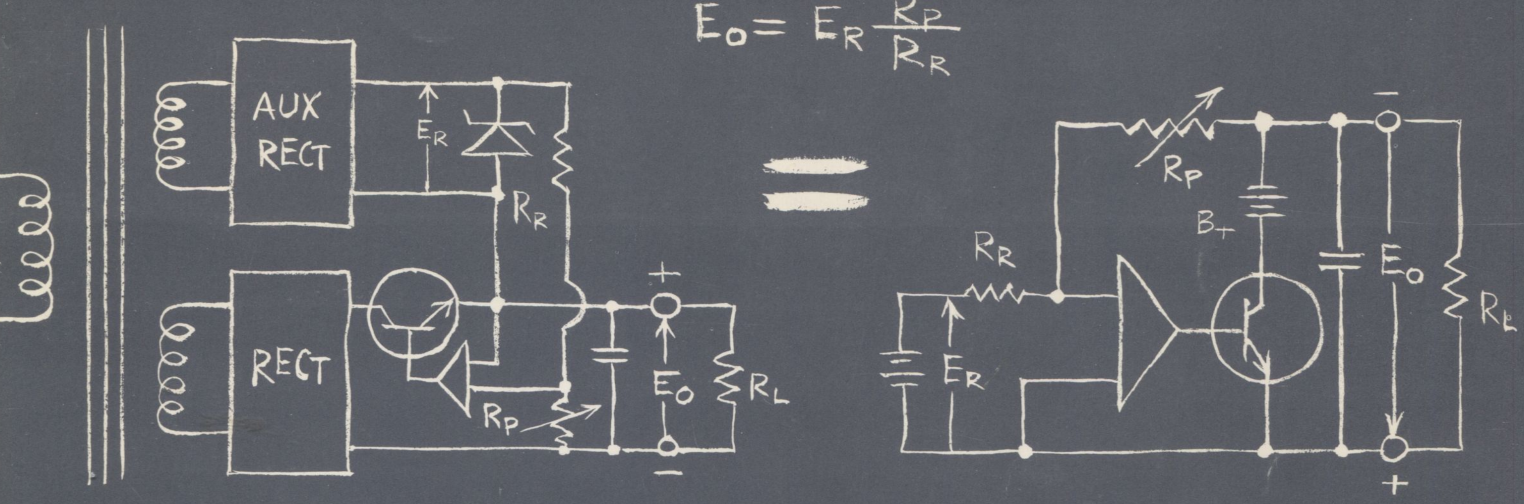


CONSTANT VOLTAGE
DC POWER SUPPLY

EQUIVALENT CIRCUIT-
AUGMENTED OP-AMP

DC POWER SUPPLY HANDBOOK

HEWLETT
PACKARD
HARRISON
DIVISION

APPLICATION NOTE 90 • 1967

TABLE OF CONTENTS

A. CIRCUIT PRINCIPLES

B. OPERATING FEATURES

C. PERFORMANCE MEASUREMENTS

D. SPECIAL APPLICATIONS

Some of the circuit principles discussed in this application manual are the subject of patents applied for, pending or granted. Patent numbers available upon request.

Printed in U.S.A.

INTRODUCTION

Since its inception the Harrison Division of Hewlett-Packard has been a leader in the design of versatile, high performance, regulated DC power supplies so necessary for the proper performance of most of today's complex load devices. A single hp DC regulated power supply employs engineering techniques drawn from the latest advances in many disciplines—low-level low-noise amplification, high-power wide-band amplifying techniques, operational amplifier and feedback principles, pulse circuit techniques, and the newest developments in semiconductor devices.

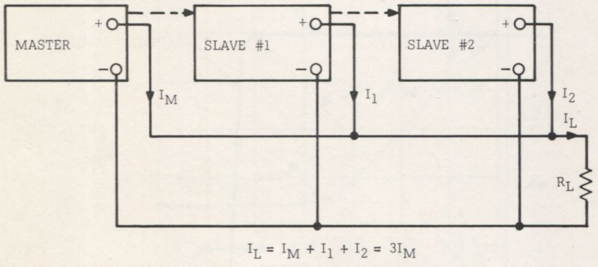
The full benefits of the engineering which has gone into a modern DC regulated power supply cannot be realized unless the user (1) recognizes the inherent versatility and high performance capabilities, and (2) understands how to apply these features. These are the two objectives of this Handbook, which includes an extensive coverage of power supply circuitry, features, specifications, measurement methods, and application tips.

DEFINITIONS

AMBIENT TEMPERATURE. The room temperature, or effective temperature of the environment in which the power supply is operating. See paragraph D7.

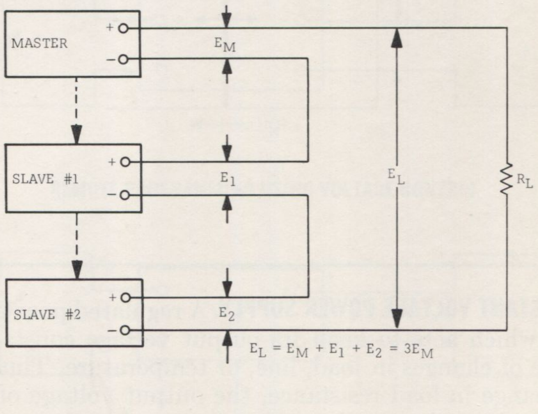
AUTO-PARALLEL or automatic parallel operation. A master-slave parallel connection of the outputs of two or more hp supplies used for obtaining a current output greater than that obtainable from one supply. Auto-Parallel operation is characterized by one-knob control, equal current sharing, and no internal wiring changes. Normally only supplies having the same model number may be connected in Auto-Parallel; in certain cases, however, supplies of the same Series are capable of mixed Auto-Parallel operation. See paragraph B7.

AUTO-PARALLEL POWER SUPPLY SYSTEM

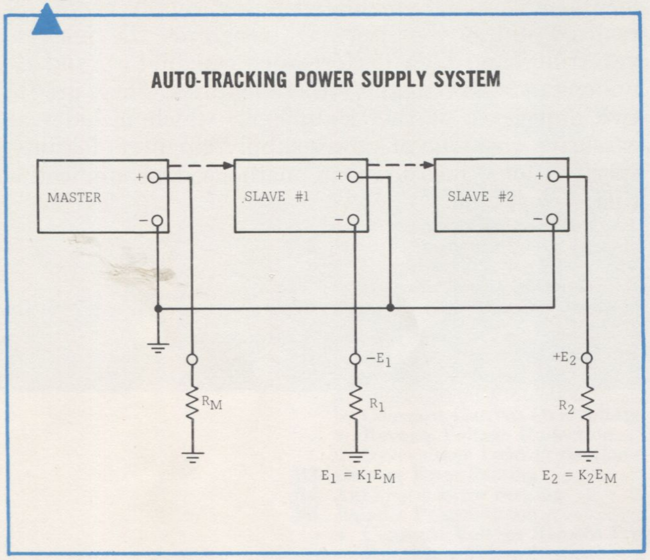


AUTO-SERIES or automatic series operation. A master-slave series connection of the outputs of two or more hp power supplies used for obtaining a voltage greater than that obtainable from one supply. Auto-Series operation, which is permissible up to 300 volts off ground, is characterized by one-knob control, equal or proportional voltage sharing, and no internal wiring changes. Supplies of mixed model numbers may be connected in Auto-Series without restriction, provided that each slave is listed as being capable of Auto-Series operation. See paragraph B9.

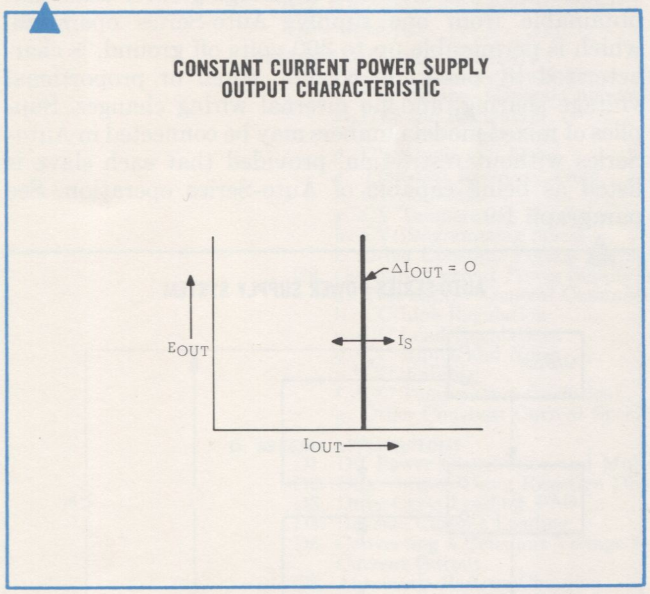
AUTO-SERIES POWER SUPPLY SYSTEM



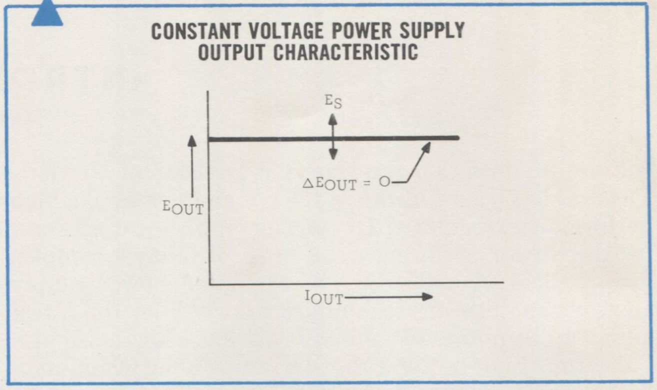
AUTO-TRACKING or automatic tracking operation. A master-slave connection of two or more hp power supplies each of which has **one** of its output terminals in common with **one** of the output terminals of **all** of the other power supplies, such a connection pattern being characterized by one-knob control, proportional output voltage from all supplies, and no internal wiring changes. Useful where simultaneous turn-up, turn-down or proportional control of all power supplies in a system is required. See paragraph B10.


AUTO-TRACKING POWER SUPPLY SYSTEM

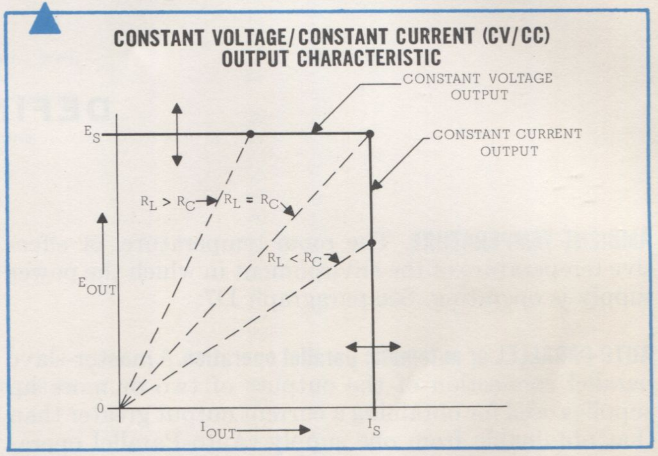
CONSTANT CURRENT POWER SUPPLY. A regulated power supply which acts to keep its output current constant in spite of changes in load, line, or temperature. Thus, for a change in load resistance, the output current remains constant to a first approximation, while the output voltage changes by whatever amount necessary to accomplish this. See paragraphs A7 and D5.


CONSTANT CURRENT POWER SUPPLY
OUTPUT CHARACTERISTIC

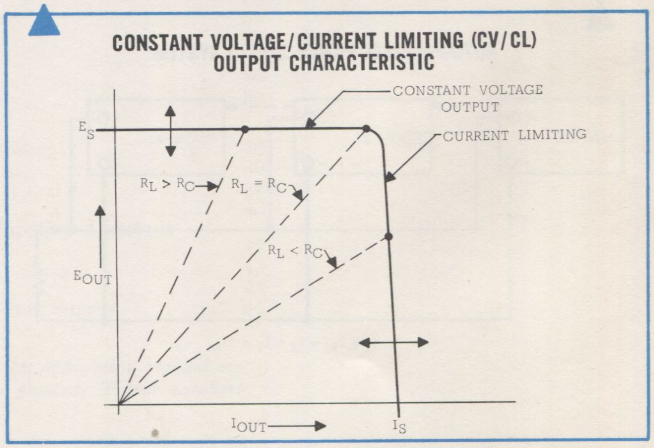
CONSTANT VOLTAGE POWER SUPPLY. A regulated power supply which acts to keep its output voltage constant in spite of changes in load, line, or temperature. Thus, for a change in load resistance, the output voltage of this type of supply remains constant to a first approximation, while the output current changes by whatever amount necessary to accomplish this. See paragraph A2.


CONSTANT VOLTAGE POWER SUPPLY
OUTPUT CHARACTERISTIC

CONSTANT VOLTAGE/CONSTANT CURRENT (CV/CC) with automatic crossover. A power supply which acts as a constant voltage source for comparatively large values of load resistance and as a constant current source for comparatively small values of load resistance. The automatic crossover or transition between these two modes of operation occurs at a "critical" or "crossover" value of load resistance $R_C = E_S/I_S$, where E_S is the front panel voltage control setting and I_S is the front panel current control setting. See paragraph A8.


CONSTANT VOLTAGE/CONSTANT CURRENT (CV/CC)
OUTPUT CHARACTERISTIC

CONSTANT VOLTAGE/CURRENT LIMITING (CV/CL) with automatic crossover. The same as CV/CC operation except for a slightly poorer regulation characteristic for low values of load resistance, i.e., in the "constant current" region of operation. See paragraph A9.


CONSTANT VOLTAGE/CURRENT LIMITING (CV/CL)
OUTPUT CHARACTERISTIC

"CROWBAR" VOLTAGE PROTECTOR. A separate circuit which monitors the output of a power supply and instantaneously throws a short circuit (or "crowbar") across the output terminals of the power supply whenever a preset voltage limit is exceeded. An SCR is usually used as the "crowbar" device.

DRIFT. A term loosely used to describe the slow variations in the output of a regulated power supply due to STABILITY and/or TEMPERATURE COEFFICIENT.

LINE REGULATION of a constant current power supply. The change in the static value of DC output current resulting from a change in AC input voltage from low line (usually 105 volts) to high line (usually 125 volts) or from high line to low line. See paragraph C2b.

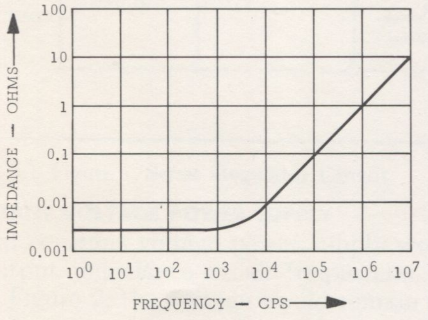
LINE REGULATION of a constant voltage power supply. The change in the static value of DC output voltage resulting from a change in AC input voltage from low line (usually 105 volts) to high line (usually 125 volts) or from high line to low line. See paragraph C1b.

LOAD REGULATION of a constant current power supply. The change in the static value of DC output current resulting from a change in load resistance from short circuit to a value which gives maximum rated output voltage. See paragraph C2c.

LOAD REGULATION of a constant voltage power supply. The change in the static value of DC output voltage resulting from a change in load resistance from open circuit to a value which yields maximum rated output current. See paragraph C1c.

OUTPUT IMPEDENCE of a power supply. At any given frequency of load change, $\Delta E_{OUT}/\Delta I_{OUT}$. Strictly speaking the definition applies only for a sinusoidal load disturbance, unless, of course, the measurement is made at zero frequency (DC). The output impedance of an ideal constant voltage power supply would be zero at all frequencies, while the output impedance for an ideal constant current power supply would be infinite at all frequencies. See paragraphs C1i and C2g.

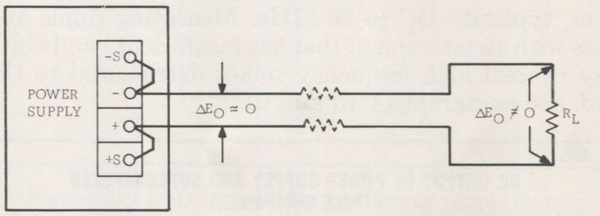
TYPICAL OUTPUT IMPEDANCE OF A CONSTANT VOLTAGE POWER SUPPLY



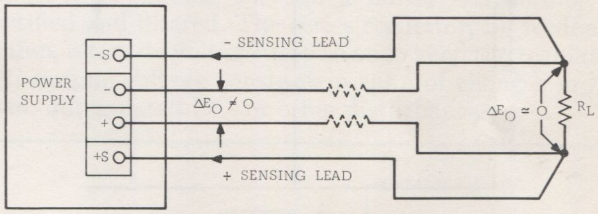
RECOVERY TIME. See Transient Recovery Time.

REMOTE ERROR SENSING or REMOTE SENSING. A feature found on most hp power supplies, which, by means of two extra wires between the supply and the load, permits the power supply to achieve its optimum regulation at the load terminals rather than at the power supply output terminals, thus compensating for the IR drop present in the current carrying leads connecting the load to its power supply. The current through the sensing leads is so small that in spite of the resistance of these leads, their voltage drop is negligible. See paragraphs B3 and D1.

POWER SUPPLY AND LOAD CONNECTED NORMALLY

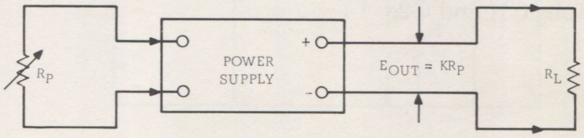


POWER SUPPLY AND LOAD CONNECTED FOR REMOTE SENSING

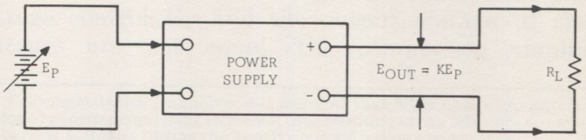


REMOTE PROGRAMMING. A feature of most hp power supplies which permits control of the regulated output current or voltage by means of a remotely varied resistance or voltage. The illustrations that follow show examples of constant voltage remote programming. CC applications are similar; see paragraph B5.

REMOTE PROGRAMMING USING RESISTANCE CONTROL



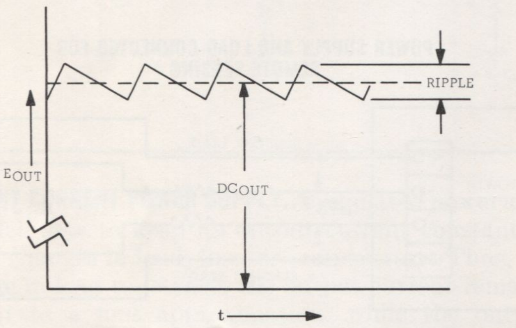
REMOTE PROGRAMMING USING VOLTAGE CONTROL



REMOTE PROGRAMMING SPEED. The time (μsec) required for the output voltage to change from zero volts to within "X" millivolts of the maximum rated output or from the maximum rated output to within "X" millivolts of zero. "X" is specified separately for each model, generally of the same order as the load regulation specification. See paragraph B5e.

RIPPLE AND NOISE. The residual AC component which is superimposed on the DC output of a regulated power supply. Ripple and noise may be specified in terms of its RMS or (preferably) peak-to-peak value. When the peak-to-peak value is specified, it should be accompanied by the maximum bandwidth of the measuring instrument, typically DC to 20 MHz. Measuring ripple and noise with an instrument that has insufficient bandwidth may conceal high frequency spikes detrimental to the load. See paragraphs C1d and C2d.

DC OUTPUT OF POWER SUPPLY AND SUPERIMPOSED RIPPLE COMPONENT



STABILITY. Obviously a misnomer, this term refers to the *instability* in power supply output which occurs in the presence of constant load, constant line and constant ambient temperature for a stated period of time (usually 8 hours) following warm-up. This small output variation which is related in part to the internal temperature rise of the power supply, is the zero frequency component of noise which must be present in any DC amplifier or regulator, even though all input, output, environmental, and control parameters are held constant. See paragraphs C1f and C2e.

TEMPERATURE COEFFICIENT. For a power supply operated at constant load and under conditions of constant input AC line voltage, the change in output voltage (for a constant voltage supply) or output current (for a constant current supply) for each degree change in the ambient temperature. See paragraphs C1g and C2f.

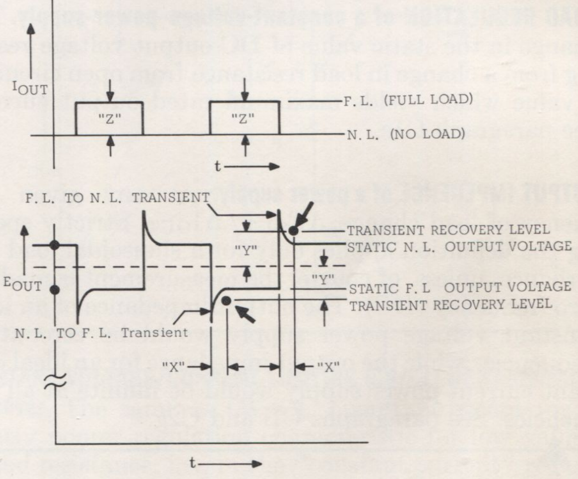
TRANSIENT RECOVERY TIME. Sometimes referred to as recovery time, transient response time, or response time —loosely speaking the time required for the output voltage of a power supply to come back to within a level approximating the normal DC output following a sudden change in load current. More exactly, Transient Recovery Time is the time "X" required for output voltage recovery to within "Y" millivolts of the nominal output voltage following a "Z" amp step change in load current —where:

(1) "Y" is specified separately for each model but is generally of the same order as the load regulation specification.

(2) The nominal output voltage is defined as the DC level halfway between the static output voltage before and after the imposed load change.

(3) "Z" is the specified load current change, normally equal to the full load current rating of the supply. See paragraph C1e.

TRANSIENT RECOVERY TIME



A. CIRCUIT PRINCIPLES

A1. INTRODUCTION

Electronic power supplies can be defined as circuits which transform electrical input power—either AC or DC—into output power—either AC or DC. This definition thus excludes power supplies based on rotating machine principles and distinguishes power supplies from the more general category of electrical power sources which derive electrical power from other energy forms (e.g. batteries, solar cells, fuel cells).

Electronic power supplies may be subdivided into four classifications:

(1) AC in, AC out—line regulators and variable frequency supplies
(2) DC in, DC out—converters
(3) DC in, AC out—inverters
(4) AC in, DC out.

This last subcategory is by far the most common of the four and is generally the one referred to when speaking of a "power supply." All of the topics of this Handbook relate to AC Input, DC Output power supplies.

Simple rectifying circuits alone are not adequate to provide a ripple-free DC whose value remains constant in spite of changes in input line voltage, load resistance, and ambient temperature. Most practical applications require a *regulated* power supply which interposes a control element either in shunt with, or in series between, the rectifier and the load device. The shunt regulator, which must withstand the full output voltage under normal operating conditions and is less efficient for most applications, is less often used than the series regulator. Figure 1 shows a simplified schematic of a power supply employing a series regulator, or series control element, which acts as a variable resistance connected in series with the load resistor.

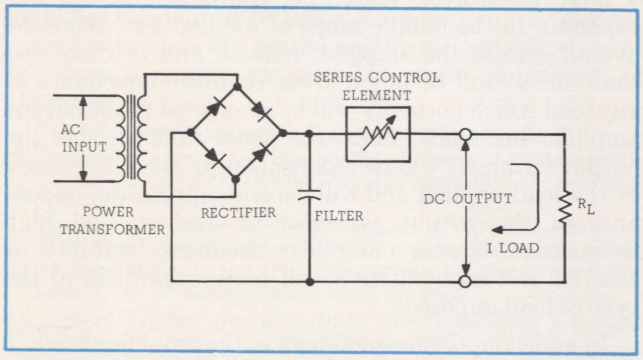


Figure 1. Series Regulator Circuit.

A2. CONSTANT VOLTAGE POWER SUPPLY

An ideal constant voltage power supply would have a zero output impedance at all frequencies. Thus, as shown in Figure 2, the voltage would remain perfectly constant in spite of any changes in output current demanded by the load.

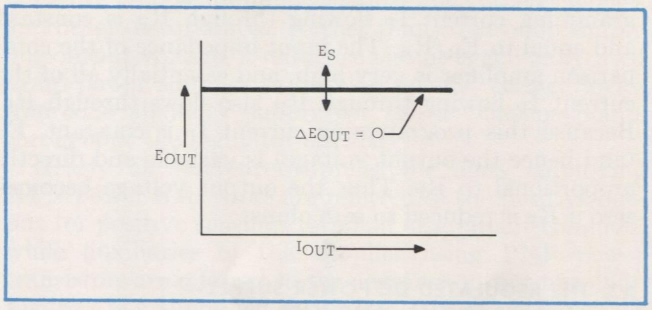


Figure 2. Ideal Constant Voltage Power supply Output Characteristic.

Figure 3 shows the basic feedback circuit principle* used in all hp constant voltage power supplies. The AC input, after passing through a power transformer, is rectified and filtered. The series regulator, by feedback action, alters its voltage drop so as to keep the regulated DC output voltage constant in spite of changes in the load, unregulated DC, or other disturbances.

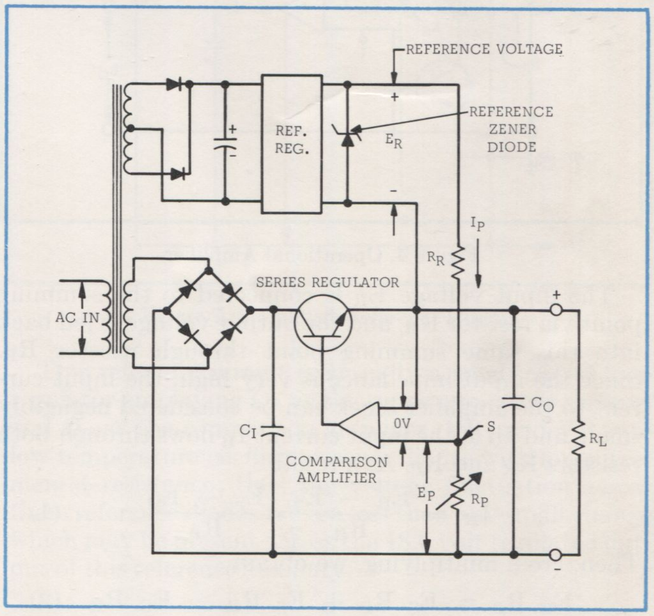


Figure 3. Constant Voltage Regulated DC Power Supply.

The comparison amplifier continuously monitors the difference between the voltage across the front panel voltage control R_P and the output voltage. If these voltages are not equal, the comparison amplifier

---

*Throughout this Handbook it is assumed that NPN power transistors are employed as series regulating elements, thus resulting in the reference circuit and comparison amplifier having the positive output bus as a common terminal. The use of PNP series power transistors merely has the effect of reversing all terminal and diode polarities (including the polarity of the reference circuit), without in any other way altering the diagrams and concepts given in this manual.

produces an amplified error signal. The error signal is of such a magnitude and polarity as to change the conduction of the series regulator, thereby changing the current through the load resistor until the output voltage equals the voltage E_P across the voltage control.

Since the net difference between the two voltage inputs to the comparison amplifier is kept at zero by feedback action, the voltage across the resistor R_R is also held equal to the reference voltage E_R. Thus the programming current I_P flowing through R_R is constant and equal to E_R/R_R. The input impedance of the comparison amplifier is very high, and essentially all of the current I_P flowing through R_R also flows through R_P. Because this programming current I_P is constant, E_P (and hence the output voltage) is variable and directly proportional to R_P. Thus the output voltage becomes zero if R_P is reduced to zero ohms.

A3. THE REGULATED DC POWER SUPPLY—AN OPERATIONAL AMPLIFIER

An operational amplifier is a special type of feedback amplifier having the shunt input and the shunt output feedback connection shown in Figure 4.*

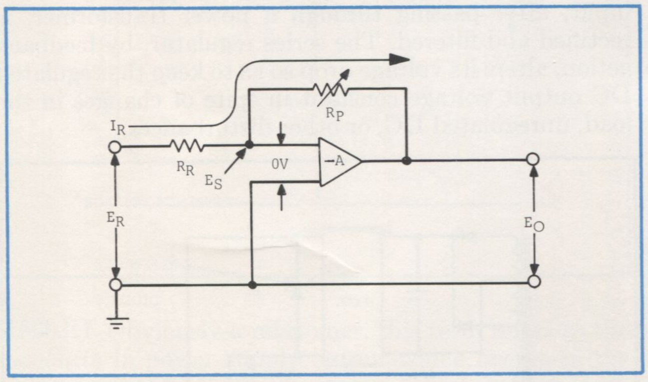


Figure 4. Operational Amplifier.

The input voltage E_R is connected to the summing point via resistor R_R, and the output voltage is fed back into this same summing point through resistor R_P. Since the input impedance is very high, the input current to the amplifier block can be considered negligibly small, and all of the input current I_R flows through both resistors R_R and R_P. As a result

$$I_R = \frac{E_R - E_S}{R_R} = \frac{E_S - E_O}{R_P} \qquad (1)$$

Then, cross multiplying, we obtain

$$E_R\,R_P = E_S\,R_P + E_S\,R_R - E_O\,R_R \qquad (2)$$

Figure 4 yields a second equation relating the amplifier output to its gain and voltage input

$$E_O = E_S\,(-A) \qquad (3)$$

which when substituted in equation (2) and solved for E_S yields

$$E_S = \frac{E_R\,R_P}{R_P + R_R\,(1 + A)} \qquad (4)$$

Normally, the operational amplifier gain is very high, with values for A of 10,000 or more being common. In equation (4)

$$\begin{array}{ll} \text{If we let} & A \rightarrow \infty \\ \text{Then} & E_S \rightarrow 0 \end{array} \qquad (5)$$

This important result is what actually enables us in the preceding constant voltage power supply discussion (Section A2) to say that the two input voltages to the comparison amplifier are held equal by feedback action.

With the normally used high values of A, the summing point voltage E_S is at most a few millivolts in modern well-regulated power supplies. If we let $E_S = 0$, and substitute this result in equation (1), we arrive immediately at the standard gain expression for the operational amplifier

$$E_O = -E_R\,\frac{R_P}{R_R} \qquad (6)$$

Notice that in both Figures 3 and 4, doubling the value of R_P doubles the output voltage.

To convert the operational amplifier of Figure 4 into a power supply we must first apply as its input a fixed DC input reference voltage E_R (see Figure 5). Across the output terminals of the operational amplifier we add a large electrolytic capacitor; the impedance of this capacitor in the middle range of frequencies (where the overall gain of the amplifier falls off and becomes less than unity) will be much lower than the impedance of any load which normally will be connected to the output amplifier terminals. Thus, the phase shift through the output terminals will be independent of the phase angle of the load applied and will depend only on the impedance of the output capacitor at medium and high frequencies. Hence, amplifier feedback stability is assured and no oscillation will occur regardless of the type of load imposed.

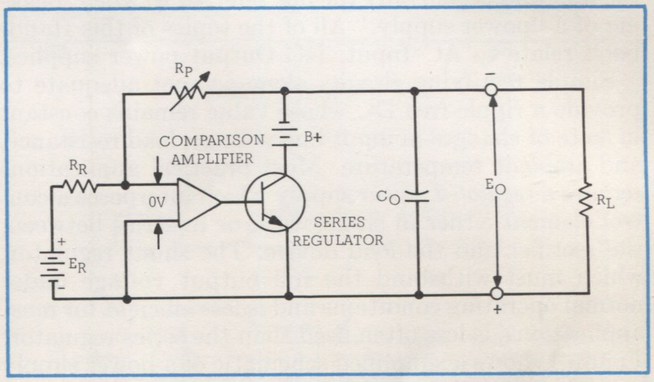


Figure 5. Operational Amplifier with DC Input Signal.

In addition, the output stage in the amplifier block in Figure 4 is removed and shown separately, leaving the remaining amplifier stages inside the amplifier block. After these changes have been carried out, the modified operational amplifier of Figure 5 results.

Next, replace the batteries of Figure 5 with rectifiers and a reference zener diode; the result is Figure 6. A point-by-point comparison of Figures 3 and 6 reveals that the two have identical topology—all connections

---

*An introduction to the operational amplifier concept can be found in Millman, J., and Taub, H.: "Pulse and Digital Circuits," chap. 1, McGraw-Hill Book Company, Inc., New York, 1956.

are the same, only the position of the components on the diagram differs!

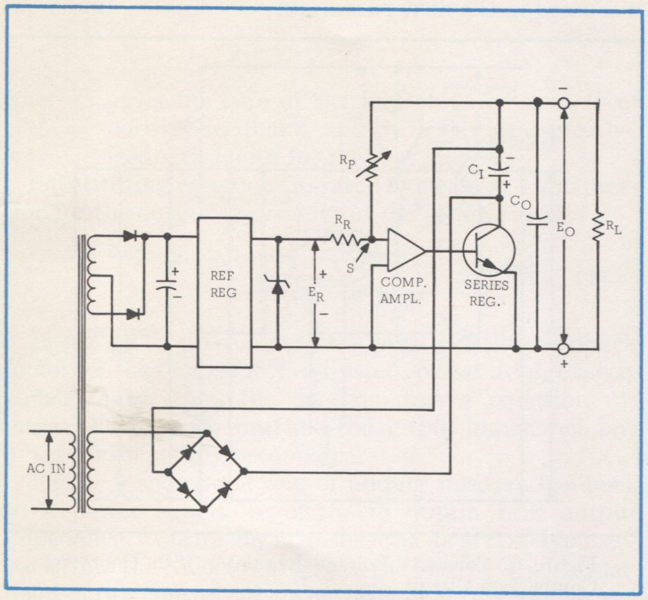


Figure 6. Operational Amplifier Representation of Adjustable CV Power Supply.

Thus, a power supply *is* an operational amplifier. The input signal to this operational amplifier is the reference voltage. The output signal is regulated DC. The following chart summarizes the corresponding terms used for an operational amplifier and a power supply.

Operational Amplifier	Constant Voltage Power Supply
Input Signal	DC Reference
Output Signal	Regulated DC
Amplifier	Regulator
Output Stage	Series Regulating Transistor
B+ Source	Rectifier
Gain Control	Output Voltage Control

As a result of the specific way in which an operational amplifier is modified to become a power supply circuit, some restrictions are placed on the general behavior of the normal power supply. The most important of these are:

1. The large output capacitor C_O limits the bandwidth.*
2. The use of a fixed DC input voltage means that the output voltage can only be of one polarity, the opposite of the reference polarity (see equation 6).*
3. The output stage can conduct current in only one direction. This, together with the fact that the rectifier has a given polarity, means that the power supply can only *deliver* current to the load, it cannot *absorb* current from the load.

In general, if the power supply user considers a power supply as an operational amplifier subject to the restrictions listed above, he can determine quickly whether this power supply is suitable for a given application and what limitations exist.

A4. REFERENCE CIRCUITRY

In all hp power supplies the reference voltage is developed across a reference zener diode having a low temperature coefficient and a low incremental resistance. This reference zener diode is in turn fed from a reference regulator—actually a low power, closed loop auxiliary supply designed to keep the operating current through the reference zener diode constant, thereby assuring reference voltage immunity against line voltage changes and other disturbances. Rather than to develop simply one output voltage, a reference circuit is generally used in hp power supplies to develop several voltage levels from one auxiliary supply for use at various points throughout the regulator circuitry.

Nearly all reference supplies for units employing NPN power transistors are referred to the positive output (or positive sensing) terminal as a circuit common, while auxiliaries of the supplies using PNP power transistors are referred to the negative output terminal. Figure 7 is a simplified schematic of a reference circuit which has its common point connected to positive sensing (+S). Most power supply voltages are given with respect to this point.

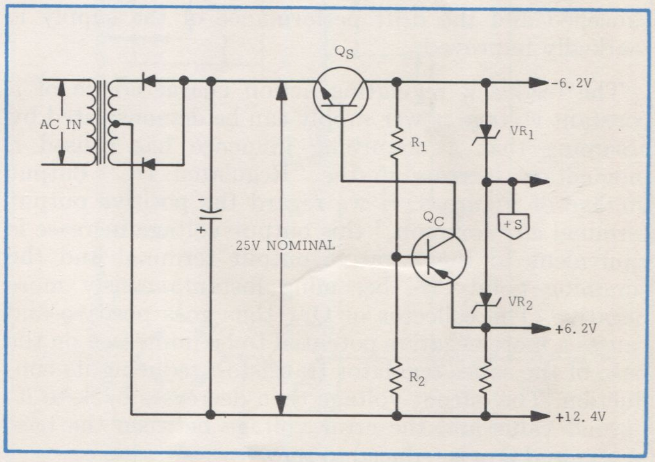


Figure 7. Simplified Reference Circuit.

This reference circuit is actually a small closed loop regulator employing Q_S as the series regulating element and Q_C as the comparison amplifier. VR_1 and VR_2 are low temperature coefficient zener diodes with low incremental resistance; thus the voltage fluctuation across these reference diodes is even less than any small change which may be present across the 18.6 volt regulated output of this reference auxiliary.

A5. COMPARISON AMPLIFIER CIRCUITRY

The comparison amplifier circuitry is second in importance only to the reference circuit in determining the degree of regulation which will be obtained. Because of the need in the input stage for low noise, low drift performance, a differential amplifier is frequently used. A normal transistor has an emitter-to-base voltage which varies approximately 2 mv per degree centigrade. Such a voltage variation in the input amplifier stage would be accompanied by a proportional change in the

---

*Special design steps have been added to the design of hp low voltage semiconductor supplies to permit a significant reduction in the size of the output capacitor merely by manipulating straps on the rear barrier strip (see Section B5e). On the PS/A Series of Power Supply/Amplifiers this output capacitor is virtually eliminated using a special feedback design. In addition, PS/A instruments are capable of an AC output and will conduct current in either direction, being continuously variable through zero (See Paragraph A18).

power supply output voltage. By using two matched transistors in a differential amplifier configuration and placing them in thermal proximity, this effect is largely cancelled and the drift performance of the supply is markedly improved.

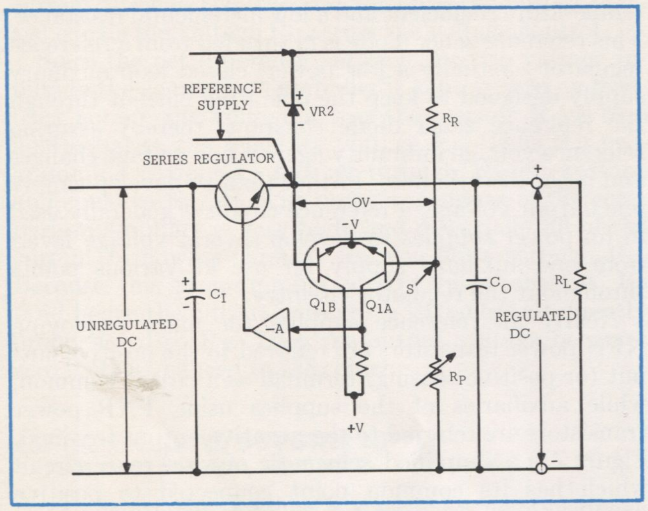


Figure 8. Constant Voltage Regulator with Simplified Comparison Circuit.

The feedback regulating action characteristic of a constant voltage power supply can be demonstrated by assuming that a disturbing influence has caused a momentary increase in the "Regulated DC" output voltage of Figure 8. If we regard the positive output terminal as "common," this output voltage increase is equivalent to the negative output terminal and the summing point "S" becoming instantaneously more negative. The collector of Q_{1A} thus goes positive and causes a more negative potential to be impressed on the base of the series regulator transistor, reducing its conduction. The output voltage then decreases back to its normal value and the error voltage between the base of Q_{1A} and Q_{1B} is reduced to zero.

Since any change in the resistance value of R_R or R_P will cause a change in the output voltage, wire-wound elements having a very low temperature coefficient are used. These resistors are operated at a level which is considerably less than their power rating so that their surface temperature will not be significantly higher than ambient and subject to thermal fluctuations.

Figure 9 shows several refinements which Hewlett-Packard typically includes in its comparison circuit in order to improve performance and reliability. Capacitor C_1 is added to improve the regulator performance with regard to ripple and other AC disturbances. Diodes CR_1 and CR_2 are added to limit the maximum voltage which can be impressed on the base of Q_{1A}. Normally there is zero volts across these diodes and they are not conducting; sudden changes in the output voltage caused by shorting the output terminals or rapidly altering the value of R_P will cause CR_1 or CR_2 to conduct, thereby preventing the burn-out of transistor Q_{1A}. Resistor R_3 is added to balance the I_{CO} effects of the bases of Q_{1A} and Q_{1B}, and is nominally equal to the base impedance of Q_{1A}. Variable resistor R_4 is one way in which positive feedback can be added within the regulator loop; the reason for the addition of this positive feedback is discussed in the next paragraph.

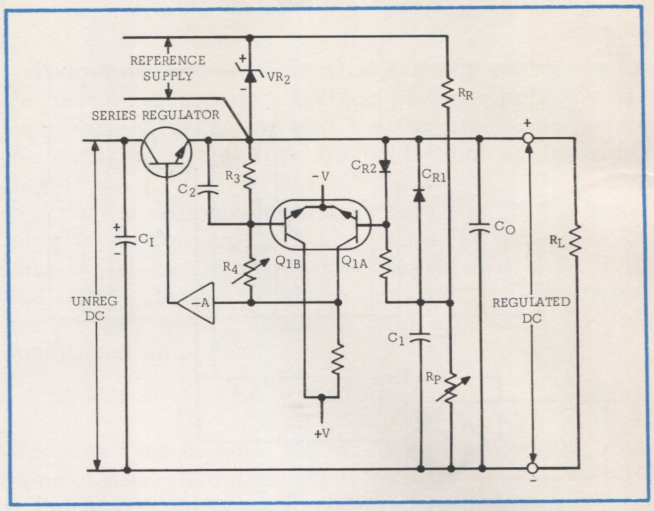


Figure 9. Constant Voltage Regulator with Improved Comparison Circuit.

A6. ZERO OUTPUT IMPEDANCE

As mentioned earlier, the ideal constant voltage power supply would have a zero output impedance at all frequencies. This would result in no change in output voltage for a change in output current from no load to full load, and would mean that there could be no mutual coupling effects between load devices connected to the same power supply. It is doubtful that the ideal constant voltage power supply can ever be achieved, but one can be realized which has a zero output impedance at zero frequency (DC) using the circuit shown in Figure 9.

The output impedance of a regulated power supply (or any negative voltage feedback amplifier) is given by

$$Z_{OF} = \frac{Z_O}{1-\mu\beta} \qquad (1)^*$$

where: Z_{OF} = the output impedance with the feedback loop closed

Z_O = the output impedance which would be present if amplifier stages within the regulator were not activated

μ = the combined voltage gain of all amplifier stages within the regulator feedback loop

β = the feedback factor from the output terminals to the first amplifier stage.

μ is actually the composite of the several stages of gain within the feedback loop. Therefore,
$\mu = \mu_1 \mu_2 \mu_3 \ldots\ldots\ldots\ldots$, where the subscripts refer to the first, second, third stage, etc. Consequently, a more exact description of the output impedance of a power supply is:

$$Z_{OF} = \frac{Z_O}{1 - \mu_1 \mu_2 \mu_3 \ldots\ldots \beta} \qquad (2)$$

---

*For *negative* feedback, $\mu\beta$ is a *negative* number, and the denominator of (1) is a positive number greater than unity.

Now let us assume that local positive feedback is added around the first stage. The gain of this stage is therefore:

$$\mu_1 = \frac{\mu_1'}{1 - \mu_1' \beta_1} \qquad (3)$$

where: μ_1' is the gain of the first stage without local positive feedback, and β_1 is the local positive feedback factor for the first stage.

Substituting equation (3) into (2) yields a new expression for the output impedance of the power supply:

$$Z_{OF} = \frac{Z_O}{1 - \dfrac{\mu_1 \mu_2 \mu_3 \ldots\ldots\ldots\ldots \beta}{1 - \mu_1' \beta_1}} \qquad (4)$$

It can be seen that if β_1, the local positive feedback factor for the first stage, is adjusted so that $\mu_1' \beta_1$ exactly equals unity, then the denominator of equation (4) increases without bound and the output impedance Z_{OF} of the power supply becomes zero.

Figure 9 shows one way of adding positive feedback to a power supply regulator to obtain zero output impedance. Control R_4 furnishes the local positive feedback from the collector of Q_{1A} to the base of Q_{1B}. Adjustment of this control enhances the gain of this comparison amplifier and permits the power supply to retain its static output voltage perfectly constant in spite of a no load to full load change in load current.

A7. CONSTANT CURRENT POWER SUPPLY

The ideal constant current power supply would exhibit an infinite output impedance (zero output admittance) at all frequencies. Thus, as Figure 10 indicates, the ideal constant current power supply would accommodate a load resistance change by altering its output voltage by just the amount necessary to insure that its output current would remain constant.

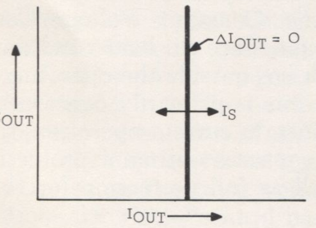


Figure 10. Ideal Constant Current Power Supply Output Characteristic.

Constant current power supplies find many applications in semiconductor circuitry, and are also well suited for supplying fixed currents to focus coils or other magnetic circuits, the current remaining constant despite temperature-induced changes in the resistance of the load. Just as loads for constant voltage power supplies are always connected in parallel (never in series), loads for constant current power supplies must be connected in series (never in parallel).

Figure 11 illustrates the elements which go into a constant current power supply, many of which are identical to the elements found in a constant voltage power supply (compare with Figure 3). The feedback loop acts continuously to keep the two inputs to the comparison amplifier equal; one of these inputs is the voltage drop across the front panel current control while the other is the IR drop developed by the load current I_L flowing through the current monitoring resistor R_M. If the two inputs to the comparison amplifier are momentarily unequal, then the comparison amplifier output changes the conduction of the series regulator, thereby changing the load current and the voltage drop across R_M until the error voltage at the comparison amplifier input is reduced to zero. Momentary unbalances at the comparison amplifier can occur as a result of manually changing the resistance of R_Q or because of instantaneous output current changes due to external disturbances. Whatever the cause, the regulator action of the feedback loop will increase or decrease the load current until the change is counteracted.

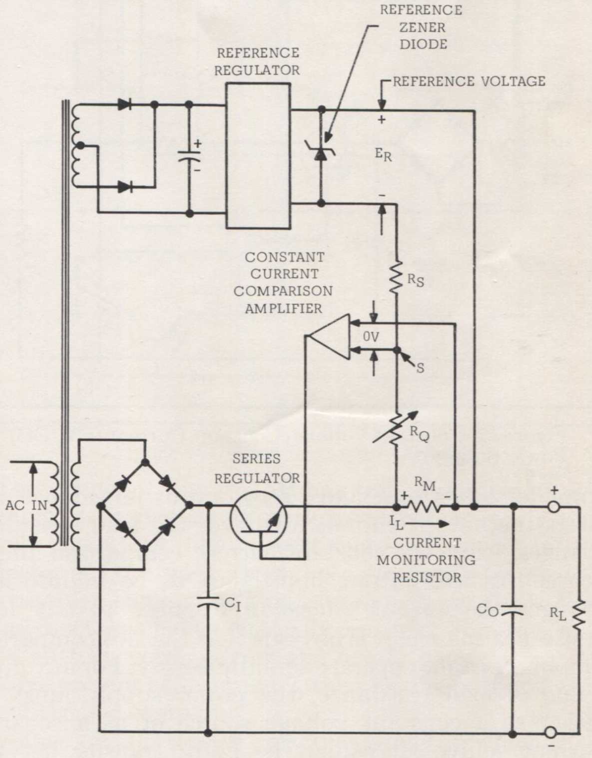


Figure 11. Constant Current Regulated DC Power Supply.

A8. CONSTANT VOLTAGE/CONSTANT CURRENT (CV/CC) POWER SUPPLIES

The fact that so many elements are common to the block diagram of the constant voltage power supply (Figure 3) and the block diagram of the constant current power supply (Figure 11) suggests the possibility of combining these two circuit principles in one supply as illustrated in Figure 12. Fortunately, most of the expensive, heavy power elements are common to both the constant voltage and constant current circuit configurations, and only low-level circuitry need be added to a constant voltage power supply so that it can also be used as a constant current source. Because of its unusual versatility and its fully adjustable output protection features, many hp supplies employ this CV/CC circuit technique.

Two comparison amplifiers are included in a CV/CC supply, one for controlling output voltage, the other for controlling output current. Since the constant voltage amplifier tends to achieve zero output impedance and alters the output *current* whenever the load resistance changes, while the constant current comparison amplifier causes the output impedance to be infinite and changes the output *voltage* in response to any load resistance change, it is obvious that the two comparison amplifiers cannot operate simultaneously. For any given value of load resistance, the power supply must act either as a constant voltage source or as a constant current source—it cannot be both; transfer between these two modes is accomplished (automatically by suitable decoupling circuitry) at a value of load resistance equal to the ratio of the output voltage control setting to the output current control setting.

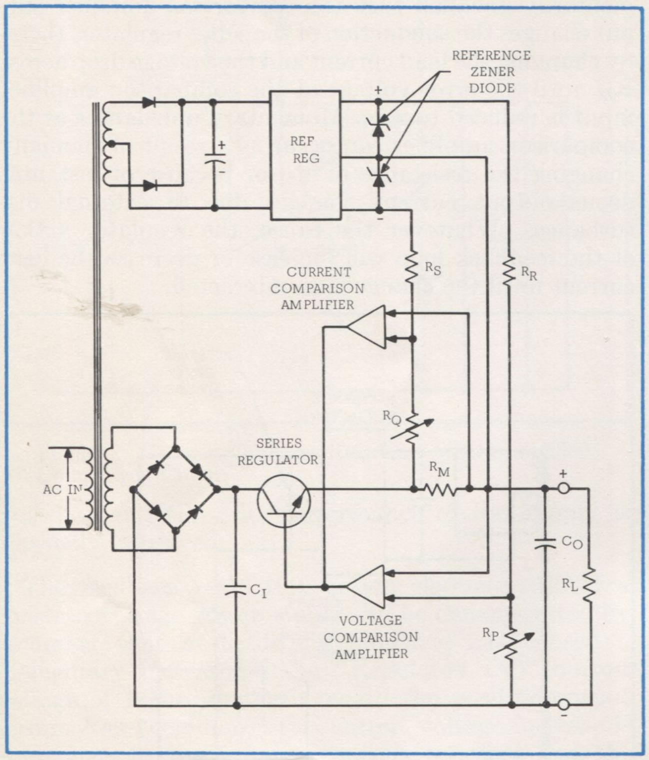


Figure 12. Constant Voltage/Constant Current (CV/CC) Power Supply.

Figure 13 shows the output characteristic of a CV/CC power supply. With no load attached ($R_L = \infty$), $I_{OUT} = 0$, and $E_{OUT} = E_S$, the front panel voltage control setting. When a load resistance is applied to the output terminals of the power supply, the output current increases, while the output voltage remains constant; point D thus represents a typical constant voltage operating point. Further decreases in load resistance are accompanied by further increases in I_{OUT} with no change in the output voltage until the output current reaches I_S, a value equal to the front panel current control setting. At this point the supply automatically changes its mode of operation and becomes a constant current source; still further decreases in the value of load resistance are accompanied by a drop in the supply output voltage with no accompanying change in the output current value. Thus, point B represents a typical constant current operating point. Still further decreases in the load resistance result in output voltage decreases with no change in output current, until finally, with a short circuit across the output load terminals, $I_{OUT} = I_S$ and $E_{OUT} = 0$.

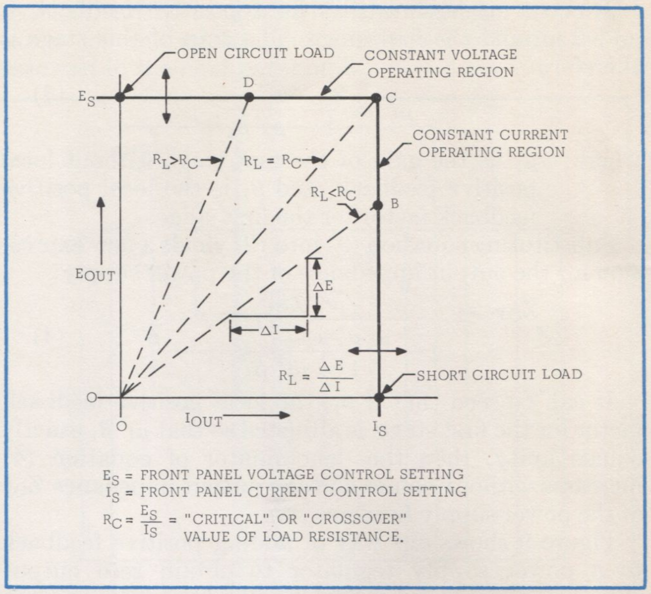


Figure 13. Operating Locus of a CV/CC Power Supply.

By gradually changing the load resistance from a short circuit to an open circuit the operating locus of Figure 13 will be traversed in the opposite direction.

Full protection against any overload condition is inherent in the Constant Voltage/Constant Current design principle since no load condition can cause an output which lies outside the operating locus of Figure 13. Whether one is primarily concerned with constant voltage or constant current operation, the proper choice of E_S and I_S insures optimum protection for the load device as well as full protection for the power supply itself.

The line connecting the origin with any operating point of the locus of Figure 13 has a slope which is proportional to the value of load resistance connected to the output terminals of the supply. One can define a "critical" or "crossover" value of load resistance $R_C = \frac{E_S}{I_S}$; adjustment of the front panel voltage and current controls permits this "crossover" resistance R_C to be set to any desired value from 0 to ∞. If R_L is greater than R_C, the supply is in constant voltage operation, while if R_L is less than R_C, the supply is in constant current operation.

A9. CONSTANT VOLTAGE/CURRENT LIMITING (CV/CL) SUPPLIES

The difference between a CV/CC power supply and a CV/CL power supply is one of degree rather than kind.

Because a current limiting supply uses fewer stages of gain in the current regulating loop, the regulation in the region of current limiting operation is not as tight as in the case of constant current operation. Thus, the current limiting portion of the locus of Figure 14 does not come as close to being a vertical line as the current operating region for a CV/CC power supply (Figure 13).

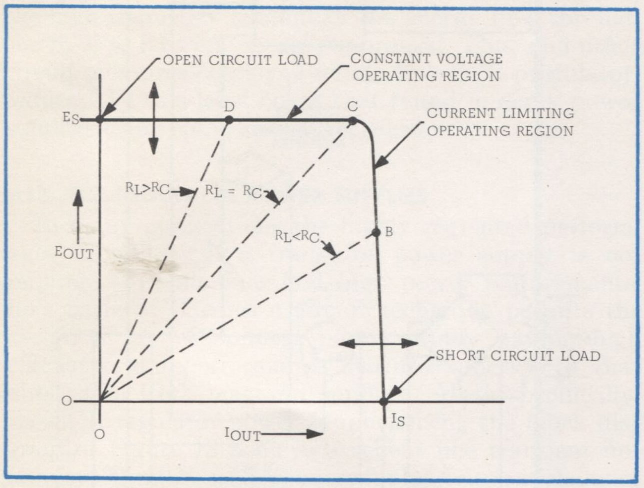


Figure 14. Operating Locus of a CV/CL Power Supply.

CV/CL supplies may employ either a fixed current limit or a continuously variable limit. In either case the change in the output current of the supply from the point where current limiting action is first incurred to the current value at short circuit is of the order of 3% to 5% of the current rating of the power supply.

A10. SERIES REGULATOR CIRCUITRY

Up to this point, all circuits shown have included only a single series transistor. It is obvious, however, that a single series transistor has an adequate power capability only for the smallest power supply. Using several series transistors in parallel is usually not desirable because (1) the number of series power transistors—probably the least reliable component in the power supply—becomes quite large even for supplies of moderate output capability, and (2) each series transistor will be subjected to the entire series regulator voltage under all operating conditions. Hewlett-Packard has placed considerable design emphasis both on reducing the power dissipated in series transistors and minimizing the number of series transistors required.

Figure 15A illustrates the simplest type of series transistor regulator; the maximum power dissipated in this series transistor is the product of its maximum voltage drop and the maximum current through it. Figure 15B illustrates the circuit principle of a two transistor series regulator employing a shunt resistor R_5 around the second series transistor. With any moderate amount of load current the circuit of Figure 15B will tend to maintain approximately 2 volts across transistor Q_A. With a proper choice of R_5 the maximum power which will be dissipated in transistor Q_A or Q_B will be approximately one-fourth the power which would be dissipated in the simple transistor regulator shown in Figure 15A—the excess power being dissipated in power resistor R_5 rather than in a power transistor.

Furthermore, the operation of this circuit assures that transistors Q_A and Q_B will not be at their conditions of maximum power dissipation simultaneously; thus a heat sink for both these transistors will have a maximum temperature rise associated with the heat dissipated by one, not two, power transistors.

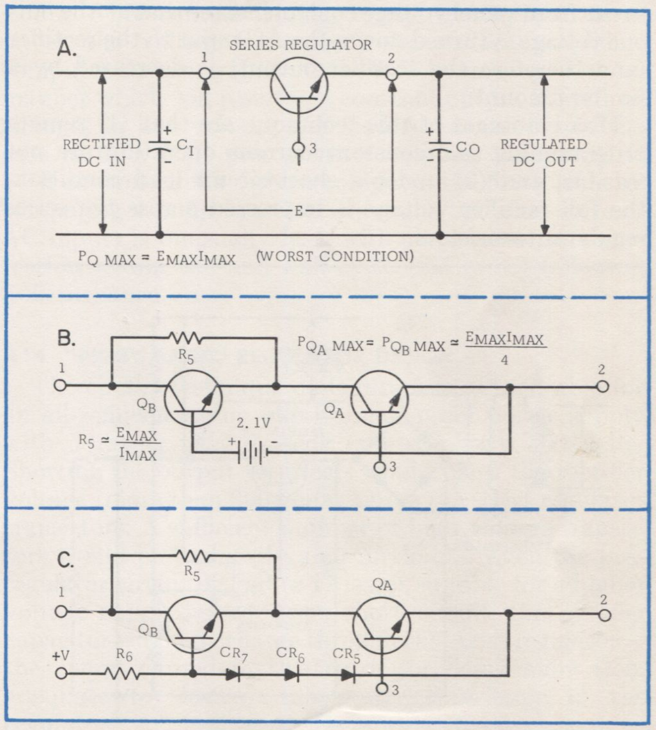


Figure 15. Series Regulator Circuits.

The circuit of Figure 15B has the advantage of performing a preregulating action, with the result that ripple and other line disturbances presented to the collector of Q_A are less than those present at terminal 1, the rectifier DC input. This is true because the base of transistor Q_B is held practically constant, differing only by a battery voltage from the nearly constant output voltage present at terminal 2, the positive output terminal of the power supply.

Figure 15C illustrates an actual circuit in which three forward conducting silicon diodes, acting as the semiconductor equivalent of VR tubes, are substituted for the battery of Figure 15B. Resistor R_6 provides the necessary path for maintaining the forward current flow through the three diodes.

Hewlett-Packard supplies employ a large number of variations on the circuit principle suggested in Figure 15C; all such combinations of power resistors, transistors, and diodes result in increased reliability, because most of the series regulator dissipation occurs in power resistors rather than power transistors.

A11. VARIABLE TRANSFORMER PREREGULATOR

In power supplies of moderate or high power output the dissipation requirements of the series regulator circuit are more severe, and an efficient, reliable, and economical design is not feasible without resorting to some sort of preregulator in the rectifier path. The purpose of such a preregulator is to allow the rectifier output to change in coordination with the output voltage so that only a small voltage drop is maintained across the series regulator, and the power dissipation in the series regulator elements is held to a small value. One of the simplest techniques for accomplishing this is shown in Figure 16. A variable transformer mechanically coupled to the front panel voltage control insures that as the output voltage is turned down, the AC input to the rectifier (and therefore the rectifier output) is decreased by a similar amount.

Disadvantages of this technique are that (1) remote programming and constant current operation are not feasible, and (2) under a short-circuit load condition, the full rectifier voltage is impressed across the series regulator transistors.

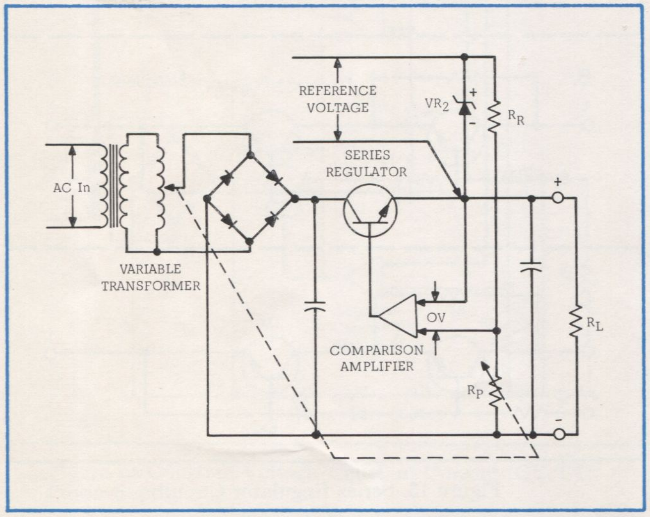


Figure 16. Constant Voltage Supply with Variable Transformer Preregulator.

A12. SCR (SILICON CONTROLLED RECTIFIER) PREREGULATORS

The use of SCR preregulators allows the circuit techniques already developed for low power output supplies to be extended readily to medium power and high power designs, without incurring the disadvantages of variable transformer preregulators. Figure 17 shows a typical regulated DC power supply utilizing an SCR preregulator.

Silicon Controlled Rectifiers, the semiconductor equivalent of thyratrons, are rectifiers which remain in a non-conductive state, even when forward voltage is provided from anode to cathode, until a positive trigger pulse is applied to a third terminal (the gate). Then the SCR "fires," conducting current with a very low effective resistance; it remains conducting after the trigger pulse has been removed until the forward anode voltage is removed or reversed.

SCR's are included in two arms of the bridge rectifier of Figure 17. By controlling the firing time of the SCR's during each half cycle of input line frequency, the duration of conduction of the bridge rectifier is varied and the rectifier output is controlled in accordance with the demands which the DC output voltage and current of the supply impose.

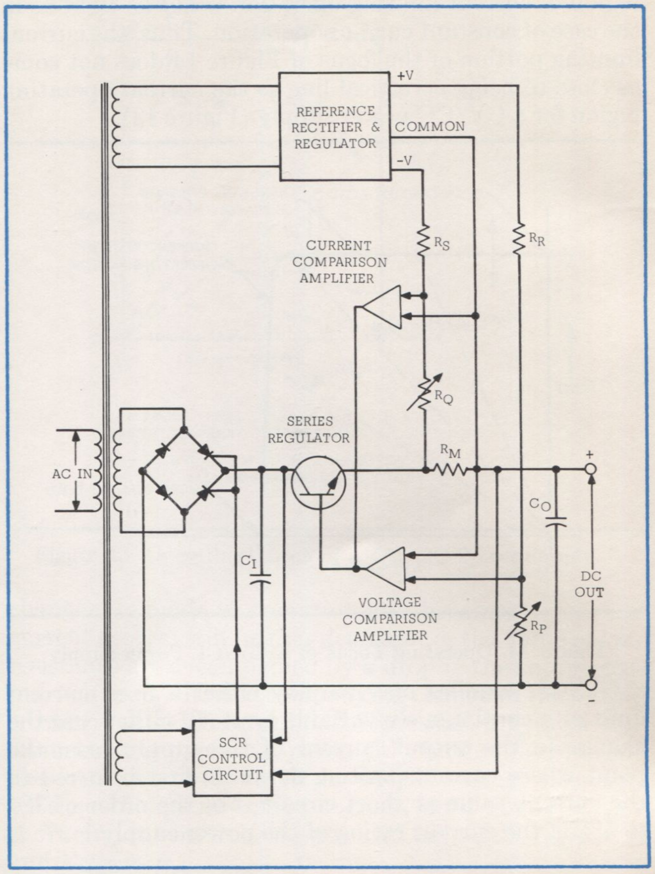


Figure 17. CV/CC Power Supply with SCR Preregulator.

The function of the SCR control circuit is to compute the firing time of the SCR trigger pulse *for each half cycle* of input AC so that the combined voltage drop across the series regulator and current monitoring resistor is held constant in spite of changes in load current, output voltage, and input line voltage. The final burden of providing the precise *output* voltage or current regulation rests with a series regulator controlled by voltage and current comparison amplifiers.

The correction action of hp's SCR control circuit is much faster than that obtained with conventional SCR or magamp circuitry. Sudden changes in line voltage or load current result in a correction in the timing of the next SCR trigger pulse, which can be no farther away than one half cycle (approximately 8 milliseconds for a 60 cycle input). The use of large electrolytic capacitors across the rectifier output allows only a small voltage change to occur during this 8 millisecond interval. Using this preregulator technique hp can operate a series regulator chain with less than 2 volts across it at all times, without risk of transient drop-out and loss of regulation due to changes in load or line. This use of an SCR preregulator with excellent transient immunity thus results in a power supply having unusually high efficiency and reliability, since the power which must be dissipated in the series regulator is held to a very small value.

The leakage inductance of the power transformer, although it does not appear explicitly in Figure 17, plays an important part in the circuit performance. It acts as a small filter choke effectively in series with the SCR's and slows down the inrush current after firing, thus reducing the peak current through the SCR's and improving their reliability. Since this inductance reduces the high frequency content of the energy flow through the SCR's, RFI effects are suppressed. This, and other circuit measures employed within hp's SCR pregulator, reduce RFI to a level below that found in many power supplies using conventional rectifiers.

A13. SCR REGULATED POWER SUPPLIES

In many applications the highly regulated performance capability of a transistor power supply is not required. For medium and high power requirements, hp's basic SCR control circuit technique permits the design of an economical power supply having high efficiency and performance features superior to that obtainable from magamp supplies. More specifically, the SCR regulator power supplies using the block diagram of Figure 18 achieve excellent line transient immunity, 50 millisecond recovery for load current changes, and smaller size and weight. The output voltage of these supplies is continuously variable down to zero, and continuously variable current limiting or constant current operation is included on all units.

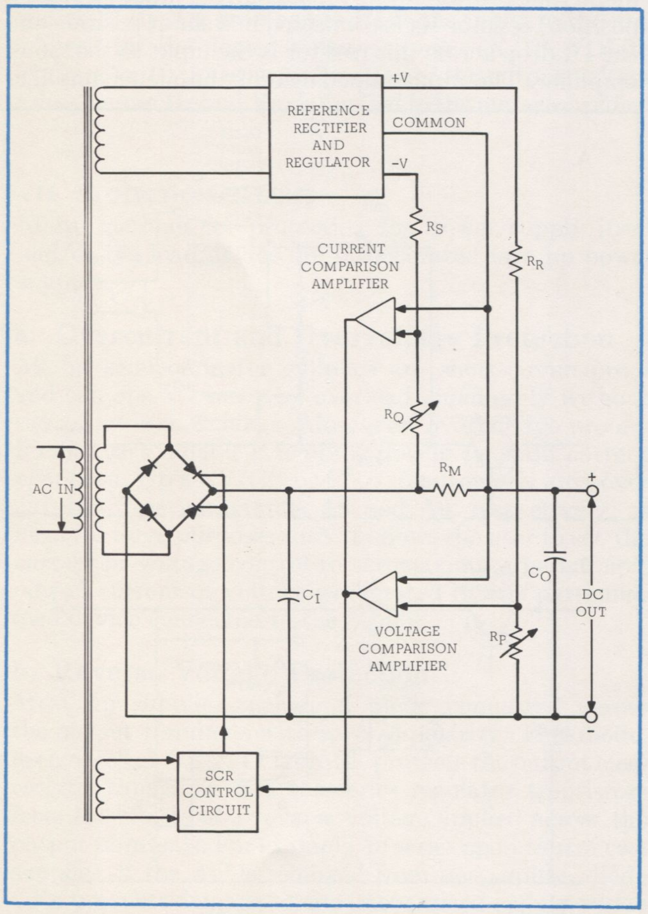


FIGURE 18. SCR Regulated Power Supply.

Figure 18 reveals that the SCR control circuit receives a control signal dependent upon the output of either a voltage comparison amplifier or a current comparison amplifier. Such supplies, therefore, have output characteristics and control characteristics similar to the CV/CC and CV/CL power supplies discussed in Paragraphs A8 and A9—except that the output voltage or current is less tightly regulated.

The SCR control circuit, receiving its input from either the voltage or current comparison amplifier, computes the firing time for the SCR's, varying this in a manner which will result in a constant output in spite of changes in line voltage and load resistance. As in the case of hp's SCR preregulator supplies, the patented SCR control circuit (which computes the firing time by comparing a ramp function with each half sine-wave of AC input) is unusually fast, with almost complete correction within the first half-cycle (8.3 msec) following a disturbance.

A14. "PIGGY-BACK" REGULATOR DESIGN

The circuit technique of Figure 3 is not suitable for an all-semiconductor, short-circuit-proof power supply with a rating that exceeds approximately 300 volts. Shorting the output terminals would place the rectifier voltage (more than 300 volts) across the series regulator transistors. A sufficient number of high voltage transistors would be too costly and unreliable. Even the preregulator circuit of Figure 17 is not suitable for a higher voltage supply; since, upon short circuit, the rectifier capacitor would discharge through the series regulator—the energy stored in this capacitor being more than adequate to destroy the power transistors in the regulator.

Several series of hp supplies utilize a novel circuit technique which extends the usefulness of series regulating transistors rated for 30 volts to short-circuit-proof power supplies rated for outputs of well over 3000 volts. As shown in Figure 19 the basic technique consists of placing a well-regulated low voltage power supply in series with a less-well-regulated supply having a greater voltage capability. Notice, however, that the amplified error signal from the voltage comparison amplifier is dependent upon the *total* output voltage—not just the output of the low voltage power supply alone. Thus, the well-regulated "piggy-back" supply continuously compensates for any ripple, load regulation, or line regulation deficiencies of the main power source and adjusts the voltage across its series regulator so that the total output voltage remains constant despite disturbances in the main voltage source.

For ease of explanation, it is assumed that the low voltage rectifier supplying the series transistor of the "piggy-back" supply develops approximately 40 volts. It is further assumed that the main voltage source is capable of providing a maximum of 300 volts. With 20 volts normally dropped across the series regulator, the maximum output of this supply is 320 volts; 20 volts from the upper supply and 300 volts from the lower supply. Thus, the series regulator of the "piggy-back" supply has a ± 20 volt range for accomplishing the dynamic changes necessary to compensate for the varia-

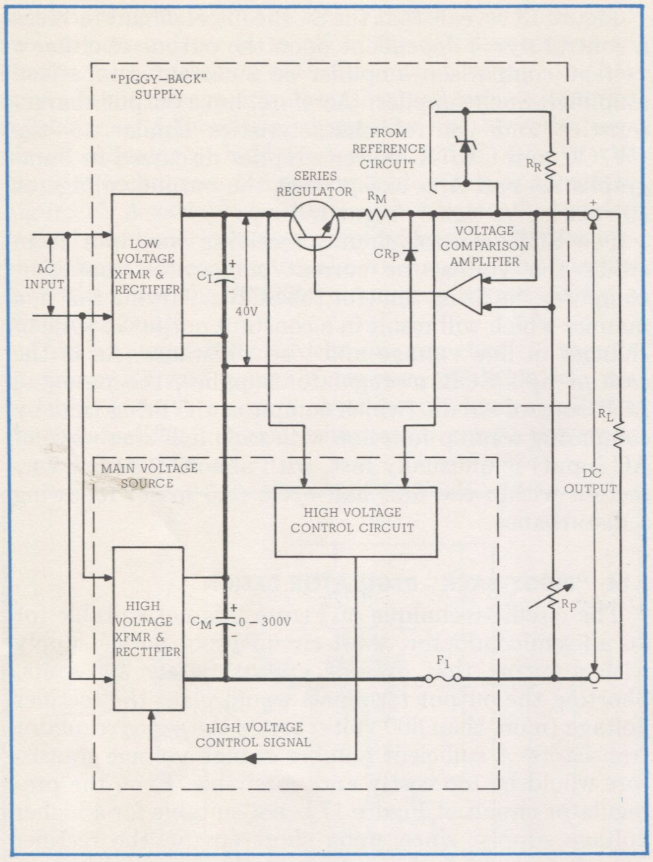


Figure 19. "Piggy-back" Power Supply.

tions of the lower power source. Short-circuit protection for the series regulator in the "piggy-back" supply is provided by diode CR_P which, if the output terminals are shorted, provides a discharge path for the rectifier capacitor C_M of the bottom supply. Since CR_P prevents the output terminals of the "piggy-back" supply from ever reversing polarity, the series regulator within this circuit will never be called upon to withstand a voltage strain greater than the 40 volts from its own rectifier.

The fuse F_1 is included so that under short-circuit or prolonged overload conditions the path between the output terminals and the rectifying elements of the main voltage source will be opened, thus protecting the rectifiers and transformer.

The high voltage control circuit for the bottom supply derives its input control signal not from the total voltage across the load resistor, nor even from the voltage across the terminals of the high voltage supply itself. Instead, this control circuit monitors the voltage across the series regulator and the current monitoring resistor and maintains this voltage drop at approximately 20 volts, thereby leaving approximately 20 volts across the output terminals of the "piggy-back" supply.

Hewlett-Packard supplies utilize three basic methods for controlling the high voltage output: (1) the control signal from the high voltage control circuit fires SCR's in the rectifier to vary the average voltage of the pulsating DC output, (2) the control signal varies the coupling of the high voltage input transformer to adjust the RMS level of the AC input to the rectifiers or (3) the control signal pulse modulates the input to the rectifier to vary the average voltage of the pulsating DC output.

A15. MULTIPLE RANGE METER CIRCUIT

Many hp supplies employ a multiple range meter circuit which allows a single front-panel meter to indicate either the output voltage or current in one of two ranges. A meter switch accomplishes the range selection which is X volts or X/10 volts, when measuring output voltage, and Y amps or Y/10 amps, when measuring output current; where X and Y are slightly greater than the maximum voltage and current ratings, respectively. Figure 20 shows a simplified version of a typical multiple range meter circuit; the A portion illustrates the meter connections when measuring current and the B portion the meter connections for voltage measurements. Measuring the output *current* of a supply presents the greatest problem and, therefore, the current measuring technique will be discussed first.

When measuring output current the entire meter circuit is connected across the current monitoring resistor R_M. As mentioned previously, the IR drop across R_M varies in proportion to the output current. A portion of this voltage drop, which appears across voltage divider R_1, R_2 and R_3, is coupled through the meter range switch to the meter amplifier whose output, in turn, deflects the meter. The range switch selects the value of divider resistance placed across the meter amplifier. With the meter range switch in the higher current range (Y AMPS position) resistor R_3 is connected in a shunt position and the IR drop across this resistor is the input to the meter amplifier. The input impedance of the meter amplifier

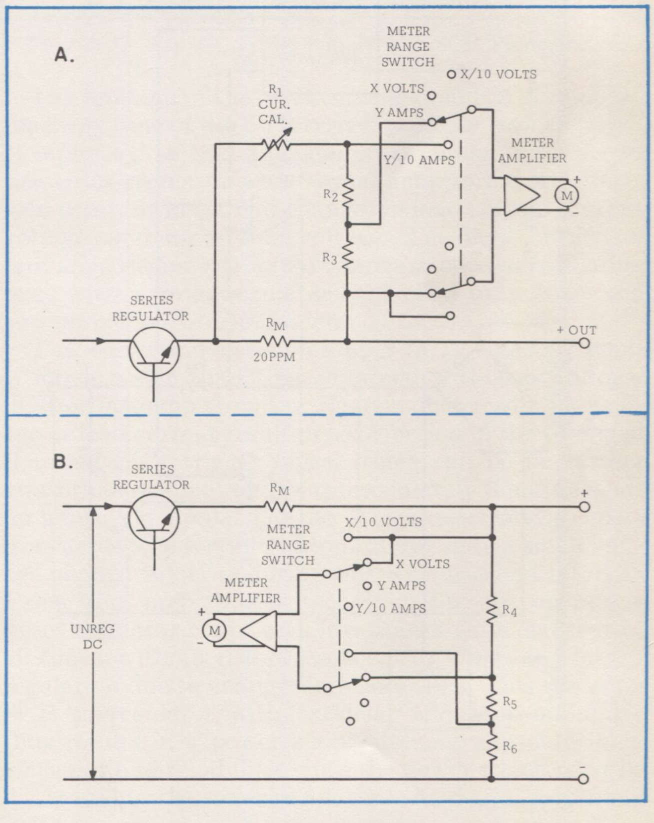


Figure 20. Multiple Range Meter Circuit.

is sufficiently high so as not to load down the shunt resistance. For low values of output current, the meter switch can be set to the lower current range (Y/10 AMPS position) switching resistors R_2 and R_3 into the shunt position. The meter amplifier now receives a voltage drop which is 10 times larger than that received when the meter range switch is in the higher current position.

The main purpose of the meter amplifier is to isolate the meter movement, which has a relatively poor temperature coefficient (of the order of 4000 PPM/°C) from the current monitoring resistor. This advantage is especially important in the low current range where the high temperature coefficient of a meter connected in series with a low resistance value across the current monitoring resistor would degrade the overall constant current temperature coefficient of the supply. The meter amplifier has an additional current limiting feature which protects the meter movement against overloads. For example, if the meter range switch is set to the low current range while the supply is actually delivering a higher output current, the meter amplifier is driven into saturation, limiting the current through the meter to a safe value.

Figure 20B shows the meter connections when measuring output voltage. The range switch determines the amount of output voltage that is applied to the meter amplifier. In the higher voltage range (X VOLTS position) the IR drop across R_4 is the input to the amplifier. In the lower voltage range (X/10 VOLTS position) a 10 times larger fraction of the output voltage (drop across R_4 and R_5) is applied to the meter amplifier.

A16. PROTECTION CIRCUITS

Many methods for protecting the power supply itself and/or the load device are incorporated into hp power supplies.

a. Overcurrent and Overvoltage Protection

All hp semiconductor supplies are short-circuit-proof and can operate into any overload indefinitely without risk of internal damage. Moreover, overvoltage protection is also available if required during constant current operation. Hp's CV/CC or CV/CL automatic crossover circuitry (see paragraphs A8 and A9, respectively) is ideal for these purposes since it allows the user to set the current or voltage control to the maximum permissible output current or voltage as dictated by the particular load device connected to the supply.

b. Reverse Voltage Protection

Most hp supplies include a diode connected across the output terminals with reverse polarity. This diode, designated as CR_O in Figure 21, protects the output electrolytic capacitors and the series regulator transistors from the effects of a reverse voltage applied across the output terminals. For example, in series operation of two supplies, if the AC is removed from one supply, diode CR_O prevents damage to the unenergized supply which would otherwise result from reverse polarity voltage.

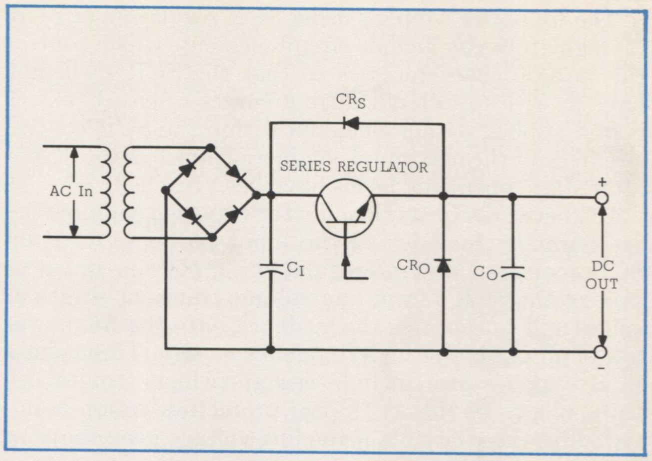


Figure 21. Protection Diodes.

Although CR_O normally is selected to have a current rating equal to or slightly greater than the current rating of its power supply, large energy sources placed across the output terminals with reverse polarity will result in its failure, usually leaving a short-circuit across the output terminals until CR_O is replaced. Such a replacement, however, brings attention to the fact that reverse energy flow is being forced through the output terminals so that a remedy can be accomplished.

Since series regulator transistors or driver transistors should not be caused to withstand reverse voltage, diode CR_S is included in most hp supplies. This diode protects the series transistors in parallel or Auto-Parallel operation if one supply of the parallel combination is turned on before the other. Normally, this would result in the output capacitor of the unenergized supply becoming charged while the rectifier capacitor is uncharged, thereby placing a reverse potential across the series regulator. However, the inclusion of CR_S allows the rectifier capacitor of the unenergized supply to be charged in parallel with the output capacitor—thus no reverse voltage can be placed across the series regulator.

c. SCR Rectifier and Preregulator Protection

With some power supplies, opening the remote programming path for an extended period of time may result in the necessity for additional protection circuits. Since opening the programming path is equivalent to inserting a very large value of programming resistance in place of R_P (see Figure 17), the power supply responds by increasing its output voltage to the highest voltage available from the rectifier. In the case of power supplies without a preregulator, this will result in no damage to the power supply, but the output voltage of SCR regulated and preregulated supplies could rise to a value considerably higher than the maximum output rating of the supply. However, hp SCR preregulator type supplies include a separate preregulator overvoltage limit (adjustable internally). With this circuit, any component failure within the main regulator loop (e.g., series transistor short, open voltage control or programming path, etc.) results in the maximum output of the supply being limited to this preset preregulator voltage limit. This limit is normally set at the factory at approximately 10% above the nominal output voltage rating.

The hp power supplies using SCR regulators or SCR preregulators also include circuit elements which control the turn-on characteristics so that the SCR's will not have to withstand large current surges when AC power is first applied. Other elements within the SCR control circuit limit the maximum conduction angle of the SCR's after static operating levels have been reached.

RC networks or semiconductor transient suppressors are normally included in the input power path of hp SCR regulated and preregulated supplies in order to protect the SCR's from line voltage transient surges or spikes and to suppress the feedback onto the AC power line of any spikes or high frequency energy. Three phase SCR supplies also include circuits which monitor all three phases of the AC input; protection action is initiated by these circuits if the line voltage goes above or below acceptable limits.

d. "Crowbar" Overvoltage Load Protection

If a series regulator transistor fails, it usually becomes a short circuit rather than an open circuit. The output voltage can then rise to the full rectifier value. Under these circumstances the normal current limit circuit (which utilizes the series regulating transistor) is no longer operative, and the load current is limited mainly by the load resistance.

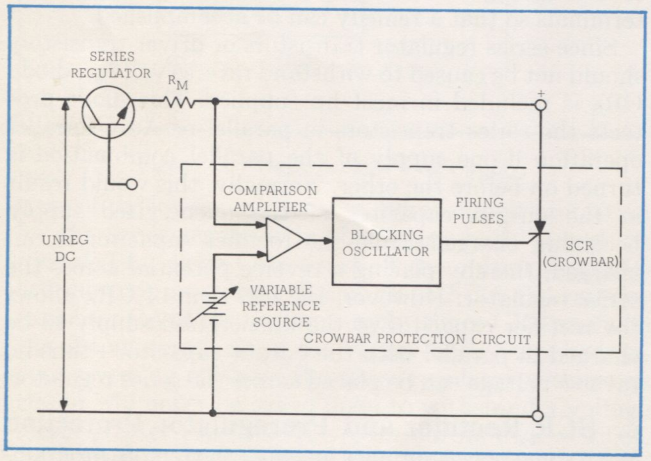


Figure 22. Typical "Crowbar" Overvoltage Protection Circuit.

Hp's "Crowbar" overvoltage protector, which operates independently of the power supply, monitors the output voltage of the supply. If the output exceeds a preset voltage threshold, an SCR "Crowbar" (connected across the output terminals of the supply) is triggered into the conducting state within 10 μseconds. A separate "Crowbar" overvoltage protection unit can be obtained for many hp supplies and is mounted externally on the supply being protected. The ICS Series of supplies, however, contains a built-in "Crowbar" device. These power supplies are designed for use with integrated circuits and other low voltage semiconductor devices. Whether the "Crowbar" protection circuit is mounted externally or internally the basic operating principles are the same.

Figure 22 shows a typical "Crowbar" protection circuit. The comparison amplifier continuously monitors the difference between the output voltage of the power supply and a variable reference voltage. If the output voltage exceeds the reference voltage an overvoltage condition exists, and the output of the comparison amplifier is of the polarity necessary to trigger the blocking oscillator. Once triggered, the blocking oscillator generates a stream of firing pulses to the gate of the SCR. When the SCR fires, the output becomes shorted, ultimately halting the firing pulses. However, the SCR remains in the conducting state until the output of the power supply is removed. Not shown on Figure 22 is additional test circuitry which permits the operator to verify that the "Crowbar" circuit is armed and ready without actually shorting the power supply or disrupting the power flow to the load.

A17. HIGH PERFORMANCE POWER SUPPLIES

The Harrison Division of Hewlett-Packard manufactures several types of high performance DC power supplies with specifications at least an order of magnitude superior to the normal well-regulated laboratory supply. Foremost among these are the STB (High Stability Bench) and CCB (Constant Current Bench) series of supplies.

a. High Stability DC Power Supply

The STB supplies are of the Constant Voltage/Current Limiting type; basic operation of these units is similar to that described in paragraph A9, with a few important exceptions. The critical components of the supply, including the zener reference diode for the voltage comparison amplifier and the low-level portions of the feedback amplifier, are enclosed in a temperature-controlled oven. Moreover, the less critical components which are not oven enclosed, are high quality components having low temperature coefficients. These techniques, together with the utilization of a high gain feedback amplifier, result in an exceptionally stable and well-regulated supply with a 0.1% programming accuracy.

b. High Performance Constant Current Power Supply

The Hewlett-Packard CCB Series is comprised of Constant Current power supplies with excellent regulation, ripple, and drift characteristics, as well as high speed programming capabilities. Special attention has been given to circuit details so that well regulated performance is maintained down to very low output currents—of the order of 1 μA and less!

(1) Major Improvements Over Standard Laboratory Supply

Figure 23 shows a simplified schematic of an improved performance Constant Current/Voltage Limiting power supply. Although many of the elements of Figure 23 are identical to those used in the standard constant current supply of Figure 11, there are two significant differences.

One of these is the inclusion of an auxiliary constant voltage supply shown in the upper portion of Figure 23. This self-contained supply is used to produce a constant programming current I_S which flows through R_Q, and also generates a guard voltage E_G across its output capacitor C_O. The guard potential is at all times exactly equal to the output voltage at the positive terminal of the main supply. (Note that because of the

O volt difference at the inputs of the auxiliary and current comparison amplifiers, $E_G = E_S = + E_{OUT}$.) The guard voltage is fed to a copper guard (depicted by a dotted line on Figure 23) that surrounds the positive output terminal and other critical circuitry. Since the positive output terminal is at the same potential as its guard, no leakage current can flow between the two points thus effectively creating a high resistance against leakage. Moreover, any leakage current that flows from the guard to some unguarded point in the circuit (such as the negative output terminal) must come from the auxiliary power supply and *not* from the main power supply output.

An added advantage of the guard potential is that it can be used to drive an internal (or external) voltmeter. Placing a voltmeter across the output terminals of a normal constant current supply degrades the load regulation and diminishes the load current. (This problem is explained and discussed more fully in Section C2, a, 5.) Attaching the voltmeter to the guard effectively isolates the voltmeter from the output terminals of the main supply, allowing the auxiliary supply to furnish the necessary meter current.

Another difference between the constant current circuit of Figure 23 and that shown on Figure 11, is that the *inboard* side of the current monitoring resistor serves as the common point in the circuit, rather than the outboard side of R_M or the positive terminal. This ensures that *only* the *output* current will flow through R_M, eliminating any offset currents due to programming or meter currents flowing through R_M. This enables the well regulated performance of this constant current supply to be maintained down to very low output current levels, while also increasing its output impedance.

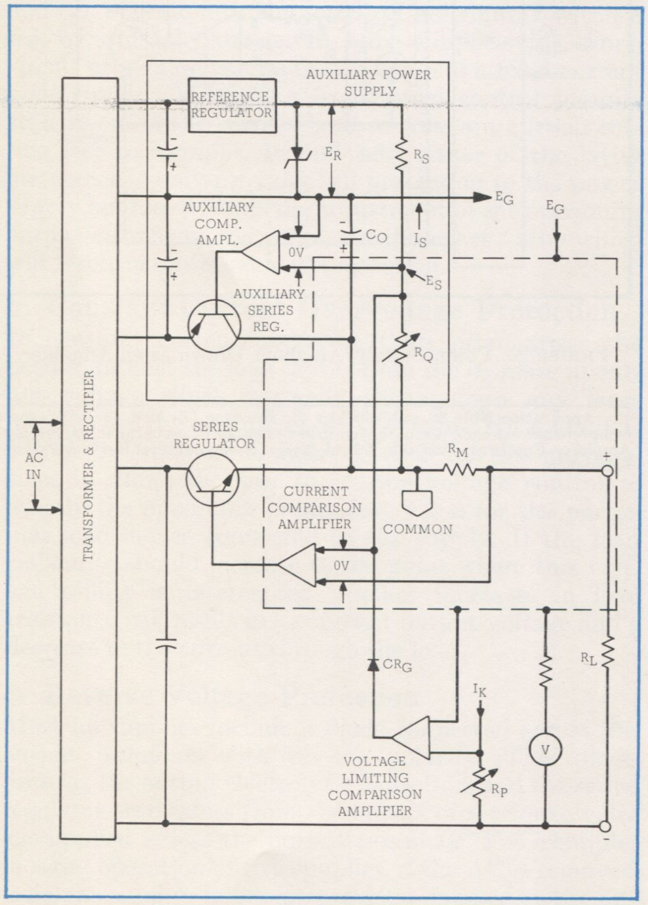


Figure 23. High Performance Constant Current Power Supply.

(2) Circuit Operation.

The operation of the current feedback loop portion of the supply is identical to that explained in paragraph A7 for the standard constant current supply. The loop maintains a constant output current by keeping the two inputs to the current comparison amplifier at equal potentials. One of these inputs is the voltage drop across the front panel control R_Q, and the other is the voltage drop across the current monitoring resistor R_M.

Note that rheostat R_Q serves as a dual purpose control; the IR drop across R_Q controls both the current comparison amplifier and the auxiliary comparison amplifier. Since the current feedback loop maintains the voltage drop across R_Q equal to the drop across R_M, the drop across R_Q is equal to the output voltage at the positive terminal with respect to the circuit common point. The output voltage is compared to the guard voltage by the auxiliary comparison amplifier and if a difference exists an error signal is fed to the auxiliary series regulator. The error signal causes the auxiliary regulator to change its conduction in the direction, and by the amount, necessary to maintain E_G equal to the output voltage.

The voltage limiting comparison amplifier monitors the difference between the output (guard) voltage and the voltage across the front panel voltage limit control R_P. If the guard voltage exceeds the voltage setting of R_P the voltage limit has been exceeded, and the output of the voltage limiting comparison amplifier forward biases gating diode CR_G. The voltage limiting feedback signal is now allowed to reduce the voltage drop across current control R_Q, and the current comparison amplifier produces the feedback control signal necessary to reduce the conduction of the series regulator so that the output voltage does not exceed the voltage limit.

Using the current comparison amplifier in both the constant current and voltage limiting modes of operation has the advantage of reducing output surge currents during rapid load changes. Under unloaded conditions when a normal power supply is in the voltage limiting mode the current comparison amplifier is saturated and has no effect on the operation of the series regulator. When a finite load is placed across the supply, a certain period of time is required before the current comparison amplifier can be driven out of saturation. This results in output current surges. This effect is greatly reduced by allowing the current comparison amplifier to function under all load conditions.

A18. POWER SUPPLY/AMPLIFIER DESIGN

In many applications a power supply is required which has a faster programming speed than can be obtained with modifications of standard power supply designs (see paragraph B5e for limitations of remote programming speed). Still other applications require a power supply which can be controlled continuously through zero over a wide span in either a positive or negative direction. These needs have been met with a design which arises directly from the operational amplifier concept of a power supply (paragraph A3). The resulting instruments, designated Power Supply/Amplifiers (PS/A), not only meet the objectives of high speed programming and output continuously variable through zero, but also are useful as direct-coupled amplifiers with very low output distortion, and bandwidth from DC to 20 kHz.

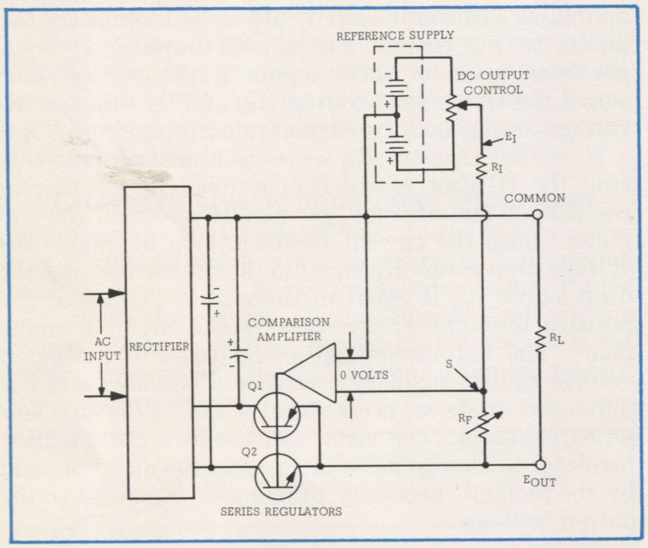


FIGURE 24. Power Supply/Amplifier Drawn as a Power Supply.

Figure 24 shows a simplified representation of this instrument drawn as a power supply. Two series transistors are used in a complementary configuration, one transistor being connected to a negative rectifier and the other to a positive rectifier. These transistors in turn are controlled by the normal comparison amplifier configuration, with the exception that a bi-polar reference supply is used, thus making the voltage E_I capable of being continuously varied through zero. The output voltage is given by the relation $E_O = -\frac{R_F}{R_I} E_I$.

Figure 25 shows the same circuit redrawn as an amplifier. Transistors Q_1 and Q_2 are arranged in a single ended push-pull configuration, and the operational amplifier aspects are more readily suggested by the configuration shown. In Figure 25 an external signal input has been substituted for the internal reference supply shown in Figure 24.

Not shown in either diagram are the circuit details of a special output sensing circuit which enables feedback stability to be insured regardless of the angle of the load imposed. The rear barrier strip on PS/A instruments includes numerous control terminals to facilitate all modes of operation including linear programming using resistance input remote programming using DC or AC voltage input (amplifier operation), etc. While inherently a constant voltage output device, any PS/A Series instrument can readily be adapted to constant current applications by adding one external current monitoring resistor in a manner similar to that discussed in paragraph D5, thus making the instrument useful as a resistance or voltage controlled constant current output power supply or amplifier.

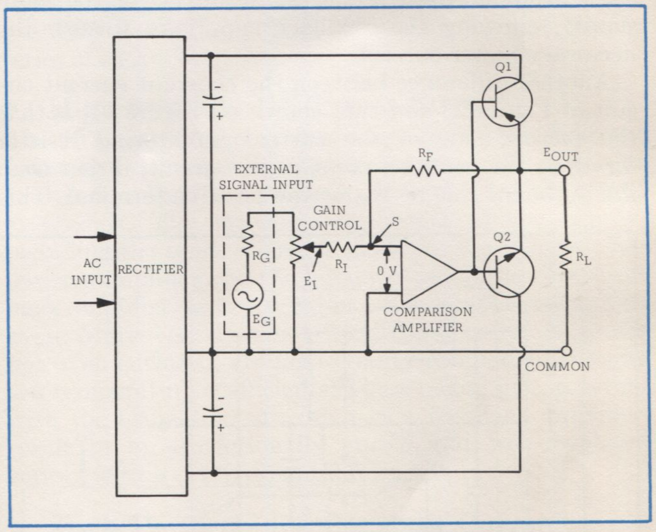


FIGURE 25. Power Supply/Amplifier Drawn as an Amplifier.

Application Note 82, published by the Harrison Division, presents a more comprehensive description of the features and applications of the Power Supply/Amplifier. Copies are available, free of charge, from your local Hewlett-Packard field office.

B. OPERATING FEATURES

B1. NO OVERSHOOT ON TURN-ON, TURN-OFF, OR AC POWER REMOVAL

Extra design precautions have been taken on all hp DC power supplies to insure that there is no transient overshoot of the output voltage when the power supply is turned on or off or if AC power is accidentally removed. To avoid turn-on overshoot the bias and control circuits must come up more rapidly than the rectifier voltage, whereas to avoid turn-off overshoot the bias and control circuits must remain operating in order to restrain the conduction of the series regulator until after the energy stored in the rectifier capacitor has largely dissipated.

B2. PROTECTION FEATURES

Many different types of protection circuits are included in hp power supplies to protect the power supply itself and/or the load device connected to the output terminals of the supply.

a. Short-Circuit Protection

All hp semiconductor supplies are short-circuit-proof and can operate into any overload indefinitely without risk of internal damage. In some supplies this short-circuit protection results from the use of a fixed current limit circuit. In others a front panel control permits adjustment of the current limit or constant current setting (see paragraphs A8 and A9); either of the latter methods not only provides full protection to the power supply but also permits the adjustment of the maximum output current of the supply to the exact value which will result in optimum load protection.

b. Constant Current Overvoltage Protection

In constant current operation there often arises the need to protect the load device from the increase in output voltage which normally accompanies any large increase in the resistance of the load. Hp's CV/CC automatic crossover circuitry is ideal for this purpose, since it allows the user to set the voltage control to exactly the maximum permissible value for the particular load device connected to the supply. If the load resistance should increase to the point where this voltage ceiling is intercepted, further increases in load resistance will result in a constant output voltage and a decrease in the current through the load.

c. Reverse Voltage Protection

Most hp supplies include a diode connected across the output terminals with reverse polarity. This diode protects the output electrolytic capacitors and the series regulator transistors from the effects of a reverse voltage applied across the output terminals. For example, in series operation of two supplies, if the AC is removed from one supply, the diode prevents damage to the unenergized supply which would otherwise result from a reverse polarity voltage. Further information on the circuit principles of the reverse voltage diode are given in paragraph A16b.

Since series regulator transistors or driver transistors cannot withstand reverse voltage, another diode is connected across the series transistor in most hp supplies. This diode protects the series transistors in parallel or Auto-Parallel operation if one supply of the parallel combination is turned on before the other.

d. Overvoltage Load Protection—"Crowbar"

If a series regulator transistor fails, it usually becomes a short circuit rather than an open circuit. The output voltage can then rise to the full rectifier value. Under these circumstances the normal current limit circuit (which utilizes the series regulating transistor) is no longer operative, and the load current is limited mainly by the load resistance. In spite of a conservative engineering approach to the rating of power transistors, and in spite of hp's unique design techniques which assure that series transistors operate at unusually low voltage and power levels, the possibility of series transistor failure, while small, still remains.

No matter how small this possibility, an expensive or irreplaceable load device may require positive protection against the statistics of power transistor failure. Hp's "Crowbar" overvoltage protector, which is completely independent of the power supply, monitors the output voltage of the supply. If the power supply exceeds a preset voltage threshold, an SCR "Crowbar" (connected across the output terminals of the supply) is triggered into the conducting state within 10 μseconds. An operator can at any time verify that this overvoltage protector is armed and ready without actually shorting the power supply or discontinuing power flow into the load.

The ICS Series, power supplies designed for use with integrated circuits, micromodular circuits, and other low voltage semiconductor circuitry, incorporates a built-in overvoltage load protection "Crowbar." The operating feature and principles of the built-in model are similar to the external "Crowbar."

Additional information on the circuit principles of the "Crowbar" are given in A16d.

B3. REMOTE ERROR SENSING

Normally, a power supply achieves its optimum load and line regulation, its lowest output impedance, drift, ripple and noise, and its fastest transient recovery performance at the power supply output terminals (Figure 26A). If the load is separated from the output terminals by any lead length, some of these performance characteristics will be degraded at the load terminals - an amount proportional to the impedance of the load leads compared with the output impedance of the power supply.

Some idea of how easily even the shortest leads can degrade the performance of a power supply at the load terminals can be obtained by comparing the output impedance of an hp power supply (typically of the order of 1 milliohm or less at DC and low frequencies) with the resistance of the various wire sizes listed in the following chart.

AWG (B & S) WIRE SIZE	Annealed Copper Resistance @ 20°C milliohms/ft.	Nominal current rating (amps)*
22	16.1	5
20	10.2	7
18	6.39	10
16	4.02	13
14	2.53	20
12	1.59	25
10	0.999	40
8	0.628	55
6	0.395	80
4	0.249	105
2	0.156	140
0	0.0993	195
00	0.0779	260

*Single Conductor in Free Air @ 30°C with rubber or thermoplastic insulation.

With remote error sensing (Figure 26B), a feature included on nearly all hp power supplies, it is possible to connect the feedback amplifier directly to the *load* terminals so that the regulator performs its function with respect to these load terminals rather than with respect to the output terminals of the power supply. Thus, the voltage at the power supply output terminals shifts by whatever amount necessary to compensate for the IR drop in the load leads, thereby retaining the voltage at the load terminals constant.

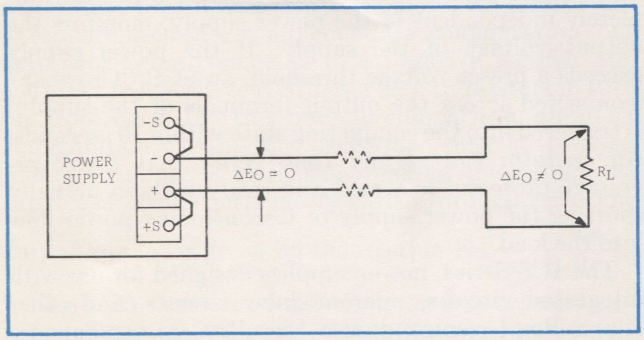


Figure 26A. Regulated Power Supply with Local (normal) Sensing.

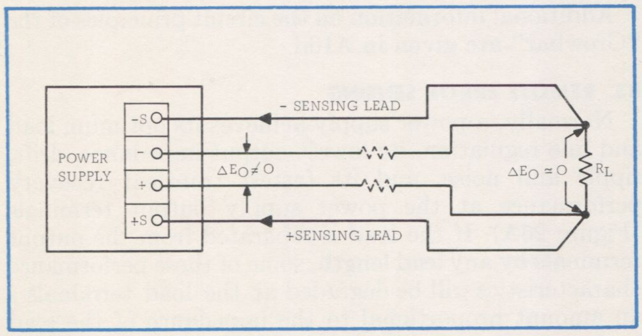


Figure 26B. Regulated Power Supply with Remote Error Sensing.

Figure 27 shows the voltage comparison amplifier circuit details of a power supply having remote sensing capability. By comparing Figure 27 with Figure 8 it can be seen that the modifications to a standard design are minor, since remote error sensing simply involves operating the input comparison amplifier Q_1 with reference to the load terminals instead of the output terminals of the power supply.

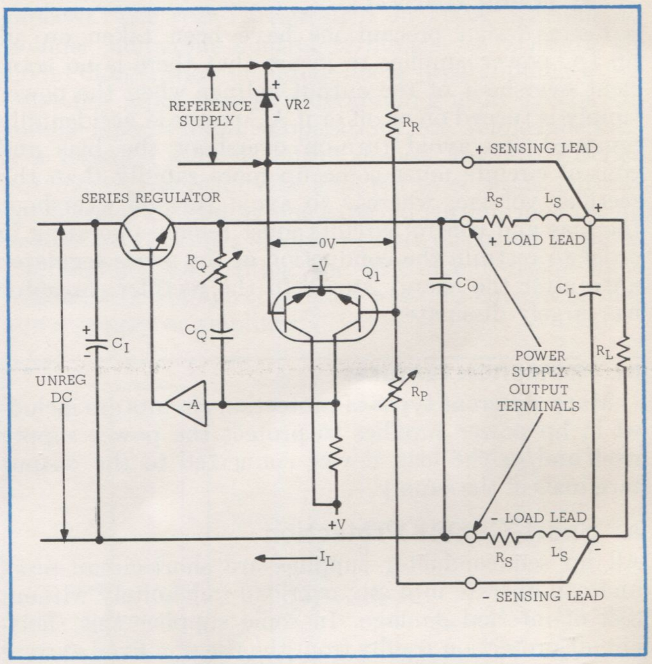


Figure 27. Effect of Load Leads on Remote Error Sensing.

Remote sensing operation of power supplies with small and moderate output current ratings is readily accomplished for load devices separated from the power supply by reasonable lead lengths. With medium or high current supplies feeding loads which are removed from the output terminals of the supply by a considerable length of wire, added precautions must be observed in order to obtain satisfactory remote sensing operation. The IR drop in the positive* load lead must be kept to less than 1 volt; otherwise resulting shifts in bias potentials in some models will prevent the proper operation of the voltage regulator and/or current limit circuit. There is also a practical limit to the voltage drop which can be allowed in the negative load lead, since the voltage drop occurring in either the positive or negative current carrying lead subtracts from the available output voltage of the power supply. Thus, a power supply which is normally rated for a maximum output of 36 volts can be used to deliver up to 32 volts at the load terminals if the wire sizes chosen result in a 1 volt drop in the positive load lead and a 3 volt drop in the negative load lead at maximum output current.

Since the current flowing in the sensing leads amounts to only several milliamperes, smaller wire sizes can be used for connecting the sensing terminals of the power

---

*All diagrams and concepts are based on a power supply employing NPN power transistors and a positive common circuit configuration. For negative common supplies, references in this paragraph to positive and negative output leads must be interchanged.

supply to the load. However, care must be taken to shield the sensing leads, since any voltage pickup on these leads increases output ripple and noise. A shielded pair should be used for the sensing leads, with one end of the shield connected to the power supply ground terminal and the other end of the shield left unconnected.

It is common in remote sensing applications to utilize a large filter capacitor at the load. Figure 27 indicates, however, that the addition of this load capacitor results in a Pi filter (in conjunction with the output capacitor and the inductance of the load leads). The phase shift associated with this filter is inside the power supply feedback loop. *Extreme* remote sensing applications can in some cases affect the overall feedback stability of the loop and cause oscillation. In many cases readjusting the transient recovery control R_Q will restore normal operation. In other cases it will be necessary to eliminate C_O so that the Pi filter is reduced to an L filter. It is important for feedback stability that the *load* capacitor have a low impedance at all frequencies, and considerable care must be exercised in selecting a suitable capacitor C_L, since using an electrolytic of inferior quality compared with the output capacitor normally present on Hewlett-Packard power supplies will make it difficult to achieve feedback stability. It is therefore recommended in extreme remote sensing applications that the electrolytic capacitor C_O be physically removed from the power supply and placed at the load terminals as C_L, the load filter capacitor. Once this has been accomplished it will be possible to eliminate any residual tendency toward oscillation by readjusting R_Q. Even following these precautions, the load transient performance with remote sensing is degraded compared to transient performance with normal sensing and short load leads. Also the power-supply user must always remember that remote sensing can only be accomplished with respect to a *single* terminal pair. If the power supply is being used to feed a large number of load terminals in parallel, or even a pair of load bus bars, remote sensing can at best provide optimum performance only at a single pair of load terminals, or at one pair of points on the bus bar.

In spite of these limitations, remote sensing does permit greatly improved power supply performance to be achieved at a remote load.

B4. AUTOMATIC ERROR SENSING

Normally, a power supply cannot provide optimum regulation at the front terminals when it is wired for rear terminal sensing, nor can it provide optimum regulation at the rear terminals when it is wired for front terminal sensing. In some cases, provision is made for strapping the sensing leads for either front or rear terminal operation.

However, hp's small laboratory type power supplies feature Automatic Error Sensing, whereby the supply senses at the front terminals if the load is attached to the front terminals, and at the rear terminals if the load is attached there—with no necessity for switching or restrapping arrangements.

Figure 28 illustrates the simple circuit technique which results in Automatic Error Sensing. The regulated output of the series regulator is fed into the front terminals, while the sensing is fed to the rear output terminals, and wire of adequate current handling capability is connected between these two terminal pairs. Thus, if the load resistance is attached to the rear terminals, error sensing is accomplished at those terminals. On the other hand, if the load is attached to the front terminals, the heavy leads which connect the front and rear output terminals become extensions of the feedback sensing leads, and sensing is accomplished at the front terminals. Thus, a significant operating convenience is obtained with no increase in circuit complexity or cost.

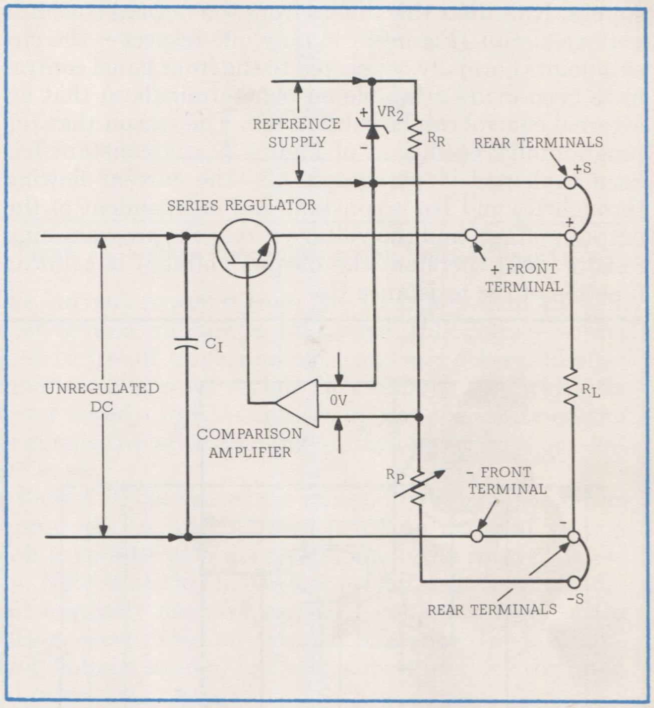


Figure 28. Constant Voltage Regulator with Automatic Error Sensing.

B5. REMOTE PROGRAMMING

Remote programming, a feature found on most hp power supplies, permits control of the regulated output voltage or current, by means of a remotely varied resistance or voltage.* Remote programming is generally accomplished by restrapping the rear terminal strip, disabling the front panel control and connecting the remote control device to rear terminals.

There are four basic types of remote programming:

(1) controlling the constant voltage output using a remote resistance,
(2) controlling the CV output using a remote voltage,
(3) controlling the constant current output using a remote resistance, and
(4) controlling the CC output using a remote voltage.

a. Constant Voltage Remote Programming with Resistance Control

Using an external resistor and/or rheostat, the output voltage can be set to some fixed value, or made con-

---

*A remotely varied current can also be used to control the regulated output voltage or current. This method of programming is discussed in Application Note 82.

tinuously variable over the entire output range, or made variable over some narrow span above and below a nominal value.

Figure 29 illustrates the essential circuit aspects of resistance programming of a constant voltage power supply. Note that this differs from the normal constant voltage circuit (Figure 8) in only one respect—the circuit points normally connected to the front panel control have been made available on rear terminals so that an external control can be substituted. The reason that the programming coefficient of Figure 29 is a constant has been explained in paragraph A2—the current flowing through R_P and R_R is constant and independent of the output voltage, and the voltage across the programming resistor (and therefore the output voltage) is a linear function of the resistance R_P.

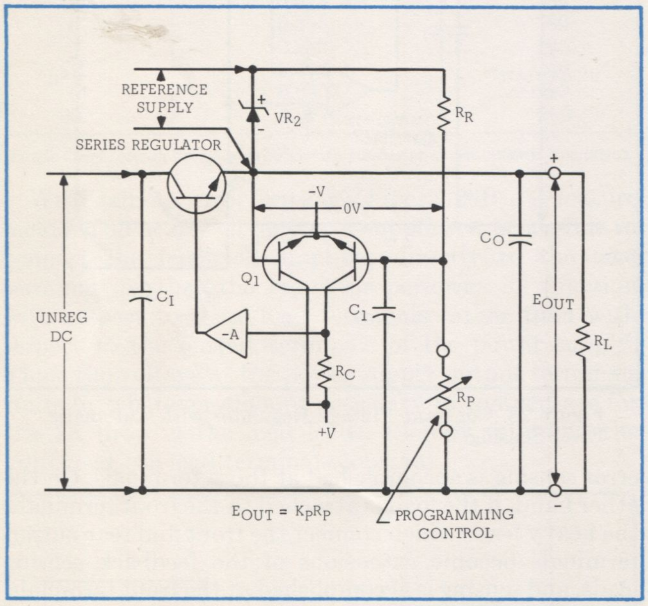


Figure 29. Constant Voltage Supply with Resistance Programming.

Programming a power supply with a 200 ohms/volt programming coefficient to an output level of 30 volts would require an R_P of 6K. The power supply will force through this programming resistor a 5 ma constant current (±2%) thus resulting in 30 volts across it, and 30 volts across the power supply output terminals.

The power consumed in the programming resistor can be readily determined by remembering that the programming current is the inverse of the programming coefficient K_P. Using the same example, a 200 ohms/volt programming coefficient corresponds to 5 ma programming current, and for 30 volts output (and thus 30 volts across the programming resistor), 150 milliwatts will be dissipated in R_P. A stable programming resistor must be used, since a percentage change in its resistance value will result in the same percentage change in the output voltage of the power supply being controlled.

In order to avoid short term temperature-dependent shifts in the resistance value (and hence the power supply output voltage) the programming resistor used should have a temperature coefficient of 20 ppm/°C or less and a wattage rating in excess of ten times the actual dissipation. Thus, in the previous example, the programming resistor should have a minimum power rating of 1.5 watts.

The leads connecting the programming resistor to the power supply should be kept short and away from stray electric fields. Any ripple which is picked up on the programming leads becomes part of the command voltage for the power supply regulator and is therefore reproduced on the output terminals; the leads to the programming resistor should therefore be twisted or, preferably, shielded two-wire cable should be used, with the shield being connected at the power supply end to the ground terminal—the other end of the shield being left unconnected.

Using remote programming, several different values of fixed output voltage can be set up with resistors and a switch, so that the output voltage of the supply can be switched to any pre-established value with a high degree of reproducibility. Figure 30 illustrates several switching schemes which can be used in conjunction with resistance programming of power supplies. Suppose it is desired to program a supply having a programming coefficient K_P of 200 ohms/volt to any of three values—5 volts, 10 volts, and 15 volts; the circuit of Figure 30A is a typical configuration. However, if a break-before-make switch is used in the configuration of Figure 30A, there will occur for a short interval during the switching action a very high resistance between the two programming terminals, and the power supply during that

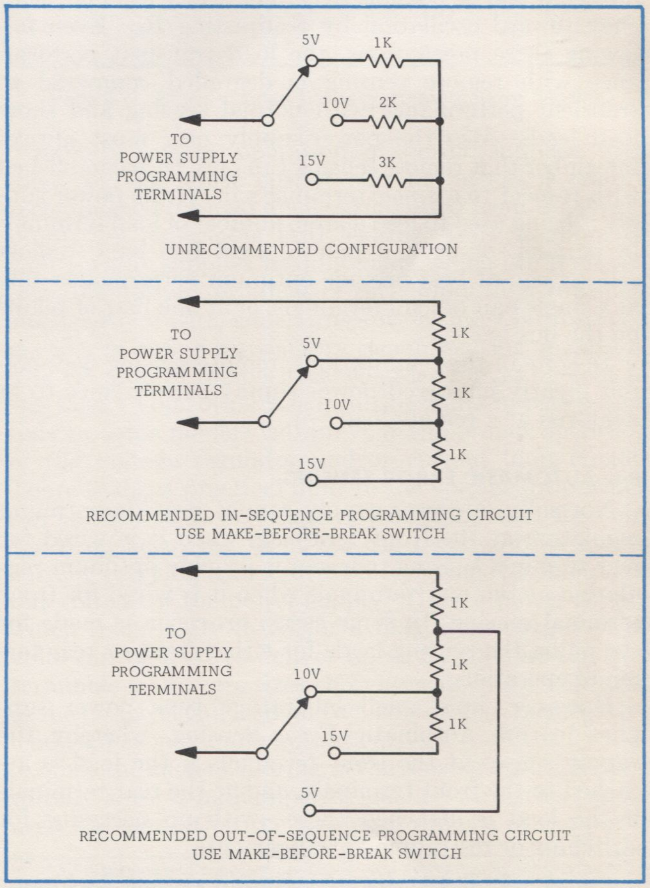


Figure 30. Remote Programming Switching Circuits.

interval will raise its output voltage in response to this high resistance input.

To eliminate this output overshoot corresponding to an infinite programming resistance, a make-before-break switch can be employed. However, this solution has the disadvantage that during the short interval when the swinger of the switch is contacting two switch terminals, two programming resistors will momentarily be paralleled across the power supply programming terminals, and the supply will for this short interval seek an output voltage which is *lower* than either the initial or the final value being programmed. This output undershoot increases the time required for the supply to settle to its new value.

The switching circuit of Figure 30B, using a make-before-break switch, eliminates both the overshoot and the undershoot problems associated with Figure 30A, since when rotated clockwise the resistance value between the two programming terminals will go directly from 1000 to 2000 ohms, and then from 2000 to 3000 ohms.

It appears at first glance that the circuit of Figure 30B also has one drawback—namely, the output voltage must always be switched in ascending or descending sequence. As Figure 30C shows, however, the same voltage divider can have its tap points returned to the switch contacts in any sequence whatever, thus permitting output voltage values to be programmed in any desired order without overshoot or undershoot.

In some applications it is possible for the programming switching circuits to be opened accidentally, thus causing the output voltage to rise to some value higher than the maximum voltage rating of the supply. With some loads this could result in serious damage. To protect these loads from accidental opening of the remote programming leads, a zener diode may be placed directly across the power supply programming terminals, this zener diode being selected to have a breakdown voltage equal to the maximum power supply voltage which can be tolerated by the load. Thus, if the programming terminals open, the programming current will cause the zener diode to break down, and the output voltage will be limited to the zener diode voltage. Such a zener diode must be capable of dissipating a power equal to the product of its breakdown voltage times the programming current I_P.

b. Constant Voltage Remote Programming with Voltage Control

Instead of controlling a power supply by means of a programming resistance, it is possible to control the output of any hp remotely programmable supply with an input voltage. Thus, the power supply becomes a low frequency DC amplifier. Paragraph B5e stresses the bandwidth and speed of response aspects of this configuration, whereas this section deals with the method of control.

Two distinct methods can be employed to voltage program an hp regulated DC power supply. The first method, shown in Figure 31, requires that the external voltage be exactly equal to the desired output voltage.

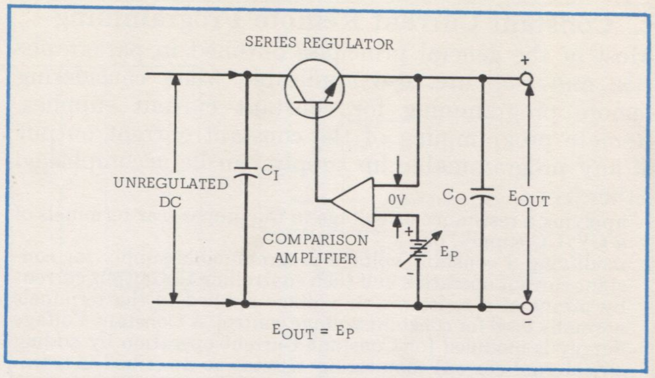


Figure 31. Voltage Programming with Unity Voltage Gain.

The current required from the voltage source E_P is at most several milliamps. Of course, this voltage source must be free of ripple and noise and any other undesired imperfections, since within the regulator bandwidth the power supply will attempt to reproduce on its output terminals the programming voltage input on a one-for-one basis.

Figure 32 illustrates the method by which the power supply can be programmed using an external voltage with a voltage gain dependent upon the ratio of R_P to R_R. Note that this method is no different from the circuit normally used for constant voltage control of the output except that an external reference (the programming voltage source) has been substituted for the internal reference.

On most hp supplies terminals have been brought out to the rear barrier strip so that the connections shown in Figure 32 can be accomplished without any internal wiring changes. In all remotely programmable hp power supplies the summing point S is made available, and the configuration of Figure 32 can always be accomplished using the external programming voltage source and external precision wirewound resistors R_P and R_R. (R_R should not exceed 10K.) As indicated by the equation in Figure 32, R_P can be selected so that the resulting voltage gain is less than or greater than unity. It is possible to use the front panel control already present in the supply as the voltage gain control, R_P.

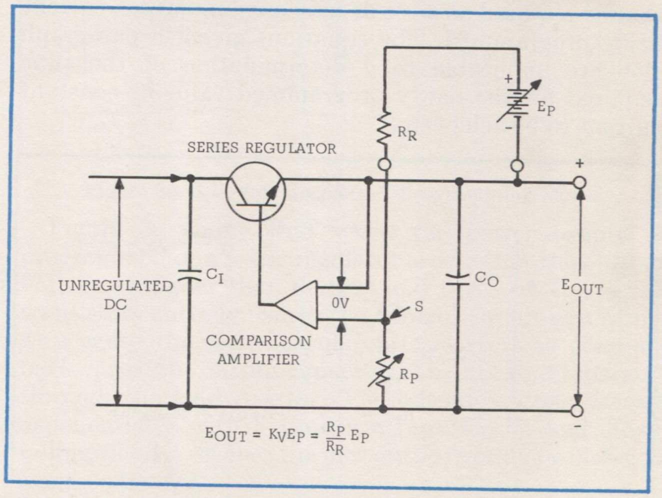


Figure 32. Voltage Programming with Variable Voltage Gain.

c. Constant Current Remote Programming

Most of the general principles outlined in paragraphs B5a and B5b are also applicable when considering remote programming for constant current supplies. Remote programming of the constant current output of any programmable hp supply can be accomplished either by:

1. applying a resistance or voltage to the proper rear terminals of a CV/CC supply, or
2. modifying a constant voltage programmable supply for constant current operation and then controlling the output current by means of a resistance or voltage applied to the terminals normally used for constant voltage control. A Constant Voltage Supply is modified for Constant Current operation by adding an external current monitoring resistor as described in paragraph D5.

Method 1 is used with any Constant Current or Constant Voltage/Constant Current hp power supply, while method 2 is used for any remotely programmable Constant Voltage/Current Limiting supply.

It is important to notice that when method 1 is used, the normal current limiting protection, which is dependent upon the constant current setting of a CV/CC power supply, will be negated if the constant current programming terminals are accidentally opened. Particular care must be taken in the design of the constant current programming network to insure that no open circuit condition can exist *even for a short interval of time*, because such open circuit conditions will result directly in the power supply delivering an output current in excess of its rating—with almost certain destruction of the series regulating components and other components within the regulator circuitry. Therefore, any constant current programming mechanism involving switches *must use make-before-break switches*.

A good safety precaution, which can be followed only if non-linear programming of the output current can be tolerated, is to place directly across the constant current programming terminals of the power supply a control resistance corresponding to the maximum output current. The remote switching mechanism can then be used to shunt this "safety" resistor to the degree necessary to achieve any lower values of output current.

The speed of response associated with constant current programming is determined by the output *voltage* change required as a result of change in output current being programmed. The equations given in paragraph B5e are applicable to a determination of the time required for the newly programmed value of constant current to be achieved.

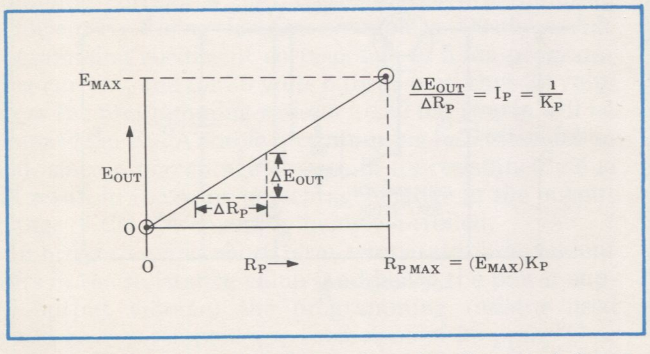


Figure 33. "Ideal" Remote Programming Characteristic.

d. Remote Programming Accuracy

Figure 33 shows the relationship between programming resistance and output voltage for a power supply with perfect remote programming. Zero ohms across the programming terminals results in exactly zero volts out, and all other values of programming resistance result in the output voltage predicted by the programming coefficient K_P.

As Figure 34 indicates, all power supplies deviate somewhat from the ideal. The application of a short-circuit across the programming terminals results in an output voltage which is slightly different from zero (typically between +20 millivolts and —50 millivolts). While the linearity of the programming characteristic is nearly perfect, the overall slope may differ from the value predicted by the programming coefficient by from 1% to 5%. The fact that this slope is extremely linear can be utilized in improving the absolute accuracy in programming a supply, for if we can pinpoint two points on this straight line segment, all other points are thereby determined. The two points which are the easiest (and best) to fix are the points corresponding to zero output voltage and the maximum output voltage. If these two points are successfully relocated, the graph of Figure 34 can be changed into one closely approximating that shown in Figure 33, which is the characteristic of an ideal supply having perfect programming accuracy.

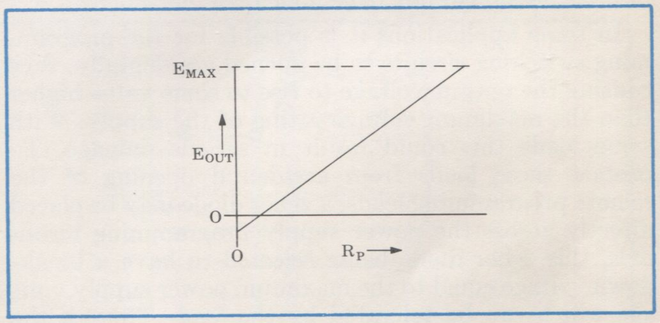


Figure 34. Practical Remote Programming Characteristic.

Regardless of programming coefficient, an ideal programmable supply having absolute programming accuracy will deliver zero volts with zero programming resistance. Thus, the first step in improving the programming accuracy of the supply of Figure 34 is to short the programming terminals and note the output voltage. Normally, this voltage will be slightly negative. If this is not the case the differential amplifier transistors can be interchanged; the output voltage with zero programming resistance will then, in most cases, become slightly negative. In some supplies, an internal control is provided for adjusting this zero offset voltage. (If a slightly negative output voltage with a zero programming resistance cannot be obtained by interchanging the differential amplifier transistors or adjusting a zero offset control, the factory should be contacted for further instructions.)

Having achieved a negative output voltage with zero programming resistance, it is now possible to insert permanently, a small resistor in series with the programming leads, this value of resistance being just sufficient to bring the output voltage up to exactly zero volts.

One point of the ideal programming characteristic has now been established. Next, the slope of E_{OUT} versus R_P characteristic must be adjusted so that this straight line will pass through the maximum output voltage with the proper value of programming resistance. Assume, for example, that we are adjusting a power supply which has a programming coefficient of 200 ohms per volt and a maximum output voltage of 20 volts. Having inserted *internally* a series programming resistance of sufficient value to bring the output voltage to zero volts with zero ohms *external* programming resistance, the next step would be to attach a precision 4000 ohm resistor across the programming terminals and adjust the programming current so that the output voltage would equal exactly 20 volts. In some supplies this programming current can be adjusted by means of an internal pot. In most cases, however, it will be necessary to "trim-up" a precision resistor (by means of shunt resistors) which determines the programming current. (This resistor will be found to be connected between the zener reference diode and the more positive of the two remote programming terminals.) Having adjusted this constant current, it may be necessary to go back once again and make a minor readjustment of the zero output crossing point by shorting the remote programming terminals and trimming the *internal* programming resistance (or offset control adjustment) to obtain exactly zero volts.

Once a power supply has its programming characteristic aligned "perfectly" in accordance with the characteristic shown in Figure 33, this alignment will retain an absolute accuracy within a tolerance found by adding the power supply specifications for:

a. load regulation
b. line regulation
c. (temperature coefficient) x (ambient temperature change)
d. stability

Any change in the load resistance, input line voltage, ambient temperature, or warmup time can be expected to cause slight variations in the output voltage of the supply even though the value of the programming resistance has not been altered. The capability for remote programming accuracy therefore increases with improvements in the four specifications mentioned, and high stability power supplies are capable of greater long-term programming accuracy than standard supplies.

e. Remote Programming Speed

A constant voltage regulated power supply is normally called upon to change its output *current* rapidly in response to load resistance changes. In some cases, however, notably in high speed remote programming applications and constant current applications involving rapidly changing load resistance, the power supply must change its output *voltage* rapidly. If the power supply does *not* employ a preregulator, the most important factor limiting the speed of output voltage change is the output capacitor and load resistor.

The equivalent circuit and the nature of the output voltage waveform when the supply is being programmed upward are shown in Figure 35. When the new output is programmed, the power supply regulator circuit senses that the output is less than desired and turns on the series regulator to its maximum value I_L, the current limit or constant current setting. This constant current I_L charges the output capacitor C_O and load resistor R_L in parallel. The output therefore rises exponentially with a time constant R_LC_O toward a voltage level I_LR_L, a value higher than the new output voltage being programmed. When this exponential rise reaches the newly programmed voltage level, the constant voltage amplifier resumes its normal regulating action and holds the output constant. Thus, the rise time can be determined using a universal time constant chart or the formula shown in Figure 35.

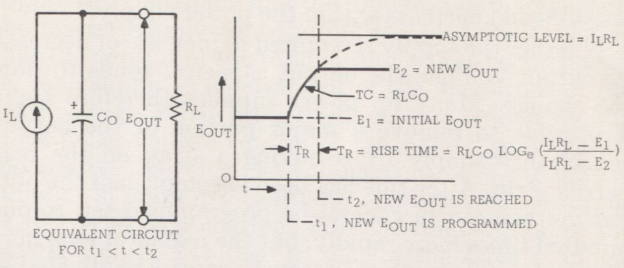


Figure 35. Speed of Response—Programming Up.

If no load resistor is attached to the power supply output terminals, then the output voltage will rise linearly at a rate of $\frac{C_O}{I_L}$ when programmed upward, and $T_R = \frac{C_O\,(E_2 - E_1)}{I_L}$, the shortest possible up-programming time.

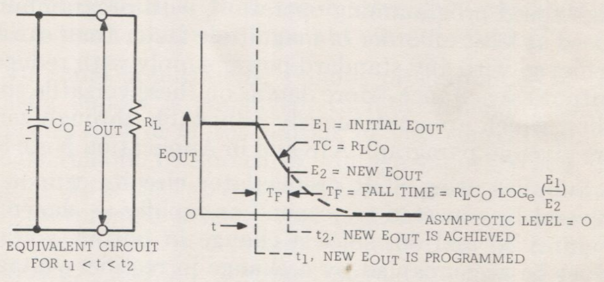


Figure 36. Speed of Response—Programming Down.

Figure 36 shows that when the power supply is programmed down, the regulator senses that the output voltage is higher than desired and turns off the series transistors entirely. Since the control circuit can in no way cause the series regulator transistors to conduct backwards, the output capacitor can only be discharged through the load resistor. The output voltage decays exponentially with a time constant R_LC_O, and stops falling when it reaches the new output voltage which has been demanded.

If no load resistor is attached to the power supply output terminals, the output voltage will fall slowly, the output capacitor being discharged only by small bleed resistors and currents within the power supply.

Whether the supply is required to increase or decrease its output voltage, the output capacitor tends to slow the change. Many hp power supplies therefore make it possible to remove a major portion of the output capacitance simply by removing a strap on the rear barrier strip. After this has been accomplished the output voltage can in general be programmed ten to one hundred times more rapidly, but the regulator loop may need to have its transient recovery control readjusted so that the supply does not oscillate under certain load conditions.

Beyond a certain point, further reduction in the size of the output capacitor C_O will not result in greater speed of programming, since other power supply circuit elements will eventually limit the maximum rate of change of the output voltage. For example, C_1 of Figure 29 eventually limits the speed of programming, but reduction or elimination of this capacitor would degrade the ripple performance. Thus, high speed programming applications can involve special circuit considerations which ultimately lead to a distinctly different power supply design.

Since up-programming speed is aided by the conduction of the series regulating transistor, while down-programming normally has no active element aiding in the discharge of the output capacitor, laboratory power supplies normally program upward more rapidly than downward. In most hp laboratory power supplies, however, a special transistor circuit provides for the more rapid discharge of the output capacitor for down-programming. With this circuit and the unstrapping of the major portion of the output capacitance, these laboratory power supplies have up and down programming speeds of 1 MS.

The PS/A Series provides ultimate performance in high speed programming operation, with programming speed at least an order of magnitude faster than can be achieved with any standard power supply with reduced output capacitance. More details on these versatile supplies, which are continuously adjustable through zero, are given in paragraph A18 and in Application Note 82.

Supplies using SCR preregulator circuits cannot in general be expected to respond as rapidly as shown in Figures 35 and 36, since a change in output voltage must be accompanied by a change in rectifier voltage; the large value of the rectifier filter plus protection circuits within the SCR preregulator, prevent the rectifier voltage from changing rapidly.

B6. PARALLEL OPERATION

The operation of two constant voltage power supplies in parallel is normally not feasible because of the large circulating current which results from even the smallest voltage difference which inevitably exists between the two low impedance sources. However, if the two power supplies feature CV/CC or CV/CL automatic crossover operation, then parallel operation is feasible, since the supply with the higher output voltage setting will deliver its constant current or current limited output, and drop its output voltage until it equals the output of the other supply, which will remain in constant voltage operation and only deliver that fraction of its rated output current which is necessary to fulfill the total load demand. For example, if two CV/CC power supplies each rated for 10 amperes were connected in parallel across a 15 amp load with one of the supplies set for 30.0 volts and the other supply set for 30.1 volts, the 30.1 volt supply would deliver 10 amperes as a constant current source, thus dropping its output voltage to 30.0 volts. The second supply would continue to act as a constant voltage source delivering 5 amps at the 30.0 volt level.

B7. AUTO-PARALLEL OPERATION

Auto-Parallel, or automatic parallel operation of power supplies permits equal current sharing under all load conditions, and allows complete control of the Auto-Parallel ensemble utilizing only the controls of the master supply.

Figure 37 illustrates the circuit principle involved. The master supply operates in a completely normal fashion and may be set up for either constant voltage or constant current operation as required. The slave supply employs its regulator circuit to compare the voltage drop across the current monitoring resistor of the master supply with the voltage drop across the current monitoring resistor of the slave supply, and adjusts the conduction of the series regulator in the slave supply so that these two IR drops are held equal. Therefore, with equal values of current monitoring resistors in the master and slave supplies, the output current contribution will always be equal regardless of the output voltage or current requirement of the load.

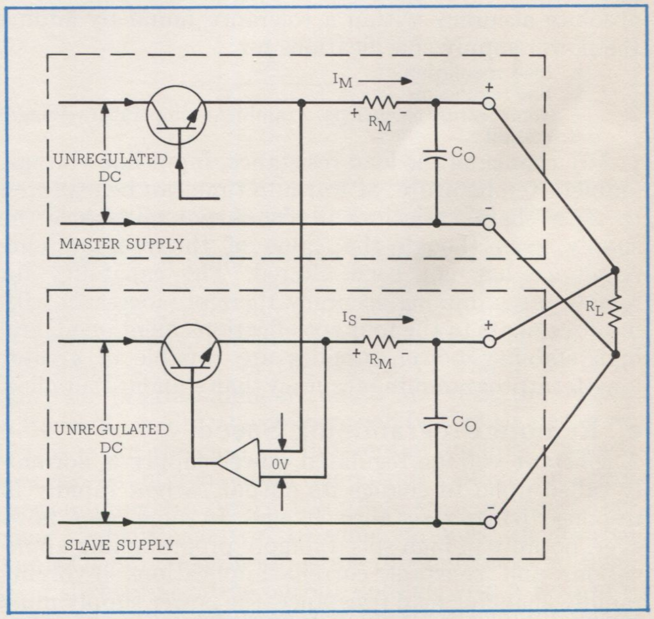


Figure 37. Auto-Parallel Operation of Two Supplies.

Normally, only supplies having the same model number should be connected for Auto-Parallel operation, since the two supplies must have the same voltage drop across the current monitoring resistor at full current rating.

As is also true of Auto-Series and Auto-Tracking operation, no internal wiring changes are necessary. All that is required is a screwdriver to change the strapping pattern on the terminals of the rear barrier strip, and one extra lead running from the barrier strip of each slave supply to another supply in the same master-slave system.

B8. SERIES OPERATION

Series operation of two or more hp power supplies can be accomplished up to 300 volts off ground (see paragraph B11). Series connected supplies can be operated with one load across both supplies or with a separate load for each supply. All hp semiconductor power supplies have reverse polarity diodes connected across the output terminals so that if operated in series with other power supplies, reverse polarity will not occur across the output terminal of any supply if the load is short-circuited or if one power supply is turned on separately from its series partners.

B9. AUTO-SERIES OPERATION

Auto-Series or automatic series operation of power supplies permits equal or proportional voltage sharing under all load conditions, with complete control of the Auto-Series ensemble being obtained from the master supply alone. Figure 38 illustrates the circuit principle involved. The slave supply is connected in series with the negative output terminal of the master supply, and a voltage divider (R_1 and R_2) is placed across the series voltage span. One input of the comparison amplifier of the slave supply is connected to the junction of these two resistors while the other input is connected to the positive output terminal of the slave supply. Since normal feedback action of the slave supply is such as to maintain a zero error between the two comparison amplifier inputs, the slave supply will contribute a fraction of the total output voltage determined by the voltage divider R_1 and R_2.

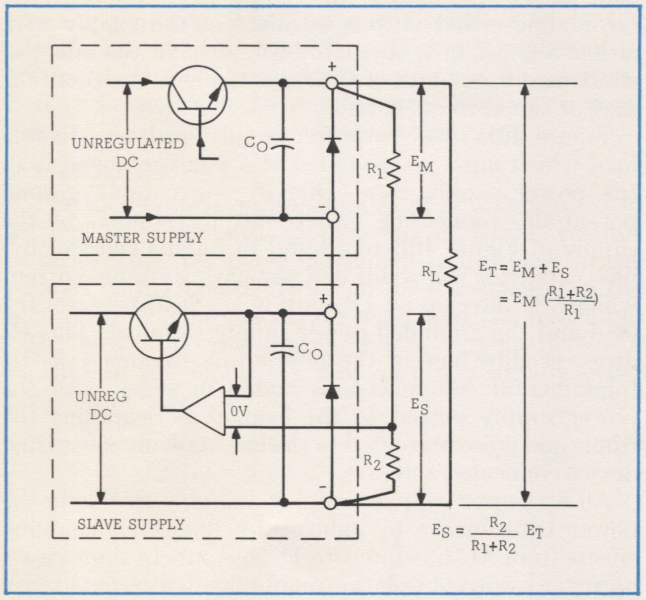


Figure 38. Auto-Series Operation of Two Supplies.

For example, if these two resistors are equal, the slave supply will contribute half the total output voltage with the master supply contributing the other half. Notice that the percent of the total output voltage contributed by each supply is independent of the magnitude of the total voltage. When using fixed resistors R_1 and R_2, the front panel voltage control of the slave supply will be inoperative. Turning the voltage control of the master supply will result in a continuous variation of the output of the series combination, with the contribution of the master's output voltage to that of the slave's voltage always remaining in the ratio of R_1 to R_2.

Since any variation in the resistance value of R_1 and R_2 will result in a change in the voltage divider ratio and hence the output of the slave supply, it is important that both these resistors have a low temperature coefficient (20 ppm/°C or better) and have a power rating at least 10 times their actual dissipation. Resistors R_1 and R_2 should be selected so that at the normal operating levels the current through them will be of the order of 1 to 5 ma.

Comparing Figure 38 with previous block diagrams for the constant voltage power supply (e.g. Figure 3), note that there is no difference in the circuit location of Resistor R_2 and the front panel voltage control normally found in hp power supplies. Thus, Auto-Series operation can be achieved using only one external resistor (R_1) and employing the front panel voltage control on the slave supply as the element which determines the *ratio* of its voltage to that of the master.

Mixed model numbers may be employed in Auto-Series combination without restriction, provided that each slave is specified as being capable of Auto-Series operation. The master supply need not be an Auto-Series supply since the internal circuit aspects of the master supply in no way affect the Auto-Series principle of operation. If the master supply is set up for constant current operation, then the master-slave combination will act as a composite constant current source.

In some applications, remote programming of the master supply is employed, thereby achieving simultaneous control of the output of two sources from a single remote resistance or voltage input. When the center tap of such an Auto-Series combination is grounded, coordinated positive and negative voltages result. This technique is commonly referred to as "rubber-banding," and an external reference source may be employed if desired. Any change of the internal or external reference source (e.g. drift, ripple) will cause an equal percentage change in the outputs of both the master and slave supplies. This feature can be of considerable use in analogue computer and other applications, where the load requires a positive and a negative power supply and is less susceptible to an output voltage change occurring simultaneously in both supplies than to a change in either supply alone.

B10. AUTO-TRACKING OPERATION

Auto-Tracking or automatic tracking operation of power supplies is similar to Auto-Series operation except that the master and slave supplies have the same output polarity with respect to a common bus or ground. Figure 39 shows two supplies connected in Auto-Tracking with their negative output terminals connected together as a common or ground point. A fraction $\frac{R_2}{R_1 + R_2}$ of the output of the master supply is provided as one of the inputs to the comparison amplifier of the slave supply, thus controlling the slave's output. The master supply in an Auto-Tracking system must be the positive supply having the largest output voltage. Auto-Series addition of still more slaves permits the expansion of an Auto-Tracking system to both positive and negative power supplies.

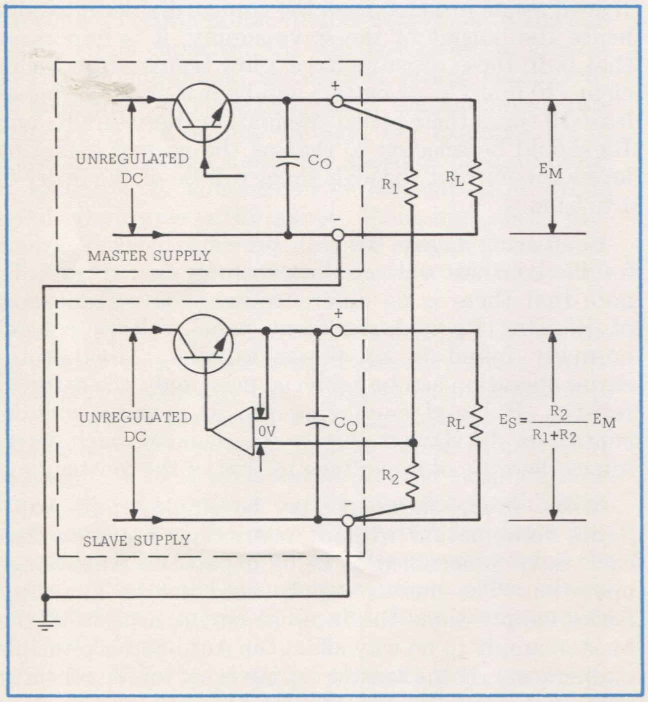


Figure 39. Auto-Tracking of Two Supplies.

Like Auto-Series operation, Auto-Tracking permits simultaneous turn-on and turn-off of power supplies in the same system, thereby preventing accidental application or removal of main power sources without proper bias potentials being present.

B11. GROUNDED AND FLOATING OPERATION

All hp semiconductor power supplies are floating—that is, a power transformer isolates the DC power supply output from the AC input, and neither the positive nor negative output terminal (nor any point within the regulator circuit) is connected to chassis or ground. Thus, the power supply may be used as either a positive or a negative DC source by grounding the negative or positive output terminal respectively.

In some applications, however, it is desirable to "float" the power supply (neither output terminal grounded). All hp supplies can be operated at up to 300 volts off ground; special factory modifications in many cases will permit operation to still higher values. One limiting factor is the mica washer which on most units separates the power transistors from the heat sink.

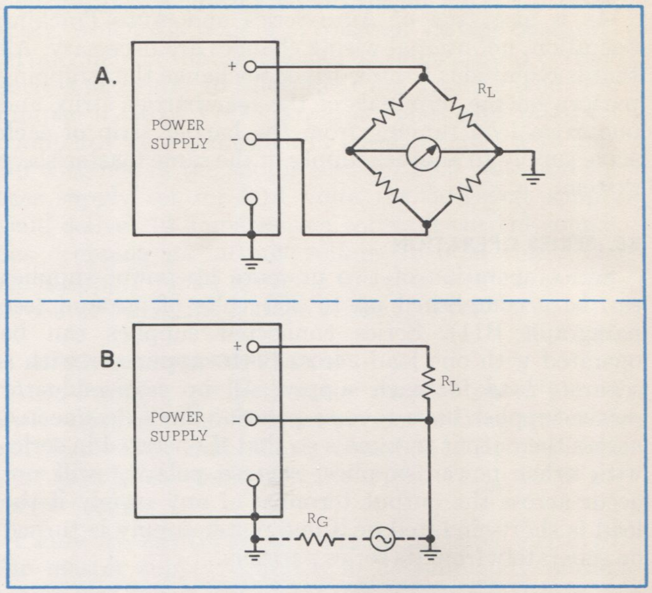


Figure 40. Power Supply Feeding Two Types of Grounded Loads.

Since the output ripple of most hp power supplies will increase somewhat when operated floating (neither output terminal shorted to ground), it is desirable in such applications to place a $1\mu f$ capacitor with short leads between the negative output terminal and ground so that the low output ripple performance of the supply may be restored.

Sometimes floating operation is desired not in order to elevate the output potential of the power supply, but to eliminate or reduce the effects of ground problems. Figure 40 illustrates two situations in which it is not practical to connect a power supply output terminal to ground either with a direct short or a by-pass capacitor.

In Figure 40A, a power supply is shown feeding a bridge circuit, one end of which must be grounded at a point other than the power supply case. This configuration arises frequently in strain gage applications. Grounding either output terminal of the supply with either a short or a capacitor would have the effect of shorting out one arm of the measurement bridge at DC and/or signal frequencies.

Figure 40B shows a power supply feeding a remote load which must be grounded at a point removed from the power supply case. Due to unavoidable ground potentials, connecting either output terminal of the supply of Figure 40B to ground through a short or by-pass capacitor will result in a circulating ground current which will develop an IR drop in the lead between the load and the grounded power supply terminal. This IR drop, usually having the power line frequency as its fundamental component, is added in series with the power supply output to the load, thus degrading the ripple and noise presented to the load and any measuring device connected across it.

All hp power supplies employ Faraday shields in the power transformer to reduce any undesired coupling effects from AC line input to DC output. In some cases, however, stringent isolation requirements associated with ungrounded operation (as given in Figure 40) may necessitate the use of a power supply employing added design restrictions. Model 801C strain gage power supply, for example, has been especially designed to reduce stray leakage effects, and employs a quadruply shielded transformer so that input-output capacitance is reduced to less than 1 pf. Further information concerning methods of measuring these leakage components can be obtained from the factory.

B12. ADJUSTABLE TRANSIENT RECOVERY

The ability of a power supply to recover quickly from a sudden change in load current demand in constant voltage operation is dependent upon the shape of the gain bandwidth curve of its feedback amplifier. It is necessary in designing a power supply to shape this open loop gain vs. frequency characteristic so that the power supply will not oscillate under any load condition —resistive, capacitive, or inductive. Part of the solution to this design problem usually involves an RC equalizing network (R_Q, C_Q of Figure 27). In many supplies the resistance of this network is made variable and is adjusted at the factory so that when a resistive load is suddenly applied or removed, the resulting output voltage transient has the fastest possible recovery with no overshoot. (Paragraph C1e gives further details on the recommended method for switching the load and measuring transient recovery characteristics.) This adjustment of the transient recovery control achieves ample phase margin against instability for all loads. Turning this control away from the critically damped setting of Figure 41A in one direction will cause the underdamped response of Figure 41B, and if the control is turned still further in this direction the power supply may oscillate. Turning the transient recovery control in the other direction will result in the overdamped response of Figure 41C, with a resulting increase in the transient recovery time.

While the factory setting of this control achieves ample phase margin against instability for all types of loads, this same setting may not be the one which achieves the fastest possible transient recovery for large phase angle loads. When using non-resistive loads, the adjustment of this control permits achievement of optimum transient recovery performance. In addition, it may be desirable to readjust this control to compensate for the effects of transistor aging, etc.

B13. METERING

The meters used on hp supplies have an accuracy of 2% full scale. In most supplies, an adjustable resistor in series with the meter movement is included on the printed wiring board. This control is adjusted at the factory for the most accurate reading at the maximum rated output of the supply. However, the user can recalibrate the meter for best accuracy at any other point on the scale.

Multiple range meters are standard on most hp laboratory supplies. Two voltage and two current ranges are included—full scale values are X volts, X/10 volts, Y amps, and Y/10 amps, where X and Y are slightly greater than the voltage and current rating respectively. A front panel switch selects the desired range and programs the meter circuit. The transistor amplifiers in the meter circuit are designed with an inherent current limiting feature which protects the meter movement against overloads. For example, if the meter switch is set to the low current position, when the supply is actually delivering a higher ampere output, the differential amplifiers are driven into saturation, limiting the current through the meter to a safe value. Refer to paragraph A15 for a discussion of the principles of the multiple range meter circuit.

The CCB Series of power supplies, high-performance constant current models, includes special meter circuits. Placing a voltmeter across the output terminals of a normal constant current power supply degrades the load regulation and diminishes the load current (see paragraph C2a(5). The CCB series eliminates this error by using an operational amplifier to feed the front panel voltmeter. This "replica" of the output voltage is also presented on rear terminals for possible connection to a more accurate differential or digital voltmeter.

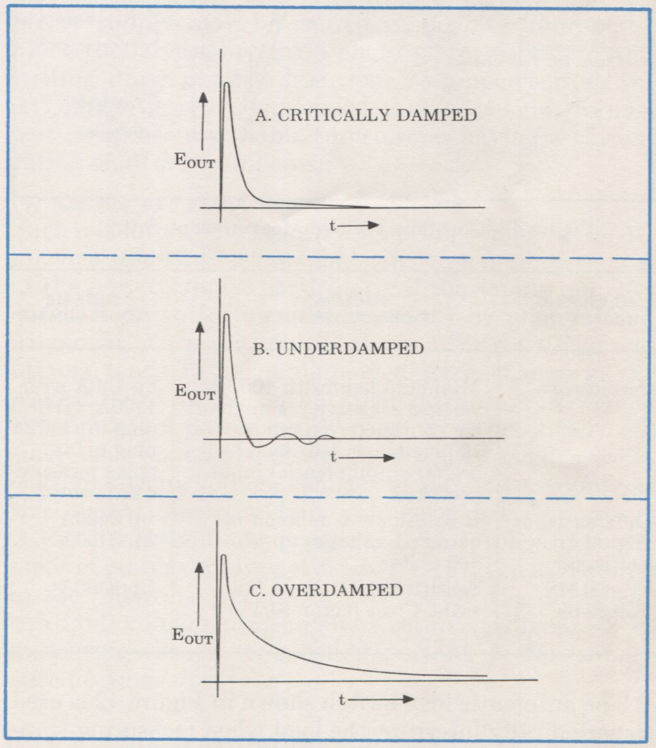


Figure 41. Constant Voltage Full Load to No Load Transient Recovery Characteristics.

C. PERFORMANCE MEASUREMENTS

C1. CONSTANT VOLTAGE POWER SUPPLY MEASUREMENTS

a. Test Setup—General Comments

Figure 42 illustrates a setup suitable for the measurement of the six most important operating specifications of a constant voltage power supply—line regulation, load regulation, ripple and noise, transient recovery time, stability, and temperature coefficient.

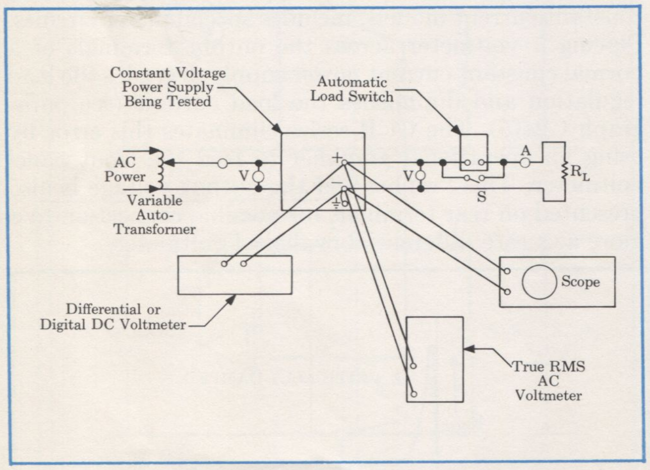


Figure 42. Constant Voltage Measurement Setup.

MEASURING INSTRUMENT	NECESSARY CHARACTERISTICS	SUITABLE MODEL NUMBER
Oscilloscope	Minimum bandwith 100 kc, vertical sensitivity 1 millivolt per centimeter minimum, 100μvolts per centimeter preferred, differential input preferred	hp 140A with 1400A vertical plug-in (1402A plug-in for spike measurements only)
Differential or Digital DC Voltmeter	Resolution—1 millivolt or better at voltages up to 300 volts	hp 3420A hp 3460A
True RMS Voltmeter	Sensitivity 100μvolts full scale. Crest factor 10:1	hp 3400A

The automatic load switch shown in Figure 42 is used to periodically interrupt the load when measuring transient recovery time. Full details of a suitable load switch and the method employing it are given later, in Section C1e, "Transient Recovery Time."

PRECAUTIONS

(1) Measure Performance at Front or Rear Terminals.

Before attaching the load and monitoring devices shown in Figure 42, it is necessary to determine (in the case of power supplies having both front and rear terminals) whether the supply is connected for front or rear terminal sensing, since both the load and monitoring devices must be connected to the same pair of output terminals to which the feedback amplifier within the power supply is connected. In the case of small laboratory supplies which feature Automatic Error Sensing, performance measurements can be made at either the front or rear output terminals but are normally accomplished at the rear terminals.

(2) Connect Leads to Power Supply Terminals Properly.

Casual clip lead connections will inevitably result in serious measurement errors—in most cases placing the measurement results beyond the power supply's specifications even though the power supply is operating perfectly. The load and monitoring leads must be connected to the power supply terminals *exactly* as shown in Figures 43A and 43B. If performance measurements are made at the front terminals (Figure 43A) the load should be plugged into the front of the terminal at (B) while the monitoring device is connected to a small lead or bus wire inserted through the hole in the neck of the binding post at (A). If performance is being measured at the rear barrier strip (Figure 43B), the measuring instrument should be connected to the plus and minus sensing terminals; in this way the monitoring device sees the same performance as the feedback amplifier within the power supply which is sensing and correcting the output.

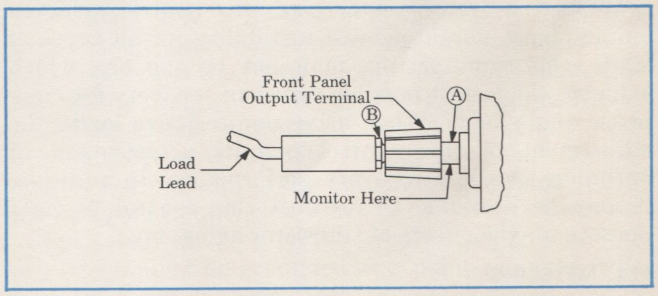


Figure 43A. Proper Front Panel Connections for Monitoring and Load Leads.

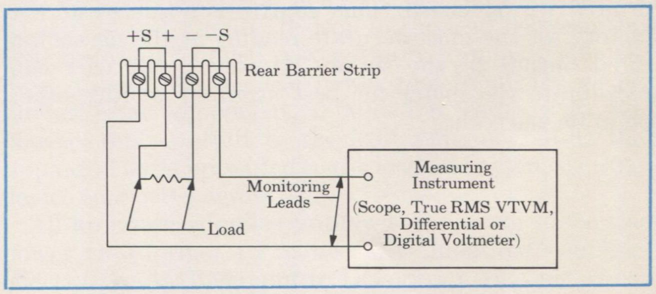


Figure 43B. Proper Rear Panel Connections for Monitoring and Load Leads.

The importance of proper connection of load and monitoring leads to the power supply output terminals cannot be overemphasized, since the most common errors associated with the measurement of power supply performance result from improper connection to the output terminals. Failure to connect the monitoring instrument to the proper points shown in Figures 43A and 43B will result in the measurement not of the power supply characteristics, but of the power supply plus the resistance of the leads between its output terminals and the point of connection. Even connecting the load by means of clip leads to the power supply terminals and then connecting the monitoring instrument by means of clip leads fastened to the load clip leads can result in a serious measurement error. Remember that the power supply being measured probably has an output impedance of less than 1 milliohm, and the contact resistance between clip leads and power supply terminals will in most cases be considerably greater than the specified output impedance of the power supply.

(3) Use Separate Leads to All Measuring Instruments.
All measurement instruments (oscilloscope, AC voltmeter, differential or digital voltmeter) must be connected *directly* by separate pairs of leads to the monitoring points indicated in Figure 43A and 43B. This is necessary in order to avoid the rather subtle mutual coupling effects which may occur between measuring instruments unless all are returned to the low imedpance terminals of the power supply. Twisted pairs (in some cases shielded cable will be necessary) should be used to avoid pickup on the measuring leads.

(4) Use an Adequate Load Resistor.
The resistance and wattage rating of the load resistor depends upon the output voltage and current of the supply; in general, a load resistor should be selected which permits operation of the supply at its maximum rated output voltage and current. Continuously variable load boxes manufactured by Rex Rheostat are excellent for this purpose and may be bought in a large variety of resistance and wattage ratings. When measuring the transient recovery time of power supplies requiring low resistance loads, it may be necessary to use non-inductive loads so that the L/R time constant of the load will not be greater than the inherent recovery time of the power supply, thus impeding the measured transient recovery performance.

(5) Check Current Limit Control Setting.
When measuring the constant voltage performance specifications, the constant current or current limit control must be set well above the maximum output current which the supply will draw, since the onset of constant current or current limiting action can cause a drop in output voltage, increased ripple, and other performance changes not properly ascribed to the constant voltage operation of the supply.

(6) Check Setup for Pickup and Ground Loop Effects.
Care must be taken that the measured performance is not unduly influenced by the presence of pickup on the measuring leads or by power line frequency components introduced by ground loop paths. Two quick checks should be made to see if the measurement setup is free of extraneous signals:

(a) Turn off the power supply and observe whether any signal is observable on the face of the CRT (with the scope connected between +S and —S).

(b) Instead of connecting the oscilloscope leads separately to the positive and negative sensing terminals of the supply, connect both leads to either the positive or the negative sensing terminals, whichever is grounded to chassis.

Signals observable on the face of the CRT as a result of either of these tests are indicative of shortcomings in the measurement setup. The most likely causes of these defects and proper corrective measures are discussed further in Section C1d, "Ripple and Noise."

(7) Connect AC Voltmeter Properly.
It is important that the AC voltmeter be connected as closely as possible to the input AC terminals of the power supply so that its indication will be a valid measurement of the power supply input, without any error introduced by the IR drop present in the leads connecting the power supply input to the AC line voltage source.

(8) Use an Auto-Transformer of Adequate Current Rating.
If this precaution is not followed, the input AC voltage presented at the power supply may be severely distorted, and the rectifying and regulating circuits within the power supply may be caused to operate improperly. Since the largest hp single phase power supply at this writing draws a little less than 25 amperes from the AC input, it is recommended that a general purpose test setup use a variable transformer having a current rating of 30 or 35 amperes.

(9) Do Not Use an AC Input Line Regulator
Such regulators tend to increase the impedance of the AC line in a resonant fashion, and can cause malfunctioning of the power supply, particularly if the supply employs an SCR or switching type regulator or preregulator. Moreover, since the control action of line voltage regulators tends to be accompanied by a change in the waveshape of the AC output, their advantage in keeping the input to a power supply constant is practically nil, since such waveshape changes are nearly as effective in causing output voltage changes of the power supply as the original uncorrected line voltage change.

Further precautions necessary to the proper measurement of power supply specifications are given as required in the following sections, which discuss the use of the constant voltage measurement setup of Figure 42 in measuring the seven most important power supply specifications.

b. CV Line Regulation

Definition: The change, ΔE_{OUT}, in the static value of DC output voltage resulting from a change in AC input voltage over the specified range from low line (usually 105 volts) to high line (usually 125 volts), or from high line to low line.

Actual measurement is accomplished by turning the variable autotransformer (Figure 42) through the specified range from low line to high line and noting the change in the reading of the digital voltmeter or differential voltmeter connected to the output terminals of the supply. The power supply will perform within its line regulation specification at any rated output voltage combined with any rated output current; the most severe test normally involves measuring line regulation at maximum output voltage combined with maximum output current.

Notice that for practically all hp power supplies the line regulation specification is not prefixed by "±", nor is the line voltage input change specified "115 volts ±10%." Thus, hp's line regulation specification sets a limit on the *total* excursion of the output voltage resulting from the *total* input AC change from low line to high line, thereby allowing only one-half the output deviation of a "±" specification.

c. CV Load Regulation

Definition: The change ΔE_{OUT} in the static value of DC output voltage resulting from a change in load resistance from open circuit to a value which yields maximum rated output current (or vice versa).

Load regulation is measured by throwing the switch S in Figure 42 and noting the resulting static change ΔE_{OUT} in the output voltage on the digital voltmeter or differential voltmeter connected to the output terminals. The power supply will perform within its load regulation specification at any rated output voltage combined with any rated input line voltage.

d. CV Ripple and Noise

Definition: The residual AC voltage which is superimposed on the DC output of a regulated power supply. Ripple and noise may be specified and measured in terms of its RMS or (preferably) peak-to-peak value.

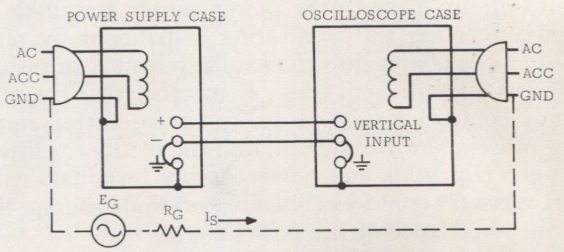
Ripple and noise measurement of an hp constant voltage regulated DC power supply can be made at any input AC line voltage combined with any DC output voltage and load current within rating.

The amount of ripple and noise that is present on the power supply output is measured either in terms of the RMS or (preferably) peak-to-peak value. The peak-to-peak measurement is particularly important for applications where noise spikes could be detrimental to a sensitive load, such as logic circuitry. The RMS measurement is not an ideal representation of the noise, since fairly high output noise spikes of short duration could be present in the ripple and not appreciably increase the RMS value.

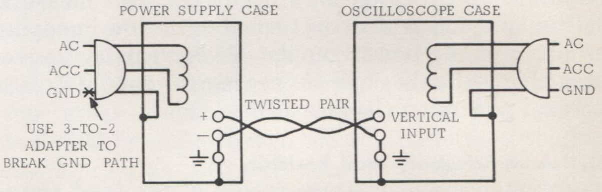
The technique used to measure *high frequency noise* or "*spikes*" on the output of a power supply is more critical than the *low frequency ripple and noise* measurement technique; therefore the former is discussed separately in paragraph(2).

(1) Ripple and Noise Measurements

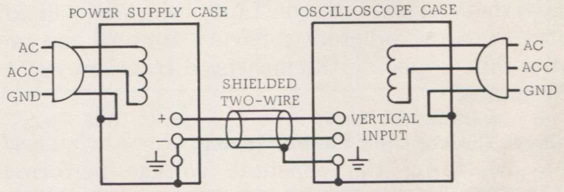
Figure 44A shows an incorrect method of measuring p-p ripple. Note that a continuous ground loop exists from the third wire of the input power cord of the power supply to the third wire of the input power cord of the oscilloscope via the grounded power supply case, the wire between the negative output terminal of the power supply and the vertical input of the scope, and the grounded scope case. Any ground current circulating in this loop as a result of the difference in potential E_G between the two ground points causes an IR drop which is in series with the scope input. This IR drop, normally having a 60 cycle line frequency fundamental, plus any pickup on the unshielded leads interconnecting the power supply and scope, appears on the face of the CRT. The magnitude of this resulting noise signal can easily be much greater than the true ripple developed between the plus and minus output terminals of the power supply, and can completely invalidate the measurement.



A. Incorrect method—Ground current I_S produces 60 cycle drop in negative lead which adds to the power supply ripple displayed on scope.



B. A correct method using a single-ended scope 3-to-2 adapter breaks ground current loop, twisted pair reduces stray pickup on scope leads.



C. A correct method using a differential scope with floating input. Ground current path is broken; common mode rejection of differential input scope ignores difference in ground potential of power supply & scope, shielded two-wire further reduces stray pick-up on scope lead.

Figure 44. Measurement of Ripple and Noise Output of a CV Supply.

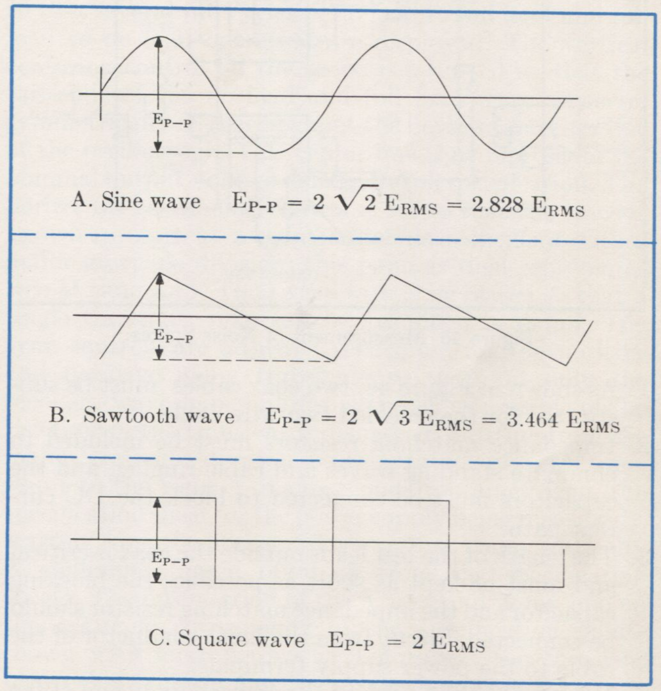
The same ground current and pickup problems can exist if an RMS voltmeter is substituted in place of the oscilloscope in Figure 44. However, the oscilloscope display, unlike the true RMS meter reading, tells the observer immediately *whether the fundamental period of the signal displayed is 8.3 milliseconds (1/120 cps) or 16.7 milliseconds (1/60 cps)*. Since the fundamental ripple frequency present on the output of an hp supply is *120 cps* (due to full-wave rectification), an oscilloscope display showing a *120 cps* fundamental component is indicative of a "clean" measurement setup, while the presence of a *60 cps* fundamental usually means that an improved setup will result in a more accurate (and lower) value of measured ripple.

Figure 44B shows a correct method of measuring the output ripple of a constant voltage power supply using a single-ended scope. The ground loop path is broken with a 3-to-2 adapter in series with the power supply's AC line plug. Notice, however, that the power supply case is still connected to ground via the power supply output terminals, the leads connecting these terminals to the scope terminals, the scope case and the third wire of the power supply cord.

Either a twisted pair or (preferably) a shielded two-wire cable should be used to connect the output terminals of the power supply to the vertical input terminals of the scope. When using a twisted pair, care must be taken that one of the two wires is connected both to the grounded terminal of the power supply and the grounded input terminal of the oscilloscope. When using shielded two-wire, it is essential for the shield to be connected to ground at *one end only* so that no ground current will flow through this shield, thus inducing a noise signal in the shielded leads.

To verify that the oscilloscope is not displaying ripple that is induced in the leads or picked up from the grounds, the (+) scope lead should be shorted to the (−) scope lead at the power supply terminals. The ripple value obtained when the leads are shorted should be subtracted from the actual ripple measurement.

In most cases, the single-ended scope method of Figure 44B will be adequate to eliminate non-real components of ripple and noise so that a satisfactory measurement may be obtained. However, in more stubborn cases, or in measurement situations where it is essential that both the power supply case and the oscilloscope case be connected to ground (e.g. if both are rack-mounted), it may be necessary to use a differential scope with floating input as shown in Figure 44C. If desired, two single conductor shielded cables may be substituted in place of the shielded two-wire cable with equal success. Because of its common mode rejection, a differential oscilloscope displays only the difference in signal between its two vertical input terminals, thus ignoring the effects of any common mode signal introduced because of the difference in the AC potential between the power supply case and scope case. Before using a differential input scope in this manner, however, it is imperative that the common mode rejection capability of the scope be verified by shorting together its two input leads at the power supply and observing the trace on the CRT. If this trace is a straight line, the scope is properly ignoring any common mode signal present, If this trace is not a straight line, then the scope is not rejecting the ground signal and must be realigned in accordance with the manufacturer's instructions until proper common mode rejection is attained.



A. Sine wave $E_{P-P} = 2\sqrt{2}\,E_{RMS} = 2.828\,E_{RMS}$

B. Sawtooth wave $E_{P-P} = 2\sqrt{3}\,E_{RMS} = 3.464\,E_{RMS}$

C. Square wave $E_{P-P} = 2\,E_{RMS}$

Figure 45. Three Possible Ripple Waveshapes.

Figure 45 shows the relationship between the peak-to-peak and RMS values of three common waveforms. The output ripple of a DC power supply usually does not approximate the sine wave of Figure 45A; in many cases the output ripple has a waveshape which very closely approximates the sawtooth of Figure 45B. In this case, the RMS ripple is $\frac{1}{3.464}$ of the peak-to-peak value displayed on the oscilloscope. The square wave is included in Figure 45 because this waveshape has the highest possible ratio of RMS to peak-to-peak. Thus, *the RMS ripple and noise present on the output terminals of a power supply cannot be greater than ½ the peak-to-peak value measured on the oscilloscope.* In most cases the ripple waveshape present on the output terminals of hp power supplies is such that the RMS value is between ⅓ and ¼ of the peak-to-peak value.

(2) Noise Spike Measurements

When a high frequency spike measurement is being made, an instrument of sufficient bandwidth must be used; an oscilloscope with a bandwidth of 20 MHz or more is adequate. Measuring noise with an instrument that has insufficient bandwidth may conceal high frequency spikes detrimental to the load.

The test setups illustrated in Figures 44A and 44B are generally not acceptable for measuring spikes; a differential oscilloscope is necessary. Furthermore, the measurement concept of Figure 44C must be modified if accurate spike measurement is to be achieved:

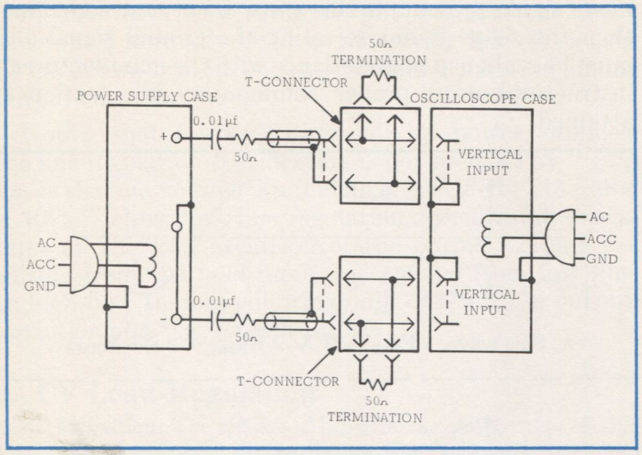


Figure 46. Measurement of Noise Spikes.

1. As shown in Figure 46, two coax cables must be substituted for the shielded two-wire cable.
2. Impedance matching resistors must be included to eliminate standing waves and cable ringing, and the capacitors must be connected to block the DC current path.
3. The length of the test leads outside the coax is critical and must be kept as short as possible; the blocking capacitor and the impedance matching resistor should be connected *directly* from the inner conductor of the cable to the power supply terminals.
4. Notice that the shields of the power supply end of the two coax cables are *not* connected to the power supply ground, since such a connection would give rise to a ground current path through the coax shield, resulting in an erroneous measurement.
5. The measured noise spike values must be doubled, since the impedance matching resistors constitute a 2-to-1 attenuator.

The circuit of Figure 46 can also be used for the normal measurement of low frequency ripple and noise; simply remove the four terminating resistors and the blocking capacitors and substitute a higher gain vertical plug-in in place of the wide-band plug-in required for spike measurements. Notice that with these changes, Figure 46 becomes a two-cable version of Figure 44C.

e. Transient Recovery Time

Definition: The time "X" for output voltage recovery to within "Y" millivolts of the nominal output voltage following a "Z" amp step change in load current—where:

"Y" is specified separately for each model but is generally of the same order as the load regulation specification.

The nominal output voltage is defined as the DC level half way between the static output voltage before and after the imposed load change, and

"Z" is the specified load current change, normally equal to the full load current rating of the supply.

Transient recovery time may be measured at any input line voltage combined with any output voltage and load current within rating.

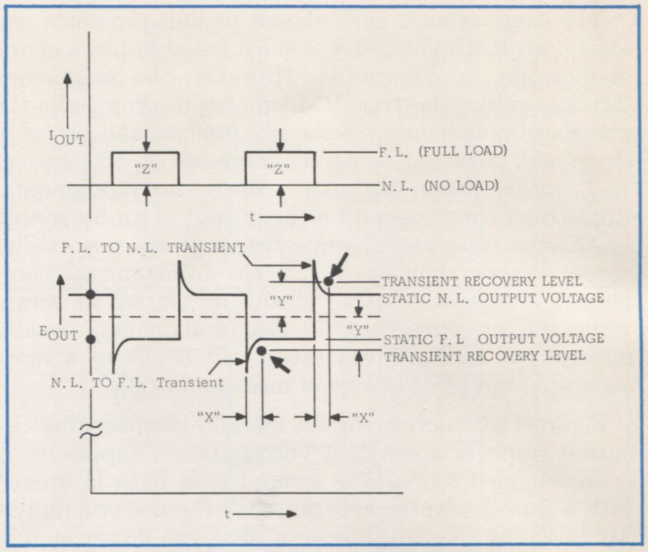


Figure 47. Transient Recovery of a Constant Voltage Power Supply.

If a step change in load current is imposed on the output of a power supply, the output voltage will exhibit a transient of the type shown in Figure 47. The output impedance of any power supply eventually rises at high frequencies, giving rise to an equivalent output inductance; if the load current is switched rapidly enough so that the high frequencies associated with the leading edge of the step change can react with this effective output inductance, there will occur on the output terminals of any power supply a spike of amplitude L di/dt, where L is the effective output inductance of the supply at high frequencies, and di/dt is the rise time of the load current change imposed. For most hp power supplies of moderate or high output rating, L is of the order of 0.16 microhenries (1 ohm at 1 megacycle), whereas for small power supplies, the output inductance may be as high as 0.3 microhenries.

Thus, it is not possible to specify the amplitude of an output voltage spike caused by a load current change unless the rise time of the load change is first established. A power supply with an effective output inductance of 0.16 microhenries will exhibit a load transient spike of about 0.16 volts if the load is switched with a rise time of 1 amp/µsec, but the spike amplitude will be only 160 µv if the load is switched at 1 amp/millisecond. In this latter case the output spike would not be evident, since it would be small compared to the static change in output voltage associated with the full load change.

While an oscilloscope with a bandwidth of the order of 100 kc is adequate to observe and measure the transient *recovery time* of a power supply, the spike *amplitude* for load switching times of less than 1 microsecond cannot be accurately determined, unless a very wide band scope is used.

Of all power supply specifications, transient recovery time is subject to the widest variation in definition, and is not defined at all by some power supply manufacturers. It is important to notice that a simple statement that a power supply has a transient recovery time of "50 microseconds" is incomplete and conveys no information. Such a specification leaves to the imagination whether the power supply will recover during the 50 μsecond interval to within 37% (1/e) of its initial value, or to within 10%, or "all the way." A definition based on 37% or 1/e recovery is not useful since the transient recovery waveshape, being dependent upon the nature of a closed feedback loop, is in general not exponential. Nor is a definition based on 90% decay of the transient useful since as mentioned previously, the amplitude of the transient varies with the rise time of the load current change imposed. Finally, one cannot define recovery "all the way" since no transient ever completely dies away, and the time measured would be dependent upon the setting of the oscilloscope vertical gain control.

Since the falling portion of the transient remains reasonably constant in spite of wide variations in the spike amplitude and the speed of the load change causing it, Hewlett-Packard has chosen to define transient recovery time in terms of recovery to a certain voltage level. For ease in oscilloscope measurement, this voltage level is referenced to a nominal output voltage half-way between no load and full load.

Reasonable care must be taken in switching the load resistance on and off. A hand-operated switch in series with the load is not adequate, since the resulting one-shot displays are difficult to observe on most oscilloscopes, and the arc energy occurring during switching action completely masks the display with a noise burst. Transistor load switching devices are expensive if reasonably rapid load current changes are to be achieved.

Hewlett-Packard employs a mercury-wetted relay, using the load switching circuit of Figure 48. When this load switch is connected to a 60 cycle AC input, the mercury-wetted relay will open and close 60 times per second. Adjustment of the 25K control permits adjustment of the duty cycle of the load current switching and reduction in jitter of the oscilloscope display.

The maximum load ratings listed in Figure 48 must be observed in order to preserve the mercury-wetted relay contacts. Switching of larger load currents can be accomplished with mercury pool relays; with this technique fast rise times can still be obtained, but the large inertia of mercury pool relays limits the maximum repetition rate of load switching and makes the clear display of the transient recovery characteristic on an oscilloscope more difficult.

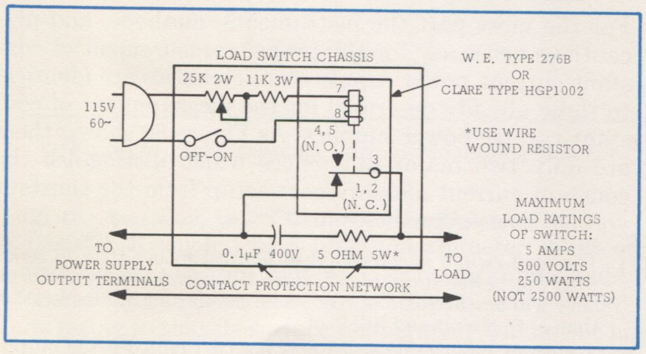


Figure 48. Automatic Load Switch for Measuring Transient Recovery Time.

The scope is set up for internal sync and the presentation is locked on either the positive or the negative load transient spike. The vertical input of the oscilloscope should be set for AC coupling so that small DC level changes in the output voltage of the power supply will not cause the display to shift. The sweep rate is first set so that several full cycles of no load to full load and full load to no load operation are displayed. The vertical centering control on the scope is adjusted so that the tail ends of the no load and full load waveforms are symmetrically displaced about the horizontal center line of the oscilloscope. This center line thus represents the nominal output voltage defined in the specification. The horizontal positioning control is set so that the trace is known to start at a point which is coincident with a major graticule division; this point is then representative of time zero. The sweep rate is increased so that a single transient spike can be examined in detail. The sync controls are adjusted separately for the positive and negative going transients so that not only the recovery waveshape but also as much as possible of the rise time of the transient is displayed. Starting from the major graticule division representative of zero time, count to the right Y microseconds (obtained from the specification sheet for the power supply being measured), starting from the horizontal center line, count vertically X millivolts (again obtained from the specification sheet). The intersection of the Y μsec and X mv line on the graticule corresponds to the specification points shown with large arrows in Figure 47; the transient recovery waveform must lie inside these points.

f. CV Stability

Definition: The change in output voltage for the first eight hours following a 30 minute warm-up period. During the interval of measurement all parameters, such as load resistance, ambient temperature, and input line voltage are held constant.

This measurement is made by monitoring the output of the power supply on a differential voltmeter or digital voltmeter over the stated measurement interval; a strip chart recorder can be used to provide a permanent record. A thermometer should be placed near the supply to verify that the ambient temperature remains constant during the period of measurement. The supply should be put in a location immune from stray air currents (open doors or windows, air conditioning vents); if possible, the supply should be placed in an oven which is held at a constant temperature. Care must be taken that the measuring instrument has a stability over the eight hour interval which is at least an order of magnitude better than the stability specification of the power supply being measured. Typically, a supply may drift less over the eight hour measurement interval than during the ½ hour warm-up period.

Stability measurement can be made while the supply is remotely programmed with a fixed wire-wound resistor, thus avoiding accidental changes in the front panel setting due to mechanical vibration or "knob-twiddling."

g. CV Temperature Coefficient

Definition: The change in output voltage per degree Centigrade change in the ambient temperature under conditions of constant input AC line voltage, output voltage setting, and load resistance.

The temperature coefficient of a power supply is measured by placing the power supply in an oven and varying it over any temperature span within its rating. (Most hp power supplies are rated for operation from 0°C to 50°C.) The power supply must be allowed to thermally stabilize for a sufficient period of time at each temperature of measurement.

The temperature coefficient specified is the maximum temperature-dependent output voltage change which will result over any 5°C interval. The differential voltmeter or digital voltmeter used to measure the output voltage change of the supply should be placed outside the oven and should have a long term stability adequate to insure that its drift will not affect the overall measurement accuracy.

h. CV Programming Speed

Definition: The time (μsecs) required for the output voltage to change from zero volts to within "X" millivolts of the maximum rated output, or from maximum rated output to within "X" millivolts of zero. "X" is specified separately for each model and is generally of the same order as the load regulation specification.

This measurement is made by monitoring the output voltage with an oscilloscope while rapidly changing the remote programming resistance from zero ohms to the value that will produce maximum output voltage. A practical method for measuring the programming speed of an hp power supply using remote resistance programming is as follows, (refer to Figure 49):

1. Restrap the power supply rear barrier strip for remote resistance programming, constant voltage. The strapping pattern for remote resistance programming of laboratory-type power supplies is illustrated in the appropriate Operating and Service Manual for each model.
2. Disconnect the output capacitor. On most hp supplies the output capacitor can be disconnected by simply removing the appropriate straps on the rear barrier strip as illustrated in the Operating and Service Manual. A minimum amount of output capacitance is permanently wired to the output and should not be removed to increase the programming speed, because the supply could oscilate under certain load conditions. The programming speed increases by a factor of from 10 to 100 when the output capacitor is removed. Further information concerning the effect of the output capacitor on programming speed is given in paragraph B5e.

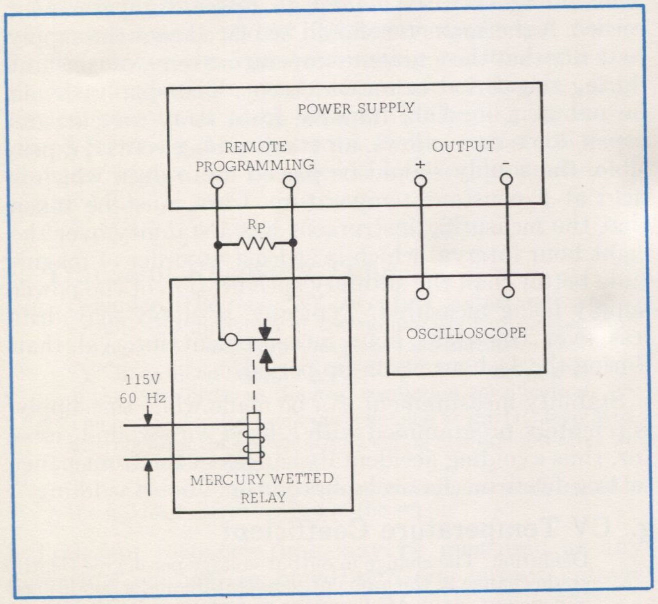


Figure 49. CV Programming Speed Test Setup.

3. Select the value of the programming resistor that will produce maximum output voltage of the supply. This value is obtained by multiplying the programming coefficient ("X" ohms/volt) by the maximum rated output voltage of the supply. The programming coefficient is printed on the hp data sheet and in the Operating and Service Manual for each model.
4. Hewlett-Packard employs a mercury-wetted relay, connected as in Figure 49, to rapidly switch the programming resistance from zero to maximum at a 60 Hz rate. A hand-operated switch connected across the programming resistor is not adequate, because the resulting one-shot displays are difficult to observe on most oscilloscopes and the arc energy occurring during switching action sometimes provides an erroneous waveform because of the noise burst.

The constant voltage programming speed of a power supply using a *remote voltage* is identical to the speed obtained when using a *remote resistance* providing that the remote voltage changes rapidly enough.

i. Other Constant Voltage Specifications

The output impedance of a power supply is normally not measured, since the measurement of transient recovery time reveals both the static and dynamic output characteristics with just *one* measurement. The output impedance of a power supply is commonly measured only in those cases where the exact value at a particular frequency is of engineering importance. Complete information on proper methods of measuring output impedance is available from your nearest hp sales office—ask for the Application Note entitled, "Measurement of Output Impedance of a Constant Voltage Power Supply."

Proper methods of measuring any of the other operating specifications for constant voltage power supplies can also be obtained by contacting your local hp sales office.

C2. CONSTANT CURRENT POWER SUPPLY MEASUREMENTS

a. Test Setup—General Comments

For the most part the instruments, methods, and precautions necessary for the proper measurement of constant current power supply characteristics are identical to those already described for the measurement of constant voltage power supplies. As Figure 50 shows, there are only two major differences which distinguish the constant current measurement setup from the constant voltage measurement setup.

1. The load switch is connected in parallel rather than in series with the power supply load, since the power supply performance will be checked between *short* circuit and full load rather than *open* circuit and full load.
2. A current monitoring resistor is inserted between the output of the power supply and the load. To simplify grounding problems, one end of this monitoring resistor should be connected to the same output terminal of the power supply which

will be shorted to ground. All constant current measurements are made in terms of the change in voltage across this resistor; the current performance is calculated by dividing these voltage changes by the ohmic value of R_I.

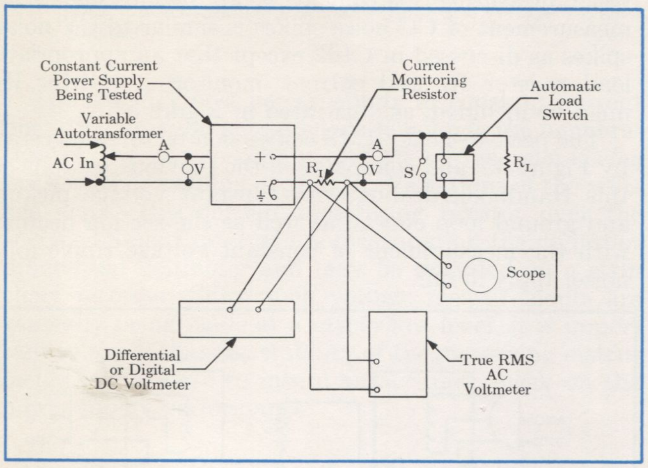


Figure 50. Constant Current Measurement Setup.

Many of the precautions listed in Section C1 with reference to a constant voltage measurement setup are equally applicable to a constant current setup. In addition, a list is provided below of other precautions peculiar to a constant current measurement setup. Many of these precautions concern the series monitoring resistor. Since all constant current performance specs will be checked by measuring the voltage drop across R_I, particular care must be given to the proper selection and connection of this element.

PRECAUTIONS

(1) R_I Must be Treated as a Four-Terminal Device.

In the manner of a meter shunt, the load current must be fed from the extremes of the wire leading to this resistor, while the voltage monitoring terminals connected to the three measuring instruments should be located as close as possible to the resistance portion itself, as shown in Figure 51.

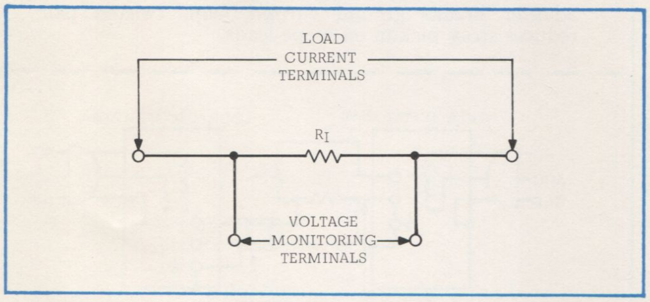


Figure 51. Four-Terminal Current Monitoring Resistor.

(2) Use Precision, Low T.C. Monitoring Resistor.

Resistor R_I should be a precision ammeter shunt or a wire-wound resistor (20ppm/°C or better) and should be operated at a power less than 1/10 (preferably 1/100) of its rating so that its surface temperature will not be high compared with ambient and therefore subject to slow thermal fluctuations which cause similar changes in the resistance value itself.

A crude "thumb rule" will suggest the order of magnitude of the measurement problems which can be encountered if adequate power derating is not applied to the current monitoring resistor. With typical wire-wound power resistors, operation at 10% of power rating will be accompanied by approximately a 50°C temperature rise above ambient at the surface of the resistor; the "bobble," or slow variation in this surface temperature, will amount to about 20% of the rise above ambient—in this case a "bobble" of about 10°C (peak-to-peak). Using a 20ppm resistor, this 10°C variation will cause roughly a .02% variation in the measured current, even though the monitoring resistor is being operated at only 1/10 of its power rating!

(3) Keep Temperature of R_I Constant.

The resistor R_I should be located and protected so that it will not be subjected to stray air currents (open doors or windows, air conditioning vents), since these will introduce a change in resistance value which may mar the measurements, particularly stability and temperature coefficient.

(4) Check Voltage Control Setting.

When measuring the constant current performance specifications, the power supply's voltage control must be set above the maximum output voltage which the supply will deliver, since voltage limiting action will cause a drop in output current, increased ripple current, and other performance changes not properly ascribed to the constant current operation of the supply.

(5) Do not Connect DC Voltmeter Directly Across Power Supply Output Terminals.

Note that in Figure 50 the DC voltmeter used to monitor the output of the power supply is connected *outside* the current monitoring resistor. Thus, the true output voltage of the supply is obtained by adding this voltmeter reading to the voltage across the current monitoring resistor. If the voltmeter were placed on the left side of the current monitoring resistor of Figure 50, a change in output voltage of the constant current supply would result in a change in current through the voltmeter input resistance. As can be seen from Figure 52, if we assume a power supply with a perfectly constant current output, this change in current through the incorrectly connected voltmeter will necessarily be accompanied by an equal magnitude change in current through the load and the current monitoring resistor, thus degrading the measured constant current performance.

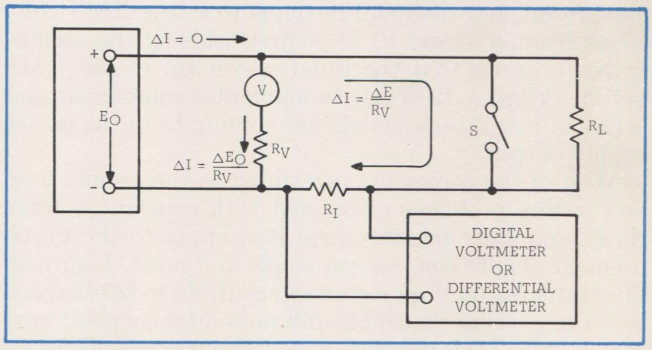


Figure 52. External Voltmeter Measurement Error on CC Power Supply.

Of course, if a sufficiently high resistance DC voltmeter is used, this precaution need not be observed, provided the voltmeter input current is small compared to the current change being measured.

Other precautions associated with the proper measurement of constant current power supply specifications are given in the following sections as required; these sections discuss the use of the constant current measurement setup of Figure 50 for measuring the most important constant current power supply specifications.

b. CC Line Regulation

Definition: The change, ΔI_{OUT} in the static value of DC output current resulting from a change in AC input voltage over the specified range from low line (usually 105 volts) to high line (usually 125 volts), or from high line to low line.

Measurement is accomplished by turning the variable autotransformer of Figure 50 through the specified input voltage range and noting the change in the reading on a digital voltmeter or differential voltmeter connected across the current monitoring resistor; this change, when divided by the value of the current monitoring resistor, yields the change in output current. The power supply will perform within its line regulation specification at any rated output current combined with any rated output voltage.

c. CC Load Regulation

Definition: The change, ΔI_{OUT} in the static value of the DC output current resulting from a change in load resistance from short circuit to a value which yields maximum rated output voltage.

Load regulation is measured by throwing the switch S in Figure 50 and noting the resulting static change on the digital voltmeter or differential voltmeter connected across the current monitoring resistor. The power supply will perform within its load regulation specifications at any rated output current combined with any rated line voltage.

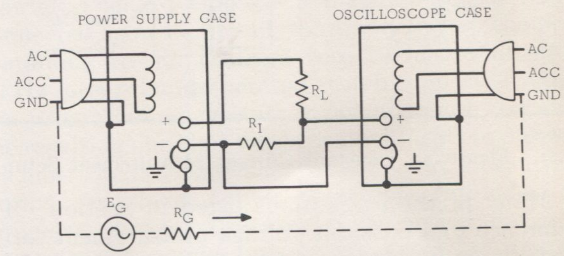
d. CC Ripple and Noise

Definition: The residual AC current which is superimposed on the DC output current of a regulated supply. Ripple and noise may be specified and measured in terms of its RMS or (preferably) peak-to-peak value.

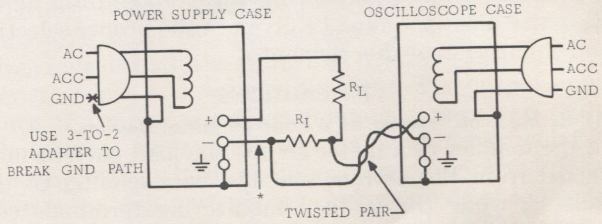
The peak-to-peak voltage measured on the oscilloscope across R_I is divided by R_I to obtain the peak-to-peak ripple current. This value can be divided by a suitable conversion factor to obtain RMS ripple. In cases where the oscilloscope measurement yields a marginal result, resort should be made to a true RMS voltmeter reading across R_I after first utilizing the oscilloscope to insure that the input waveform to the RMS voltmeter has a 120 cycle fundamental component and is free of extraneous signals not coming from the power supply output.

Most of the comments pertaining to the ground loop and pickup problems associated with constant voltage ripple and noise measurement also apply to the measurement of constant current ripple and noise. Figure 53 illustrates the most important precautions to be observed when measuring the ripple and noise of a constant current supply. The presence of a 120 cycle waveform on the oscilloscope is normally indicative of a correct measurement method. A waveshape having 60 cycles as its fundamental component is typically associated with an incorrect measurement setup. As before, the basic measuring instrument is an oscilloscope. The measurement of CC noise spikes is similar to CV noise spikes as discussed in C1d2 except that an appropriate load resistor R_L and current monitoring resistor R_I must be included, as illustrated in Figure 53C.

The peak-to-peak/RMS conversion factors suggested by Figure 45, and comments in the previous sections of this Handbook dealing with constant voltage pickup and ground loop effects, as well as the section dealing with the measurement of constant voltage ripple and noise, apply in full.

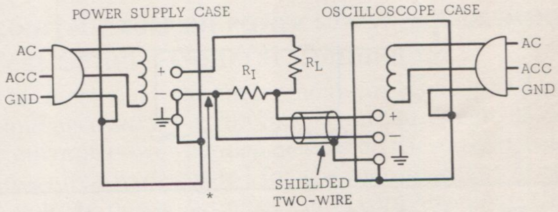


A. Incorrect method—Ground current I_S produces 60 cycle drop in negative lead which adds to the power supply ripple displayed on scope.



*Length of lead between R_I and grounded output terminal of power supply must be held to absolute minimum.

B. A correct method using a single-ended scope. 3-to-2 adapter breaks ground current loop, twisted pair reduces stray pickup on scope leads.



*Length of lead between R_I and grounded output terminal of power supply must be held to absolute minimum.

C. A correct method using a differential scope with floating input. Ground current path is broken; common mode rejection of differential input scope ignores difference in ground potential of power supply & scope, shielded two-wire further reduces stray pickup on scope lead.

Figure 53. Measurement of Ripple and Noise Output of a CC Power Supply.

e. CC Stability

Definition: The change in output current for the first 8 hours following a 30 minute warm-up period. During the interval of measurement all parameters such as load resistance, ambient temperature, and input line voltage are held constant.

The stability of a power supply in constant current operation must be measured while holding the temperature of the power supply *and the current monitoring resistor* R_I *as constant as possible*. Variations of the voltage across this current monitoring resistor over the specified 8-hour interval are measured on the digital or differential voltmeter and may be recorded on a strip chart recorder. Since such voltage measurements are generally being made at a rather low level, it is important to check that the stability of the measuring instruments is adequate to insure an accurate check on the power supply performance.

f. CC Temperature Coefficient

Definition: The change in output current per degree Centigrade change in the ambient temperature under conditions of constant input AC line voltage, output current setting, and load resistance.

The constant current power supply must be placed in an oven and operated over any temperature span within the power supply rating. The current monitoring resistor R_I should not be placed in the oven, but must be held at a constant temperature while this measurement is made.

g. Other Constant Current Specifications

The measurement of transient recovery time, output impedance, programming speed, and other performance specifications is less often required in the case of constant current power supplies. Complete information on proper methods of measuring any other constant current specifications beyond those listed above can be obtained by contacting your nearest hp field sales office.

D. SPECIAL APPLICATIONS

D1. DC POWER DISTRIBUTION AND MULTIPLE LOADING

Figure 54A illustrates the most common error in using DC regulated power supplies. The effective source impedance feeding each of the three loads is the output impedance of the power supply *plus* the effect of any lead resistance and inductance which separates each load from the power supply terminals. Since nearly all practical load devices draw from a constant voltage power supply a current which varies somewhat with time, there will be a variation of the voltage drop in the leads connecting the loads of Figure 54A to the power supply.

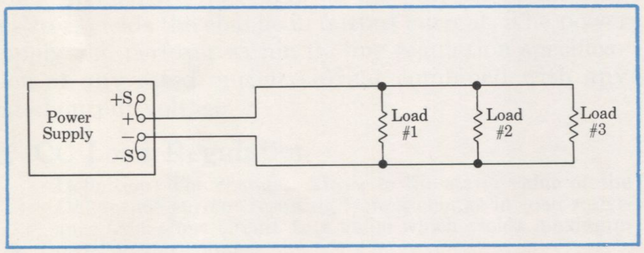


Figure 54A. Incorrect DC Power Distribution.

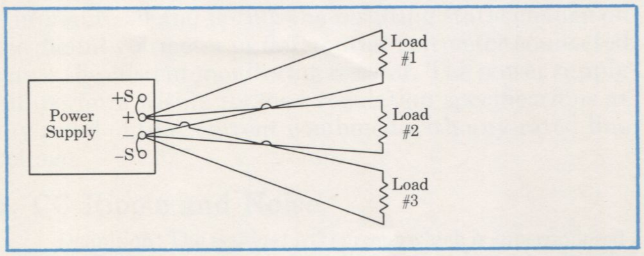


Figure 54B. Correct DC Power Distribution Using Local (Normal) Sensing.

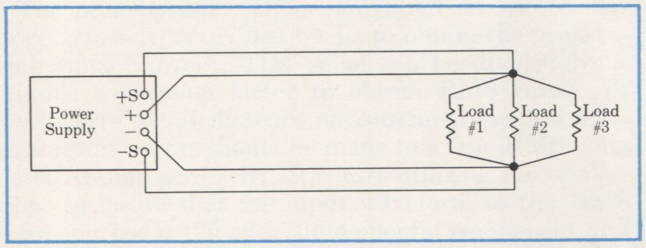


Figure 54C. Correct DC Power Distribution Using Remote Sensing.

Since the output impedance of a well-regulated power supply is extremely low, frequently less than a milliohm, any load wire common to two or more loads seriously increases the mutual coupling. This mutual coupling effect can be particularly serious in logic circuitry, where improper load wiring may result in large spikes being developed across the impedance of the load leads, with such spikes causing false triggering of other logic circuits fed from the same power supply leads.

To achieve proper DC power distribution without mutual coupling effects, one must first decide where the distribution terminals of the power system will be located. If the output terminals of the power supply are to be used as the distribution point, then local sensing is employed and each of the several load devices being fed by the power supply must have *separate pairs* of leads connected directly from the load to the power supply terminals as shown in Figure 54B.

If the distribution terminals are to be located separately from the power supply output terminals, then remote sensing should be employed between the power supply output and the remote distribution terminals by a *separate pair* of leads (Figure 54C). It will be desirable in most cases to add a large electrolytic capacitor across the remote distribution terminals to further minimize mutual coupling effects at high frequencies. However, the precautions described under Section B3 "Remote Error Sensing" should be observed.

D2. DUAL OUTPUT USING RESISTIVE DIVIDER

Often it is required to use both a positive and negative DC power source having roughly the same voltage and current capability. It might seem reasonable to meet such requirements using a single regulated DC power supply with a resistive voltage divider center-tapped to ground. Figure 55 shows, however, that such an arrangement results in a drastic increase in the effective DC source impedance feeding each load; assuming that the power supply has a zero output impedance, each load looks back into a source impedance consisting of the two arms of the voltage divider in parallel with each other and the other load resistance.

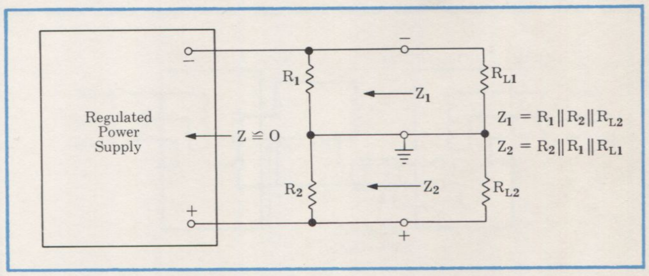
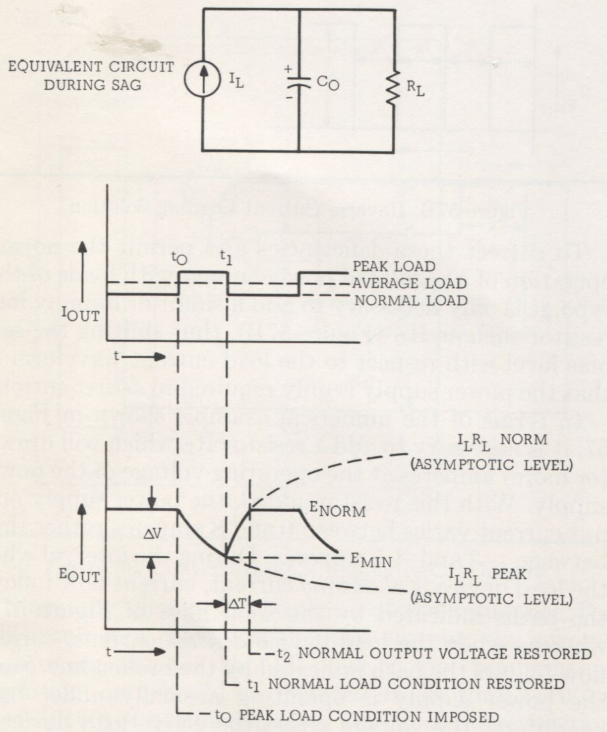


Figure 55. Center-tapped Power Supply Output.

Thus, a change in the current requirement of either load results not only in a change in its own DC voltage, but also in a change of the DC voltage feeding the other load, and extreme conditions of unbalance can develop. In nearly all cases, a simultaneous need for positive and negative DC voltages necessitates the use of two separate regulated power supplies.

D3. DUTY CYCLE LOADING

In some applications the load current varies periodically from a minimum to a maximum value. At first it might seem that a transistor regulated power supply having current rating in excess of the *average* load requirement (but less than the *peak* load value) would be adequate for such applications. However, it must be remembered that the current limit or constant current circuit within a semiconductor power supply limits the output current on an instantaneous, not an average basis, since such protection circuits must be extremely fast in order to provide adequate safeguard against burn-out of the series regulating elements.



$$\text{VOLTAGE SAG} = \Delta V = E_{NORM} - E_{MIN} = \left(E_{NORM} - I_LR_{L\ PEAK}\right)\left(1 - e^{\frac{-(t_1 - t_O)}{R_LC_O}}\right)$$

$$\text{SAG RECOVERY TIME} = \Delta T = t_2 - t_1 = R_LC_O \log_e \left(\frac{I_LR_{L\ NORM} - E_{MIN}}{I_LR_{L\ NORM} - E_{NORM}}\right)$$

Figure 56. Short-term Overload Equivalent Circuit and Output Voltage.

The first question which must be answered when powering a DC load which would draw a large current during some portion of its operating cycle is whether (1) the power supply need only *withstand* without damage or automatic turn-off the low load resistance corresponding to the peak load condition, or whether (2) the power supply must continue to deliver its full value of regulated output voltage during the peak load interval.

Examples of the first category are DC motors and filaments for large vacuum tubes. While the starting resistance of these loads is very low compared to the normal operating value, it is not necessary that the power supply be able to deliver this peak current—it is necessary that the supply withstand without damage this initial peak load condition and that it continue to operate through the peak load interval until normal load conditions are established. For such loads Constant Voltage/Constant Current or Constant Voltage/Current Limiting supplies rated for the normal (not the peak) load condition are adequate and, in some cases preferable, since the limited output current can provide protection for the load device during the peak load interval. Peak load demands in excess of the current rating of the power supply will not result in damage to the power supply; the output voltage will merely drop to a slightly lower value. Normal output voltage will be restored automatically by the power supply after the peak or transient load condition has passed.

As for the second category, if it is desired to meet a duty cycle requirement similar to that illustrated in Figure 56 *while retaining the full value of regulated output voltage during peak load conditions*, then a power supply must be selected which has a current rating equal to or greater than the *peak* load requirement. However, if the peak load condition is of relatively short duration, then the stored energy in the power supply output capacitor may prevent an excessive output voltage sag.

Thus for peak loads of either category (1) or (2), it is of interest to know how much the output voltage will drop for a *peak load condition in excess of the power supply current rating*, and how long it will take for the supply to recover to its normal output voltage following the removal of the overload. Figure 56 illustrates the equivalent circuit and output voltage waveform which are characteristic of a power supply experiencing a short term overload. When the overload condition is first imposed, the power supply goes into the current limit mode and is, therefore, equivalent to a constant current generator I_L feeding the output capacitor C_O (already charged to E_{NORM}) in parallel with the lowered value of load resistance $R_{L\ PEAK}$. Thus the capacitor C_O begins discharging exponentially toward the final output voltage value which would result if the overload condition were retained, namely $I_LR_{L\ PEAK}$. The amount of voltage sag ΔV depends upon the output time constant and the duration of the overload peak load condition; the equation for this voltage sag is given in Figure 56. When the peak load condition is removed, R_L is restored to its normal value and the supply continues in the current limiting mode, charging the output capacitor on another exponential curve. This time the asymptotic level approached by the exponential curve is $I_LR_{L\ NORM}$. However, this charging action stops when the voltage level has risen back up to the normal level, and the regulator changes from the current limit mode to the normal constant voltage mode. Figure 56 also gives the equation for the time required for this voltage recovery following the removal of the peak load condition.

Thus, the equations of Figure 56 enable one to evaluate whether the voltage sag and recovery time resulting from an overload condition lie within acceptable limits, thus permitting the use of a power supply having a current rating less than the peak load demand. For short term overloads, a quick approximation can be made to determine the amount of voltage sag:

$$\Delta V \cong \frac{(I_P - I_L)\ \Delta T}{C_O}$$

where:

ΔV = The voltage sag

$I_P = \dfrac{E_{NORM}}{R_{L\ PEAK}}$ = Peak load current demand

I_L = The current limit or constant current setting

C_O = The output capacitor (in farads)

ΔT = Duration of overload condition (in seconds)

This approximation is pessimistic since it assumes that the discharge of the output capacitor proceeds linearly at the rate of $\frac{I}{C}$ instead of decaying exponentially.

D4. REVERSE CURRENT LOADING

In some applications it is necessary for a power supply to retain its normal regulated output voltage in the presence of reverse current flow during part of the operating cycle of an active load device connected to the power supply. Such situations can arise, for example, in pulse and digital circuitry and in bias supplies for class C amplifiers.

Figure 57A illustrates the nature of this problem. It is assumed that the active load device normally draws a current of 5 amperes, but that during part of its operating cycle it *delivers* a current of 3 amperes. Since the series transistor cannot conduct current in the reverse direction, the reverse current furnished from the load device would charge the output capacitor of the power supply, causing an increase in the output voltage with loss of regulation and possible damage to the output capacitor and other components within the power supply.

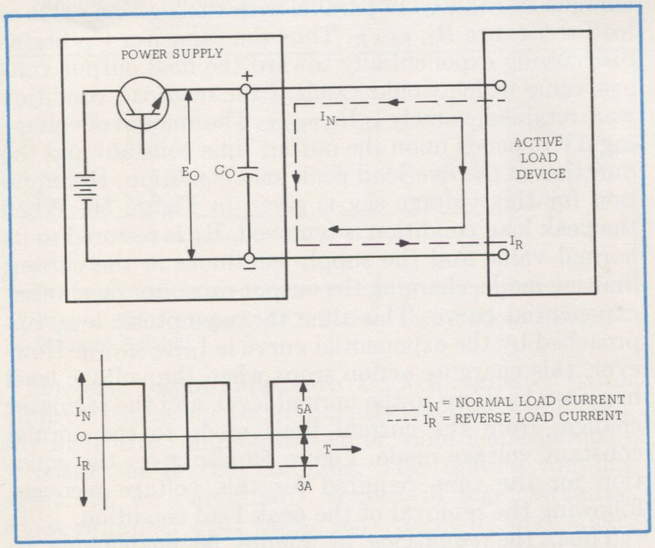


Figure 57A. Reverse Current Loading—Problem

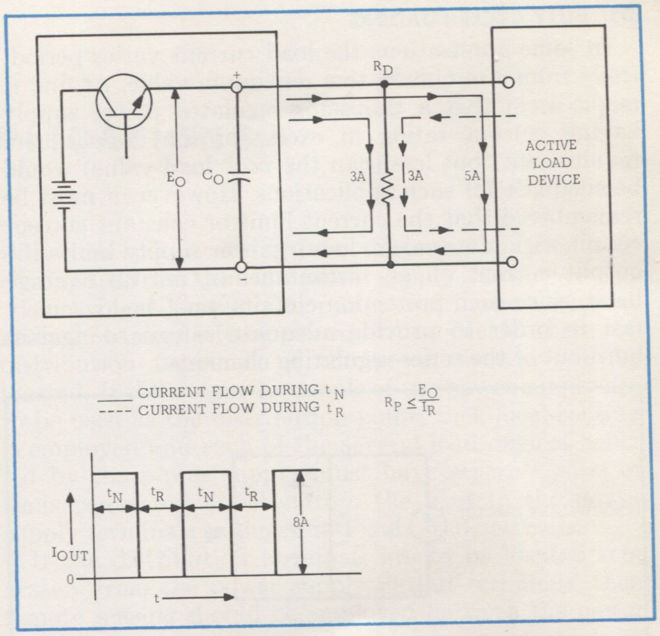


Figure 57B. Reverse Current Loading Solution.

To correct these deficiencies and permit the normal operation of a regulated power supply with loads of this type, it is only necessary to add a shunt or dummy load resistor such as R_D (Figure 57B), thus shifting the zero bias level with respect to the load current waveform so that the power supply is only required to *deliver* current.

In terms of the numerical example shown in Figure 57, it is necessary to add a resistor R_D which will draw 3 (or more) amperes at the operating voltage of the power supply. With this resistor added, the power supply output current varies between 0 and 8 amperes rather than between −3 and +5 amperes. During the interval when the load device is *absorbing* current, current flow follows the paths indicated by the solid lines of Figure 57B, whereas when the load device *delivers* current, current flow follows the path indicated by the broken line. Since the power supply is operating normally under both conditions, the voltage across the active load device is maintained continuously at the regulated level.

D5. CONVERTING A CONSTANT VOLTAGE POWER SUPPLY TO CONSTANT CURRENT OUTPUT

Many, but not all, hp power supplies are capable of constant current operation. Those which are not designed for normal operation as a constant current source can readily be converted, provided the supply has remote programming capability.

As Figure 58 indicates, it is only necessary to add a single external current monitoring resistor to a remote programming constant voltage power supply in order to convert it to constant current operation. (Also any 100 ohm resistor connected inside the supply from −S to −OUT must be removed.) Because the proper operation of hp regulator circuitry requires that the positive output and positive sensing terminals be at nearly the same potential, the external current monitoring resistor R_M must be connected to the positive output terminal, while the constant current load must be connected to the negative output terminal.* The front panel control (or remote programming control) is used to determine the voltage E across the current monitoring resistor R_M. Since this voltage E will be held equal to the voltage E_P across the control resistance by feedback action, a constant current $I_T = \frac{E}{R_M}$ will be caused to flow through the current monitoring resistor R_M. The load current I_L consists of the current flowing through monitoring resistor plus the programming current I_P (normally negligibly small compared to I_T). Both the current through the monitoring resistor and the programming current are held constant by regulator action; thus the net load current is also constant.

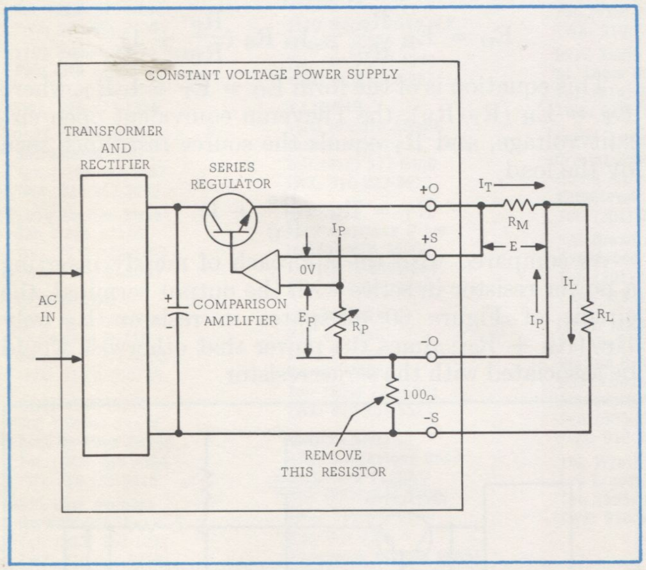


Figure 58. Converting a CV Supply to CC Output.

Since any change in the value of the resistance R_M will result in a change in the load current, the current monitoring resistor should have a low temperature coefficient and should be operated at less than 1/10 (or even 1/100) of its power rating. This, plus the restriction that the total IR drop across R_M and R_L in series cannot exceed the voltage rating of the power supply, means that R_M will be selected so that its IR drop will be of the order of 1 volt, depending upon the constant current value required.

The constant current performance of a supply connected in the method shown in Figure 58 can be predicted by dividing the constant voltage specification by the value of R_M, and then adding on a percentage basis any change in the value of R_M due to temperature effects. The lowest constant current output level is limited to the programming current I_P, typically 5 milliamps.

More details on this method of adapting constant voltage power supplies to constant current applications, including all design details necessary for the proper selection of R_M, are discussed in an hp Application Note on this topic, which is available free on request.

D6. AUTOMATIC BATTERY CHARGING

Automatic battery charging is readily accomplished using any hp CV/CC or CV/CL power supply with automatic crossover. For such applications, current limiting supplies differ from constant current supplies only in the accuracy of the charge rate setting; in both cases, the constant voltage limit can be set with sufficient accuracy to avoid overcharging or "gassing".

Operation is extremely simple; one need only short the output terminals of the supply and set the current limit or constant current control to the desired charge rate (amperes = coulombs/second). Next, the output terminals are left open and the voltage control is set for the final value of voltage to which it is desired to charge the battery. Finally, the battery, regardless of its state of charge, is connected directly across the output terminals of the supply. Charging action is completely automatic, and it is not necessary for an attendant to monitor the battery during charging or to readjust any controls on the power supply.

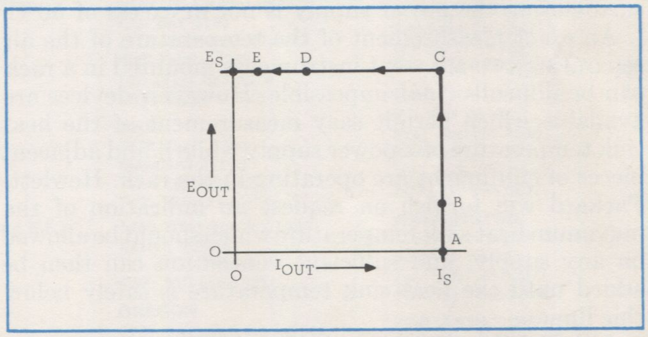


Figure 59. Operating Locus of a Supply Used for Battery Charging.

A completely uncharged battery will in most cases appear as something approximating a short circuit being fed by a constant current I_S, the front panel current control setting. This is shown as operating point A in Figure 59. As the charging action proceeds, the voltage across the battery increases, with the current through the battery still remaining constant (Point B). When the charging action nears completion, the voltage across the battery achieves a level corresponding to point C, and the power supply automatically transfers to constant voltage operation, reducing the charging current to whatever value is necessary to maintain the battery voltage at the value E_S, the front panel voltage control setting. The power supply proceeds through operating point D to point E, the full charge point. Notice that this final operating point has associated with it some small value of current which will exactly offset the leakage current within the battery. Thus the battery remains in its fully charged condition, with a trickle charge being provided until the battery is removed from the power supply terminals and placed into service.

In some battery charging applications, the internal resistance of the battery is such that its IR drop (not the current limit setting of the power supply) limits the current value of the charging current. This has the effect of decreasing the charge rate as the battery voltage is increased, but the final voltage to which the battery

---

*For supplies employing PNP power transistors and a negative common circuit configuration, the current monitoring resistor R_M must be connected to the negative output terminal and all polarities associated with this paragraph and Figure 58 are reversed.

charges remains the same, and automatic unattended battery charging is still accomplished in a fool-proof fashion.

Automatic battery discharging can also be accomplished using hp CV/CC and CV/CL power supplies. Contact the factory for further information.

D7. OPERATION AT ELEVATED TEMPERATURES

Almost all hp power supplies are rated for operation at 0°C to 50°C (32°F to 122°F) ambient temperature without degradation of output rating or any other specifications. Care must be taken, however, when rack mounting power supplies closely together or in proximity with other heat-producing units that the power supplies are not surrounded by an actual air temperature greater than 50°C. An unventilated rack full of equipment may surround a power supply with an effective ambient of 55°C or 60°C even though the room temperature is kept at or below 40°C. In such cases, ventilation must be provided to insure that the temperature immediately surrounding the power supply is not in excess of 50°C.

An exact measurement of the temperature of the air separating two adjacent instruments mounted in a rack can be difficult if not impossible. However, devices are available which permit easy measurement of the heat sink temperature of a power supply while it and adjacent pieces of equipment are operating in the rack. Hewlett-Packard will furnish on request an indication of the maximum heat sink temperature which should be allowed on any supply, and sufficient ventilation can then be added until the heat sink temperature is safely below this limit.

Although rated for a maximum of 50°C ambient, most hp power supplies can be operated at somewhat higher temperatures under certain circumstances. Further information concerning any necessary derating can be furnished on request and depends on the model number, the input line voltage, and the output voltage and current.

D8. INCREASING THE OUTPUT RESISTANCE OF A POWER SUPPLY

Normally it is desired to use a regulated Constant Voltage power supply with an output impedance as close to zero as possible. In some cases, however, it is desired to increase the output resistance in a predictable and controlled fashion. Such applications arise, for example, when it is desired to simulate a battery, a less-well-regulated power supply, to produce a power supply whose output voltage decays linearly with output current according to some prescribed formula, or when feeding a negative resistance load device. The following paragraphs outline a method for increasing the output resistance of a well-regulated Constant Voltage power supply. This procedure is applicable to all supplies which are remotely programmable, regardless of rating.

To increase the output resistance of a Constant Voltage power supply of small or even moderate output current capability, it is practical to add a resistor of the desired value in series with the output terminal. However, if it is desired to increase the output resistance of a high current power supply, or to conveniently vary this output resistance, the method of adding a single output resistor becomes impractical because of the dissipation required and the lack of easily varied high power resistors. In such instances, the external addition of a small load current resistor R_S and an associated feedback resistor R_U (see Figure 60) causes the load voltage to drop with output current in a predictable and remotely controllable fashion.

The output voltage equation is

$$E_O = E_R \frac{R_P}{R_R} - I_O R_S \left(\frac{R_P}{R_U} + 1\right).$$

This equation is of the form $E_O = E_T - I_O R_T$, where $E_T = E_R (R_P/R_R)$, the Thevenin equivalent open circuit voltage, and R_T equals the source resistance seen by the load,

$$R_T = R_S \left(\frac{R_P}{R_U} + 1\right).$$

As compared with the approach of merely inserting a power resistor in series with the output terminal, the circuit of Figure 60 dissipates in resistor R_S only $R_U/(R_P + R_U)$ times the power that otherwise would be associated with the series resistor.

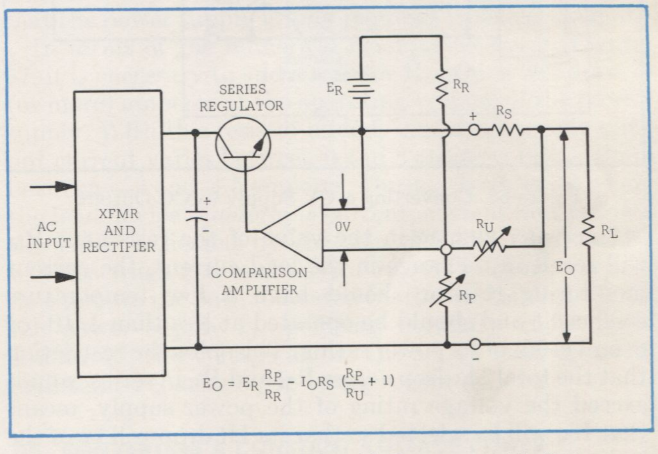


Figure 60. CV Power Supply with Programmable Output Resistance.

In operation, R_P is first set to the desired output voltage value E_T with no load applied; then, R_L is attached and varied until some designated output current is flowing through the load. R_U is then adjusted so that the voltage across the load E_O becomes the desired value at that load current.

A more detailed description on how to increase the output resistance of a constant voltage power supply is given in Application Note 83, available free on request.

HEWLETT-PACKARD SALES AND SERVICE OFFICES

UNITED STATES

ALABAMA
P.O. Box 4207
2003 Byrd Spring Road S.W.
Huntsville 35802
TWX: 510-579-2204
Tel: (205) 881-4591

ARIZONA
3009 North Scottsdale Road
Scottsdale 85251
Tel: (602) 945-7601
TWX: 910-950-1282

232 South Tucson Boulevard
Tucson 85716
Tel: (602) 623-2564
TWX: 910-952-1162

CALIFORNIA
3939 Lankershim Boulevard
North Hollywood 91604
Tel: (213) 877-1282
TWX: 910-499-2170

1101 Embarcadero Road
Palo Alto 94303
Tel: (415) 327-6500
TWX: 910-373-1280

2591 Carlsbad Avenue
Sacramento 95821
Tel: (916) 482-1463
TWX: 910-367-2092

1055 Shafter Street
San Diego 92106
Tel: (714) 223-8103
TWX: 910-335-2000

COLORADO
7965 East Prentice
Englewood 80110
Tel: (303) 771-3455
TWX: 910-935-0705

CONNECTICUT
508 Tolland Street
East Hartford 06108
Tel: (203) 289-9394
TWX 710-425-3416

111 East Avenue
Norwalk 06851
Tel: (203) 853-1251
TWX: 710-468-3750

DELAWARE
3941 Kennett Pike
Wilmington 19807
Tel: (302) 655-6161
TWX: 510-666-2214

FLORIDA
Suite 106
9999 N.E. 2nd Avenue
Miami Shores 33138
Tel: (305) 758-3626
TWX: 810-848-7262

P.O. Box 20007
Herndon Station 32814
621 Commonwealth Avenue
Orlando
Tel: (305) 841-3970
TWX: 810-850-0113

P.O. Box 8128
Madeira Beach 33708
410 150th Avenue
St. Petersburg
Tel: (813) 391-0211
TWX: 810-863-0366

GEORGIA
3110 Maple Drive N.E.
Atlanta 30305
Tel: (404) 233-1141
TWX: 810-751-3283

ILLINOIS
5500 Howard Street
Skokie 60076
Tel: (312) 677-0400
TWX: 910-223-3613

INDIANA
4002 Meadows Drive
Indianapolis 46205
Tel: (317) 546-4891
TWX: 810-341-3263

LOUISIANA
P.O. Box 856
1942 Williams Boulevard
Kenner 70062
Tel: (504) 721-6201
TWX: 810-955-5524

MARYLAND
6707 Whitestone Road
Baltimore 21207
Tel: (301) 944-5400
TWX: 710-862-0850

P.O. Box 727
Twinbrook Station 20851
12303 Twinbrook Parkway
Rockville
Tel: (301) 427-7560
TWX: 710-828-9684

MASSACHUSETTS
Middlesex Turnpike
Burlington 01803
Tel: (617) 272-9000
TWX: 710-332-0382

MICHIGAN
24315 Northwestern Highway
Southfield 48076
Tel: (313) 353-9100
TWX: 810-232-1532

MINNESOTA
2459 University Avenue
St. Paul 55114
Tel: (612) 646-7881
TWX: 910-563-3734

MISSOURI
9208 Wyoming Place
Kansas City 64114
Tel: (816) 333-2445
TWX: 910-771-2087

2812 South Brentwood Blvd.
St. Louis 63144
Tel: (314) 644-0220
TWX: 910-760-1670

NEW JERSEY
Crystal Brook Prof. Bldg.
Route 35
Eatontown
Tel: (201) 747-1060

391 Grand Avenue
Englewood 07631
Tel: (201) 567-3933
TWX: 710-991-9707

NEW MEXICO
P.O. Box 8366
Station C 87108
6501 Lomas Boulevard N.E.
Albuquerque
Tel: (505) 255-5586
TWX: 910-989-1665

156 Wyatt Drive
Las Cruces 88001
Tel: (505) 526-2486
TWX: 910-983-0550

NEW YORK
1219 Campville Road
Endicott 13760
Tel: (607) 754-0050
TWX: 510-252-0890

236 East 75th Street
New York 10021
Tel: (212) 879-2023
TWX: 710-581-4376

82 Washington Street
Poughkeepsie 12601
Tel: (914) 454-7330
TWX: 510-248-0012

39 Saginaw Drive
Rochester 14623
Tel: (716) 473-9500
TWX: 510-253-5981

1025 Northern Boulevard
Roslyn, Long Island 11576
Tel: (516) 869-8400
TWX: 510-223-0811

5858 East Molloy Road
Syracuse 13211
Tel: (315) 454-2486
TWX: 710-541-0482

NORTH CAROLINA
P.O. Box 5187
1923 North Main Street
High Point 27262
Tel: (919) 882-6873
TWX: 510-926-1516

OHIO
5579 Pearl Road
Cleveland 44129
Tel: (216) 884-9209
TWX: 810-421-8500

1250 West Dorothy Lane
Dayton 45409
Tel: (513) 298-0351
TWX: 810-459-1925

OREGON
2737 S.W. Corbett Avenue
Portland 97201
Tel: (503) 228-5107

PENNSYLVANIA
Park Place Office Building
Camp Hill
Tel: (717) 737-6791

Monroe Complex
Moss Side Boulevard
Monroeville 15146
Tel: (412) 271-0724
TWX: 710-797-3650

144 Elizabeth Street
West Conshohocken 19428
Tel: (215) 248-1600, 828-6200
TWX: 510-660-8715

TEXAS
P.O. Box 7166
3605 Inwood Road
Dallas 75209
Tel: (214) 357-1881
TWX: 910-861-4081

P.O. Box 22813
4242 Richmond Avenue
Houston 77027
Tel: (713) 667-2407
TWX: 910-881-2645

GOVERNMENT CONTRACT OFFICE
225 Billy Mitchell Road
San Antonio 78226
Tel: (512) 434-4171
TWX: 910-871-1170

UTAH
2890 South Main Street
Salt Lake City 84115
Tel: (801) 486-8166
TWX: 910-925-5681

VIRGINIA
P.O. Box 6514
2111 Spencer Road
Richmond 23230
Tel: (703) 282-5451
TWX: 710-956-0157

WASHINGTON
11656 N.E. Eighth Street
Bellevue 98004
Tel: (206) 454-3971
TWX: 910-443-2303

FOR AREAS NOT LISTED, CONTACT:
Hewlett-Packard
1501 Page Mill Road
Palo Alto, California 94304
Tel: (415) 326-7000
TWX: 910-373-1267
Telex: 34-8461

CANADA

BRITISH COLUMBIA
Hewlett-Packard (Canada) Ltd.
2184 West Broadway
Vancouver
Tel: (604) 738-7520
TWX: 610-922-5050

ONTARIO
Hewlett-Packard (Canada) Ltd.
880 Lady Ellen Place
Ottawa 3
Tel: (613) 722-4223
TWX: 610-562-1952

Hewlett-Packard (Canada) Ltd.
1415 Lawrence Avenue West
Toronto
Tel: (416) 249-9196
TWX: 610-492-2382

QUEBEC
Hewlett-Packard (Canada) Ltd.
275 Hymus Boulevard
Pointe Claire
Tel: (514) 697-4232
TWX: 610-422-3022
Telex: 01-2819

FOR AREAS NOT LISTED, CONTACT:
Hewlett-Packard Inter-Americas
1501 Page Mill Road
Palo Alto, California 94304
Tel: (415) 326-7000
TWX: 910-373-1267
Telex: 034-8461
Cable: HEWPACK Palo Alto

More than 50 international sales and service offices are established. For sales and service assistance, request the name and address of the nearest office from:

CENTRAL AND SOUTH AMERICA

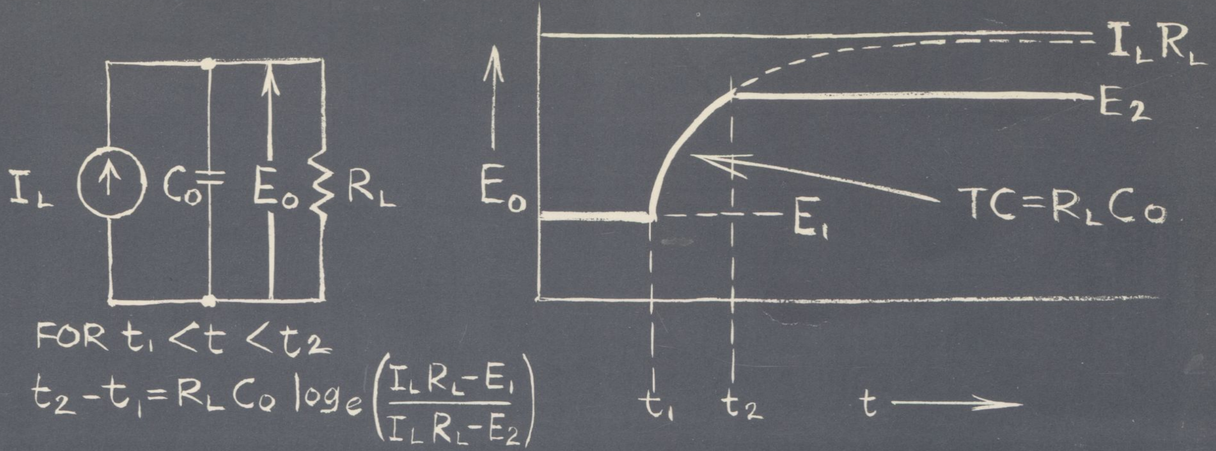
Hewlett-Packard Inter-Americas
1501 Page Mill Road
Palo Alto, California 94304
Tel: (415) 326-7000
TWX: 910-373-1267
Telex: 034-8461
Cable: HEWPACK Palo Alto

EUROPE

Hewlett-Packard S.A.
54 Route des Acacias
Geneva, Switzerland
Tel: (022) 42 81 50
Telex: 2.24.86
Cable: HEWPACKSA Geneva

AFRICA, ASIA, AUSTRALIA

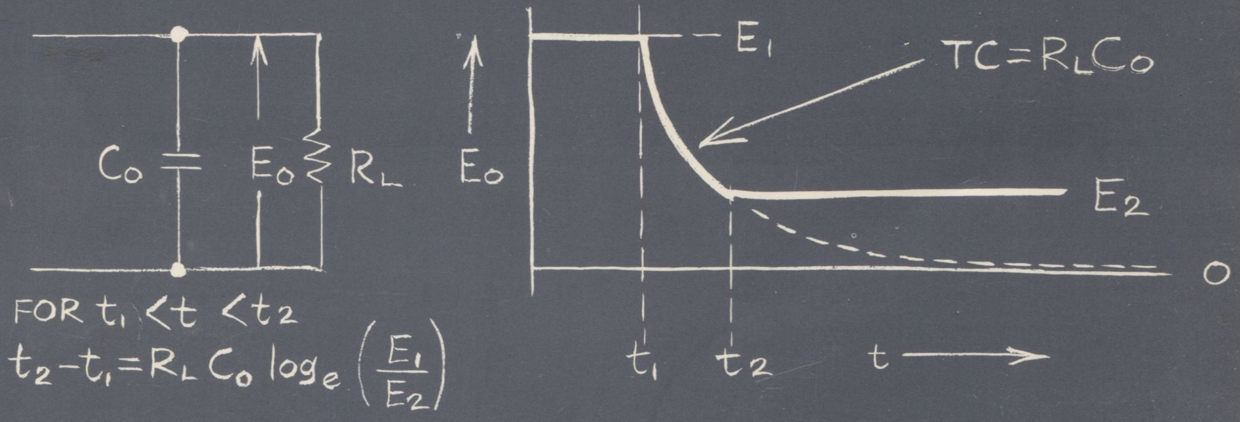
Hewlett-Packard Export Marketing
1501 Page Mill Road
Palo Alto, California 94304
Tel: (415) 326-7000
Telex: 034-8461
Cable: HEWPACK Palo Alto



FOR $t_1 < t < t_2$

$$t_2 - t_1 = R_L C_O \log_e \left(\frac{I_L R_L - E_1}{I_L R_L - E_2} \right)$$

UP PROGRAMMING



FOR $t_1 < t < t_2$

$$t_2 - t_1 = R_L C_O \log_e \left(\frac{E_1}{E_2} \right)$$

DOWN PROGRAMMING

HEWLETT PACKARD hp HARRISON DIVISION

100 Locust Avenue, Berkeley Heights, New Jersey 07922, U. S. A. Tel. (201) 464-1234