by the control circuit IC1. Transformer T2, with its rectifiers and shunt regulator Q4, provides positive and negative supplies for operational amplifier IC2; this operational amplifier drives the current-limiting control Q3. Output voltage is sensed at resistance string (R6 + R13), and load current is sensed by R_S.



T1	Signal Transformer Co., Part No. 24-4 or equivalent
T2	Signal Transformer Co., Part No. 12.8-0 25 or equivalent
CR1-CR4	RCA-1N1614
CR5	Zener Diode, 1N5225 (3.3 V)
CR6, CR7, CR9, CR10	Power Rectifier, RCA-1N3193
CR8	Zener Diode, 1N5242 (12 V)
C1	5900 μF, 75 V, Sprague Type 36D592F075BC or equivalent
C2	0.005 μF, ceramic disc, Sprague TGD50 or equivalent
C3, C7, C10	50pF, ceramic disc, Sprague 30GA-Q50 or equivalent
C4	2μF, 25 V, electrolytic, Sprague 500D G025BA7 or equivalent
C5	0.01 μF, ceramic disc, Sprague TG510 or equivalent
C6	500 μF, 50 V, Cornell-Dubilier No. BR500-50 or equivalent
C8	250 μF, 25 V, Cornell-Dubilier BR 250-25 or equivalent
C9	0.47 μF, film type, Sprague Type 220P or equivalent
R1	5 ohms, 1 watt, IRC type BWH or equivalent
R2	1000 ohms, 5 watts, Ohmite type 200-5 1/4 or equivalent
R3	1200 ohms, 1/2 watt, carbon, IRC type RC 1/2 or equivalent
R4	100 ohms, 1/2 watt, carbon, IRC Type RC 1/2 or equivalent
R5	430 ohms, 2 watts, wire wound, IRC Type BWH or equivalent
R6	9100 ohms, 2 watts, wire wound, IRC Type BWH or equivalent
R7	470 ohms, 1/2 watt, carbon, IRC type RC 1/2 or equivalent
R8	5100 ohms, 1/2 watt, carbon, IRC type RC 1/2 or equivalent
R9, R14	1000 ohms, 2 watts, wire wound, IRC type BWH or equivalent
R10, R15	250 ohms, 2 watts, 1% wire wound, IRC type AS-2 or equivalent
R11, R17	1000 ohms, 1/2 watt, carbon, IRC type RC 1/2 or equivalent
R12	82 ohms, 2 watts, IRC type BWH or equivalent
R13	1000 ohms, potentiometer, Clarostat Series U39 or equivalent
R16	1200 ohms, 2 watts, wire wound, IRC type BWH or equivalent
R18	510 ohms, 1/2 watt, carbon, IRC type RC 1/2 or equivalent
R19	10,000 ohms, 1/2 watt, carbon, IRC type RC 1/2 or equivalent

Fig. 2— Schematic diagram of 60-watt, 20-volt regulated power supply with foldback current limiting.

R20	300 ohms, potentiometer, Clarostat Series U39 or equivalent
R21	510 ohms, 3 watts, wire wound, Ohmite type 200-3 or equivalent
R_C	240 ohms, 1%, wire wound, IRC type AS-2 or equivalent
R_S	(See text for fixed portion); 1 ohm, 25 watts, Ohmite type H or equivalent
IC1	RCA-CA3055
IC2	RCA-CA3030
Q1	RCA-2N3055
Q2	RCA-2N5781
Q3, Q4	RCA-40347

Miscellaneous

(1 Req'd)	Heat Sink, Delta Division Wakefield Engineering NC-423 or equivalent
(3 Req'd)	Heat Sink, Thermalloy #2207 PR-10 or equivalent
(1 Req'd)	8-pin socket Cinch #8-ICS or equivalent
(1 Req'd)	14-pin DIL socket, T.I., #IC 014ST-7528 or equivalent
(2 Req'd)	TO-5 socket ELCO #05-3304 or equivalent
	Vector Board #838AWE-1 or equivalent
	Vector Receptacle R644 or equivalent
	Chassis – As required
	Cabinet – As required
	Dow Corning DC340 filled grease

Fig. 2– Schematic diagram of 60-watt, 20-volt regulated power supply with foldback current limiting. (cont.)

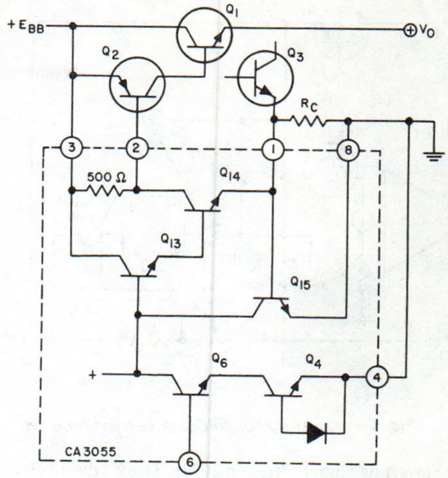


Fig. 3– CA3055 control of the power transistors.

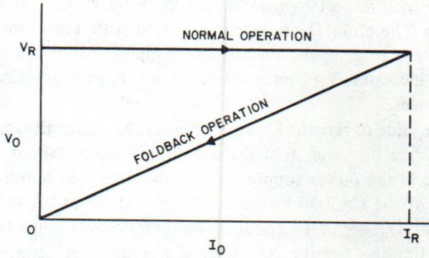


Fig. 4– Foldback current-limiting characteristic.

Voltage Regulation

The power-supply output voltage is sampled by the voltage divider (R6 + R13), and a portion is fed to terminal No. 6 (the inverting input) of the CA3055. (This portion is less than the 3.3-volt breakdown voltage of zener diode CR5; the zener is present only to protect the integrated circuit from accidental overvoltages.) If the output voltage decreases, the base-to-emitter voltage of Q2 increases, as explained in the next paragraph. Therefore the pass transistor Q1 is driven harder, and as a result the output voltage increases to its original value (minus the error dictated by the system gain).

The process by which a voltage decrease at terminal No. 6 of the CA3055 produces an increase of Q2 base-to-emitter voltage can be understood with the aid of Fig. 3, which shows some of the internal circuitry of the CA3055.[1] The drop of voltage at terminal No. 6 causes a higher base-to-emitter voltage at the Darlington combination Q13-Q14. Therefore the collector current of Q14 increases, and thus increases the voltage drop across the 500-ohm resistor, which is the base-to-emitter voltage of Q2.

Foldback Current Limiting

The purpose of the current-limiting circuit is to prevent the power supply from passing a load current that could damage the pass transistor if a very low impedance (or a short circuit) is placed across the output terminals. Fig. 4 shows the effect of this circuit. The supply voltage remains constant until the load current reaches the threshold for activation of the limiting circuit; any further decrease of load impedance causes output voltage V_O and load current I_O to decrease, so that the V_O-I_O characteristic folds back to limit the power dissipation in the pass transistor. Activation of foldback disables the voltage-regulation circuit.

The circuitry for foldback current limiting, shown in Fig. 5, uses the CA3030 integrated circuit as a differential amplifier.[2-5] A signal from the voltage divider RR1 and RR2*, which is across V_O and the E_{BB} return, is applied to

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*RR1 actually consists of R5 and the upper portion of R20 in the schematic diagram of Fig. 2; RR2 is the lower portion of R20.

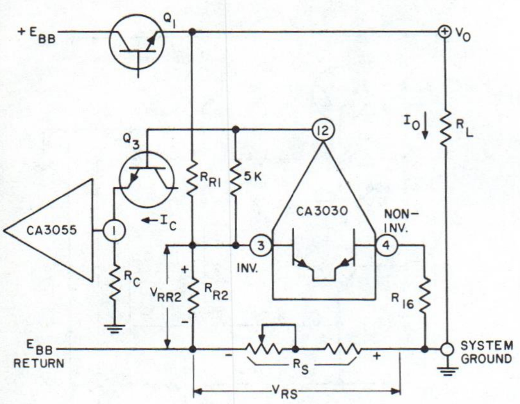

Fig. 5– Circuitry for foldback current limiting.

the inverting input (terminal No. 3) of the differential amplifier. The non-inverting input is tied to system ground through R16. Thus the base-to-base signal that actuates the differential amplifier is the difference between V_{RS} ($=I_OR_S$) and V_{RR2}. The CA3030 output, which is the voltage at terminal No. 12, varies linearly with the actuating voltage, as shown in Fig. 6. When the load current is zero* , V_{RS} is zero; therefore (V_{RS} - V_{RR2}) is negative, terminal 12 is negative with respect to ground, and Q3 is back-biased (i.e., cut off). Therefore Q3 does not interfere with the normal voltage-regulated operation of the supply. As the load current increases, V_{RS} increases and the voltage at terminal 12 increases.

The value of resistor R_S is adjusted so that when the load current reaches the foldback-activation value (about 3 amperes in the power supply shown), the voltage at terminal No. 12 of the CA3030 becomes positive. At about 0.7 volt, transistor Q3 begins to conduct; current flows through the current-limiting resistor R_C, with the result that terminal No. 1 of the CA3055 control circuit is driven positive. Q15 of Fig. 3 turns on, and the base-to-emitter voltage of Q13-Q14 is therefore reduced; the base-to-emitter voltage of Q2 is reduced, and the output voltage of the power supply decreases. This decrease of V_O tends to reduce the load current; however, V_{RR2} also decreases with V_O, so that (V_{RS}-V_{RR2}) remains fixed and Q3 continues to conduct at the same emitter current. If the load impedance is reduced, Q3 will be driven even harder, and therefore the output voltage and the load current will decrease even further. Fig. 4 shows the foldback as R_L decreases.

This process is reversible. If the load impedance R_L is increased, I_O and V_O will increase. When I_O reaches the foldback-activation level, Q3 will cut off again and the power supply will return to regulated operation.

The CA3030 must be operated as a linear voltage amplifier in the foldback circuit, so that the gain is as shown in Fig. 6. If the CA3030 is adjusted otherwise, a Schmitt trigger action can occur. Such operation may be desirable in latching-type current protection, e.g., in circuits that switch off at overload. However, those circuits introduce other problems such as lack of automatic turn-on, hysteresis effects on varying loads during the shutdown process, and capacitive and nonlinear loads; therefore, latching protection is not considered in this Note.

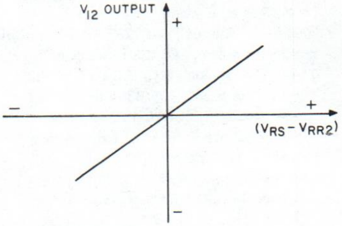

Fig. 6– Output voltage from the CA3030 operational amplifier as a function of actuating voltage.

DESIGN CONSIDERATIONS

For maximum performance from this power-supply circuit, several design features must be analyzed. These features include the equivalent source resistance of the rectifier filter circuit, the foldback-circuit parameters, and the maximum power dissipation in the pass transistor. In addition, safe-operation and thermal-fatigue ratings for the transistors are important.

Equivalent Resistance of the Raw DC Source

A full-wave bridge rectifier[6] provides the raw dc power for this supply; the rectifier and its filter are shown in Fig. 7(a). The output current and power capability would be improved by use of a custom-wound transformer, and even greater capability would be attained by use of a full-wave center-tapped rectifier circuit with a custom transformer. However, a custom transformer would increase the unit cost, particularly if no winding facilities were available; therefore, a commercially available transformer is used in this supply.

The load regulation of the transformer is approximately 10 per cent. This value is used as the approximate R_g/R_L parameter in Schade's curves[7] to select input capacitor C1. The value of C1 that will keep peak-to-peak ripple below 2.4 volts is found to be 5900 microfarads. With this capacitance, the measured value of equivalent source (generator) resistance R_g is 2 ohms. Fig. 7(b) shows the equivalent circuit of the rectifier and filter.

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* The currents in the 1-kilohm bleeder resistor and the 10-kilohm sensing string are neglected in this discussion.

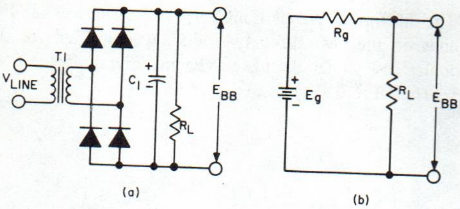

Fig. 7– Full-wave bridge rectifier and filter that provide raw dc for power supply: (a) circuit diagram; (b) equivalent circuit.

At high line voltage (130 volts ac) the cold-temperature, no-load dc voltage of the rectifier filter is 39.4 volts; this value is just below the 40-volt maximum rated voltage of the CA3055. At low line voltage (105 volts ac) the hot full-load dc voltage of the rectifier filter is 25.4 volts; the theoretical minimum necessary voltage for the supply is shown in Appendix A to be 25.4 volts.

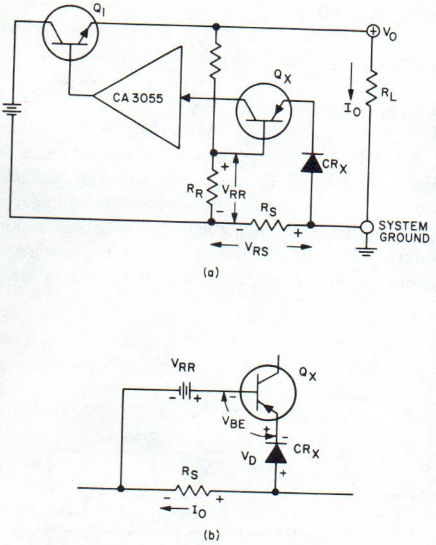

Fig. 8– A simple conventional foldback circuit that uses a single-ended amplifier instead of a differential amplifier: (a) circuit diagram; (b) equivalent circuit.

Foldback-Circuit Parameters

A simple conventional foldback circuit, in which a single-ended amplifier is used instead of the differential amplifier described above, is shown in Fig. 8(a). The equivalent circuit is shown in Fig. 8(b). Analysis of this circuit (see Appendix B) shows that the ratio of maximum load current just before foldback activation, I_X, to the rated load current I_R, is approximately given by

$$\frac{I_X}{I_R} = \frac{V_D + V_{BE} + V_{RR}}{V_D + V_{RR}} \tag{1}$$

in which V_D is the voltage drop across the diode (= 0.7 volt for a silicon diode). I_R is the zero-bias level for Q_X; when I_O exceeds I_R, Q_X becomes forward-biased and causes loss of regulation.

The ratio of the short-circuit current, I_{SC}, to the rated load current is approximately given by

$$\frac{I_{SC}}{I_R} = \frac{V_D + V_{BE}}{V_D + V_{RR}} \tag{2}$$

When the values of the circuit components are inserted into these equations, these ratios have the following values:

$$\frac{I_X}{I_R} = 1.23 \tag{3}$$

$$\frac{I_{SC}}{I_R} = 0.47 \tag{4}$$

Eq. (3) shows that the pass transistor must have a current capability 23 per cent greater than the rated current value of the supply, or, equivalently, that the pass transistor is utilized at only 77 per cent of its current and power-dissipation capabilities at rated supply current. This utilization is reduced even further by the source resistance of the generator, as discussed below.

Another disadvantage of the simple foldback circuit is indicated in Appendix A: the minimum voltage across filter capacitor C1 is increased by at least $(V_D + V_{BE} + V_{RR})$.

The foldback circuit used in the supply shown, which uses a differential amplifier and a low actuating signal, is free of the drawbacks encountered in the simple conventional circuit. Actual values measured on the differential-amplifier foldback circuit, set for a 0.2-volt actuating signal and a rated load current of 3 amperes, are as follows:

$$I_{SC} = 0.125\ \text{A}$$

$$I_X = 3.15\ \text{A}$$

$$\frac{I_X}{I_R} = \frac{3.15}{3} = 1.05$$

$$\frac{I_{SC}}{I_R} = \frac{0.125}{3.00} = 0.042$$

The maximum load current to actuate foldback is 5 per cent greater than the rated current, and the short-circuit current is 4 per cent of the rated current.

Maximum Power Dissipation in the Pass Transistor

Power dissipation in the pass transistor reaches maximum during foldback. This worst-case value can be calculated by the analysis given in Appendix C, which uses the equivalent circuit shown in Fig. 9. (The use of a power-sharing resistor in parallel with the pass transistor is neglected in this discussion because transformer T1 operates at its maximum capacity.) Because the maximum-dissipation situation might occur during operation, the power supply must be designed to withstand this worst-case condition.

Maximum power dissipation occurs when the output voltage is given by

$$V_{OX} = \frac{E_g}{2(1 + \sigma R_g)} \tag{5}$$

where E_g is the generator voltage, σ is the load conductance ($\sigma = I_R/V_R = 1/R_L$, I_R is the rated current, V_R is the rated voltage, and R_g is the generator resistance. The value of the maximum power, P_X, is given by

$$P_X = \frac{\sigma E_g{}^2}{4\,(1 + \sigma R_g)} \tag{6}$$

The rated current is determined as a function of rated voltage, maximum power, generator voltage, and generator resistance, as follows:

$$I_R = V_R\ \frac{4P_X}{E_g2 - 4\,P_X\,R_g} \tag{7}$$

The maximum power limit for the pass transistor, P_X, depends on the heat sink. Appendix D shows that for the particular case under discussion the maximum power is 47 watts. Therefore, I_R is given by

$$I_R = 20\,\frac{4 \times 47}{(40)^2 - 4 \times 47 \times 2} = 3.07\ \text{A}$$

The value of V_{OX} is then determined as follows:

$$V_{OX} = \frac{E_g}{2(1 + I_R/V_R\,R_g)} = \frac{40}{2(1 + \frac{3.07}{20} \times 2)} = 15.4\ \text{V} \tag{8}$$

Idealized curves of various power-supply parameters in regulated operation and in foldback are shown in Fig. 10. Maximum dissipation is 46 watts, at $V_{OX} = 15.4$ volts. This condition can occur if the supply is turned on with a load that causes worst-case foldback operation. As the transformer heats up, the capacitor voltage decreases (i.e., R_g increases), and dissipation is slightly reduced. Even at maximum dissipation in the transistor, however, the power supply can provide continuous trouble-free operation.

Safe Operation of Power Transistors

The current capability of the circuit can be increased almost indefinitely by use of drivers and output transistors with higher current and dissipation capability, by paralleling transistors, or by providing one or more additional stages in a Darlington configuration, along with increased heat sinking, transformer and rectifier capability, and filter capacitance. Information on the proper operation of transistors can be

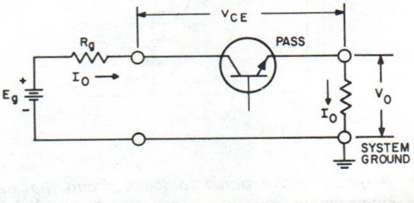

Fig. 9— Equivalent circuit used for calculation of power dissipated in pass transistor.

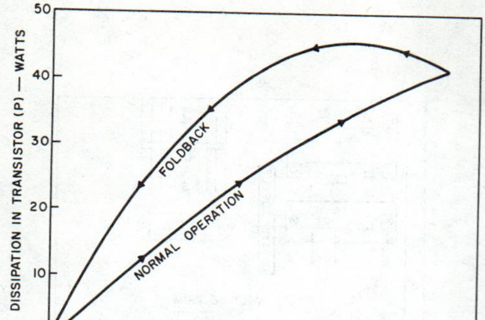

Fig. 10– Idealized operating characteristics of foldback current-limiting circuit.

found in published data sheets.[8,9] Safe-area charts, derating curves, thermal resistance, and maximum junction-temperature specifications are given in the data sheets. Worst-case-operation conditions for the transistors can be determined for a number of possible values of rated voltage and current, and these values can be checked against the specified ratings.

The current capability of linear series regulators is usually limited by the safe dissipation levels of the pass devices, rather than by maximum current ratings or available gain, especially if simple (not foldback) current limiting is used, as for an adjustable voltage supply. Safe operating area encompasses the limitations of power dissipation and second breakdown.[10] RCA hometaxial-base transistors, such as the 2N3055, show little or no second-breakdown limitation in the safe area. Because the published safe area is guaranteed by 100-per-cent factory testing, the user is sure of reliable service even in such severe applications as linear regulators.

Thermal-Fatigue Considerations

A transistor is constructed of materials that have various thermal-expansion coefficients. When the transistor is subjected to a range of internal temperatures in the course of normal operation, the different coefficients of expansion result in stresses on various parts of the internal transistor structure. These stresses are proportional to the change in temperature, the difference in expansion coefficients between two materials in contact, and the pellet size. When the stresses are severe enough and are repeated enough times, they can cause the transistor to fail, usually by rupture of the solder bonds between the pellet and the top contacts or between the pellet and the mounting base. Large power transistors that operate at high power levels, such as the pass devices in linear series regulators (e.g., the RCA-2N3055 family of transistors in the circuit described in this Note), operate in a mode of high thermal-fatigue stress.

RCA has recognized the thermal-fatigue problem and has developed transistors that are extremely resistant to thermal-fatigue failure. This resistance to thermal-fatigue failure is the result of a proprietary Controlled Solder Process (CSP), by which impurities and voids are reduced or eliminated from the solder system. Impurities enhance the propagation of cracks induced by thermal-fatigue stresses, and thus contribute to early failure of the solder bonds. Voids under the pellet act as insulation, and can lead to hot spots that cause high thermal-fatigue stresses. CSP is now employed on all RCA hermetic power transistors.

RCA has developed power-transistor thermal-cycling ratings that indicate expected life, in number of thermal cycles, as a function of power dissipation and case-temperature change. These ratings are calculated from theoretical models based on actual measurements.[11,12] This rating system shows that the RCA-2N3055 pass transistor, used as described in this Note (maximum power dissipation of 46 watts, case-temperature change of 43°C), can survive more than 50,000 thermal cycles without failure. The RCA-2N5781 and the smaller devices in the circuit should last even longer.

The combination of homotaxial construction for ruggedness and CSP for long thermal-fatigue life makes these power transistors the best choice for power-supply applications.

OPERATIONAL PERFORMANCE

Adjustment of Current-Sensing Resistor R_S

The fixed portion of current-sensing resistor R_S is simply a short length of resistance wire; its resistance is about 0.064 ohm. This resistor must be adjusted on each power supply, because both the over-all loop system gain and the current-limiting voltage across terminals 1 and 8 of the CA3055 can vary from unit to unit. The two-step procedure for adjusting the fixed portion of the R_S is as follows:

(a) Set the reference voltage by adjusting the 250-ohm potentiometer (R20) until the voltage from the arm of the potentiometer to ground is 200 millivolts (with the load current zero, and total sensing resistor $R_S = 0$).

(b) Use a variable resistor across the output terminals to set the load current at 3.15 amperes. Then insert the fixed portion of the sensing resistance and increase it until current foldback is just initiated. Initiation of foldback is evidenced by sudden reduction in output voltage.

This fixed resistor should be made of resistance wire such as Driver Harris Manganin #18 (0.176 ohms per foot) or equivalent. Copper wire can be used provided I^2R heating does not change its resistance, and effects of ambient-temperature change are taken into consideration. (The temperature coefficient of copper wire is 3.9 x 10^{-3} per °C. If the copper resistor were adjusted at 20°C, and the ambient temperature then changed to 55°C, the current required to activate foldback would be reduced from 3.15 amperes to 2.7 amperes).

The variable portion of current-sensing resistor R_S is a 1-ohm potentiometer. It is used to set the current-limitation threshold at levels below 3 amperes, if such operation is desired.

Adjustment of Current-Limiting Resistor R_C

The CA3055 voltage regulator would function most effectively if current-limiting resistor R_C were zero, but R_C is necessary for foldback operation. Therefore, as a compromise between regulation and protection sensitivity, R_C is adjusted to provide an over-all regulation of ± 0.25 per cent for all load currents from 0 to 3 amperes. This value of R_C results in a reasonable short-circuit current (0.125 amperes). If R_C is made smaller (to permit better regulation), the ratio R8/R16 must be increased to provide more gain in the current-limiting circuit. This change may require restabilization of the circuit.

Power-Supply Performance

With the circuit adjusted as described above, the power supply performs as shown in Table II.

CONSTRUCTION

Fig. 11 shows the assembled power supply; it is 8 inches long, 8 inches wide, and 5 3/4 inches high (these dimensions can be reduced if necessary). The chassis is made of 0.052-inch aluminum, perforated on top and sides for ventilation; a commercial chassis such as the BUD CA1751 or equivalent could also be used.

The control circuit is built on a pre-punched fiber board. Good wiring techniques are observed, all leads to the integrated circuits are kept as short as possible, and heat sinks are attached where required.

The positive and negative supplies for the operational amplifier are also constructed on pre-punched fiber board. The board is attached with an L-bracket to the diode support, as shown in the diagram.

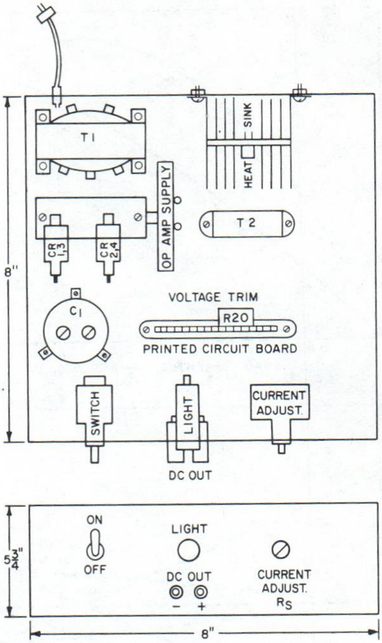

Fig. 11– Layout of power supply.

The pass-transistor heat sink is mounted vertically, with 1/4-inch clearance from the bottom of the chassis to provide adequate convection. The circuit board is mounted as far as possible from the pass-transistor heat sink to achieve maximum thermal isolation.

Construction of this supply is flexible. Wiring is not critical, but heavy wire should be used for the leads that carry high current. The total allowable IR drop in the wiring is 0.1 volt; at a current of 3 amperes, therefore, the total allowable resistance (including contact resistance) is 33 milliohms.

As in all error-detecting systems, the sampling should be accomplished at the terminals of the power supply, i.e., at the +20-volt and ground terminals. Therefore all of the system ground points indicated in Fig. 2 are connected with heavy wire to avoid ground loops. Output capacitor C6 is wired directly to the output terminals.

APPENDIX A. Minimum Voltage Across Filter Capacitor

The minimum voltage across filter capacitor C1 is obtained as follows:

$$V_{\text{Cap (min)}} = V_O + V_{O\text{-PK}} + V_{BE\ 2N3055} + V_{CE\ 2N5781} + V_{R1} + V_{TOL} + V_{RS} + V_{LD}$$

Table II - Performance of Regulated Power Supply

<table>
<tr><td colspan="4">Normal Operation: V_O set at 20.000 VDC with $I_O = 3$ A @ $V_{line} = 115$ VAC.</td></tr>
<tr><th>PARAMETER</th><th>CONDITIONS</th><th colspan="2">VALUE</th></tr>
<tr><td>Load regulation</td><td>$I_O = O \rightleftarrows 3A$, $V_{Line} = 105$ VAC</td><td colspan="2">±0.25%</td></tr>
<tr><td>Load regulation</td><td>$I_O = O \rightleftarrows 3A$, $V_{Line} = 115$ VAC</td><td colspan="2">±0.25%</td></tr>
<tr><td>Load regulation</td><td>$I_O = O \rightleftarrows 3A$, $V_{Line} = 130$ VAC</td><td colspan="2">±0.25%</td></tr>
<tr><td>Line regulation</td><td>$I_O = O$, $V_{Line} = 105 \rightleftarrows 130$ VAC</td><td colspan="2">±0.25%</td></tr>
<tr><td>Line regulation</td><td>$I_O = 3A$, $V_{Line} = 105 \rightleftarrows 130$ VAC</td><td colspan="2">±0.25%</td></tr>
<tr><td>Total regulation spread</td><td>$O \leqslant I_O \leqslant 3A$, $105 \leqslant V_{Line} \leqslant 130$ VAC</td><td colspan="2">0.77%</td></tr>
<tr><td>Ripple (peak-to-peak)</td><td>$I_O = 3$ A</td><td colspan="2">33 mV</td></tr>
<tr><td>Ripple (rms)</td><td>$I_O = 3$ A</td><td colspan="2">9.5 mV</td></tr>
<tr><td>Transients</td><td>Full load (3 A) to no load (O A)</td><td colspan="2">$\leqslant 100$ mV, $t_{recovery} \leqslant 50\ \mu s$</td></tr>
<tr><td>Transients</td><td>No load (O A) to full load (3 A)</td><td colspan="2">$\leqslant 100$ mV, $t_{recovery} \leqslant 50\ \mu s$</td></tr>
<tr><td>Transients</td><td>Turn on (105 or 130 VAC)</td><td colspan="2">0</td></tr>
<tr><td>Transients</td><td>Turn off (105 or 130 VAC)</td><td colspan="2">0</td></tr>
<tr><td>Drift</td><td>$I_O = 3$ A</td><td colspan="2">$\leqslant 15$ mV/8 hours</td></tr>
<tr><td>Case Temperature Rise:</td><td>After 8 hours @ $I_O = 3$ A and $V_{Line} = 130$ VAC</td><td colspan="2"></td></tr>
<tr><td>2N3055</td><td></td><td colspan="2">43°C</td></tr>
<tr><td>2N5781</td><td></td><td colspan="2">49°C</td></tr>
<tr><td>CA3055</td><td></td><td colspan="2">15°C</td></tr>
<tr><td>I_{SC}</td><td>$V_{Line} = 105$ or 130 VAC</td><td colspan="2">0.125 A</td></tr>
<tr><td colspan="4">Abnormal Operation: Circuit in fold back operation at worst-case condition ($V_O = 15.4$ VDC)</td></tr>
<tr><th>PARAMETER</th><th>CONDITIONS</th><th colspan="2">VALUE</th></tr>
<tr><td>Case Temperature Rise:</td><td>After 8 hours in foldback @ $V_{Line} = 130$ VAC</td><td>Measured</td><td>Calculated</td></tr>
<tr><td>2N3055</td><td></td><td>50°C</td><td>60°C</td></tr>
<tr><td>2N5781</td><td></td><td>63°C</td><td>85°C</td></tr>
<tr><td>CA3055</td><td></td><td>17°C</td><td>–</td></tr>
</table>

where

V_O = output voltage = 20 V
$V_{0\text{-}PK}$ = ripple voltage (zero to peak = 1/2 peak to peak) = 1.2 V
V_{BE} 2N3055 = worst case V_{BE} of pass transistor = 1.4 V
V_{CE} 2N5781 = worst case V_{CE} of driver transistor = 1 V
V_{R1} = Voltage across collector resistor R1 = 1 V
V_{TOL} = 0.5-volt tolerance on output = 0.5 V
V_{RS} = voltage of current-sensing resistor = 0.2 V
V_{LD} = voltage drop in wiring = 0.1 V

Therefore

$$V_{Cap}\,(\text{min}) = 20 + 1.2 + 1.4 + 1 + 1 + 0.5 + 0.2 + 0.1 = 25.4 \text{ volts}$$

APPENDIX B. Foldback Parameters

As a first approximation, the following equations describe the three conditions of load current in the circuit of Fig. 8(b):

General equation: $I_O R_S = V_D + V_{BE} + V_{RR}$

At rated current I_R, it is desirable that $V_{BE} = 0$.

$$\therefore I_R R_S = V_D + V_{RR}$$

At maximum load current, just before foldback is initiated,

$$I_X R_S = V_D + V_{BE} + V_{RR}$$

At short-circuit current, $V_O = 0$, and therefore $V_{RR} = 0$.

$$I_{SC} R_S = V_D + V_{BE}$$

By dividing appropriate equations,

$$\frac{I_X}{I_R} = \frac{V_D + V_{BE} + V_R}{V_D + V_R}$$

and

$$\frac{I_R}{I_{SC}} = \frac{V_D + V_R}{V_D + V_{BE}}$$

To make the maximum current close to rated current,

$$V_D + V_{BE} + V_R \approx V_D + V_R$$

$$\therefore (V_D + V_R) \gg V_{BE}$$

However, if V_D is large, the initiating voltage must also be large. Therefore, the minimum voltage across C1 must also be increased.

If V_D is one diode drop (0.7 volt) and if $(V_D + V_R)$ is 3 volts as a compromise, then V_R = 2.3 volts, and

$$\frac{I_X}{I_R} = \frac{0.7 + 2.3 + 0.7}{0.7 + 2.3} = 1.23$$

and

$$\frac{I_R}{I_{SC}} = \frac{0.7 + 2.3}{0.7 + 0.7} = 2.14$$

$$\therefore I_{SC} = \frac{I_R}{2.14} = 0.468\, I_R$$

APPENDIX C. Maximum Power Dissipation in the Pass Transistor

The equivalent circuit used to calculate the power dissipation in the pass transistor is shown in Fig. 9. R_g includes the 64-milliohm resistance used for sensing the 3.15-ampere actuating current. The additional current supplied for I_{CO} of Q1 and the current supplied to the CA3055 regulator are neglected.

The voltage across the transistor is given by

$$V_{CE} = E_g - V_O - I_O R_g = E_g - (V_O + I_O R_g)$$

The power dissipated in the transistor is given by

$$P = [E_g - (V_O + I_O R_g)]\; I_O$$

The ideal foldback characteristic is shown in Figs. 4 and 10. The measured values are within 5 per cent of the ideal values. Therefore a small error is introduced if the ideal characteristic is used for the analysis.

Equations that describe operation during foldback are derived as follows:

$$y = mx + b = mx + 0$$

$$m = \frac{V_R}{I_R}$$

$$V_O = \frac{V_R}{I_R}\, I_O$$

$$I_O = V_O \frac{I_R}{V_R} = V_O \sigma$$

$$P = E_g I_O - V_O I_O - I_O^2 R_g$$

$$= E_g V_O \sigma - V_O^2 \sigma - V_O^2 \sigma^2 R_g$$

$$P + V_O^2 [\sigma + \sigma^2 R_g] - V_O [\sigma E_g] = 0$$

or

$$P + V_O^2 A - V_O B = 0$$

$$P = BV_O - AV_O^2$$

$$\frac{dP}{dV_O} = B - 2AV_O$$

For maximum power, $\frac{dP}{dV_O} = 0$; therefore,

$$B - 2AV_O = 0$$

$$2AV_O = B$$

$$V_O = \frac{B}{2A} = \frac{1}{2} \left[\frac{\sigma E_g}{\sigma + \sigma^2 R_g} \right] = \frac{1}{2} \left[\frac{E_g}{1 + \sigma R_g} \right]$$

Thus maximum power occurs when

$$V_O = \frac{E_g}{2(1 + \sigma R_g)}$$

Substitution of this solution into the power equation yields

$$P = BV_O - AV_O^2$$

$$= \sigma E_g V_O - (\sigma + \sigma^2 R_g) V_O^2$$

$$= \sigma E_g \left[\frac{\frac{E_g}{2}}{1 + \sigma R_g} \right] - (\sigma + \sigma^2 R_g) \left[\frac{\left(\frac{E_g}{2}\right)^2}{(1 + \sigma R_g)^2} \right]$$

However,

$$\sigma + \sigma^2 R_g = \sigma (1 + \sigma R_g)$$

$$\therefore P = \frac{\sigma \frac{E_g^2}{2}}{1 + \sigma R_g} . \frac{\sigma (1 + \sigma R_g) \left(\frac{E_g}{2}\right)^2}{(1 + \sigma R_g)^2}$$

$$P = \frac{\sigma \frac{E_g^2}{2}}{1 + \sigma R_g} - \frac{\sigma \frac{E_g^2}{4}}{1 + \sigma R_g} = \frac{\sigma \frac{E_g^2}{4}}{1 + \sigma R_g}$$

$$\frac{4P}{E_g^2} = \frac{\sigma}{1 + \sigma R_g}$$

Let

$$\frac{4P}{E_g^2} = G$$

Solving for σ,

$$\sigma = G(1 + \sigma R_g)$$

$$\sigma = G + \sigma G R_g$$

$$\sigma (1 - GR_g) = G$$

$$\sigma = \frac{G}{1 - GR_g}$$

Because $\sigma = \frac{I_R}{V_R}$

then

$$I_R = V_R \left[\frac{G}{1 - GR_g} \right] = \frac{V_R 4P}{E_g^2 - 4PR_g}$$

APPENDIX D. Maximum Power Dissipation Allowable for a Given Thermal Resistance

The heat sink selected is a Wakefield (Delta Division #NC-423) type. This heat sink has a thermal resistance to air in convection cooling of 0.8°C/watt. Any heat sink with similar or lower thermal resistance is suitable.

The case-to-junction thermal resistance of the 2N3055 is rated at 1.5°C/watt, and the heat-sink-to-case thermal resistance is 0.5°C/watt maximum if a mica washer and DC340 filled grease or equivalent are used.

The total junction-to-air thermal resistance is:

Ambient to Heat Sink	0.8°C/watt
Heat Sink to Case	0.5
Case to Junction	1.5
TOTAL	2.8°C/watt

If it is assumed that the ambient temperature is 55°C and the junction temperature is 200°C,

200°C - 55°C = 145°C
145°C/2.8°C/W = 52 watts

If a 10-per-cent safety factor is allowed, the maximum allowable power dissipation by the pass transistor is 52 - 5 = 47 watts.

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