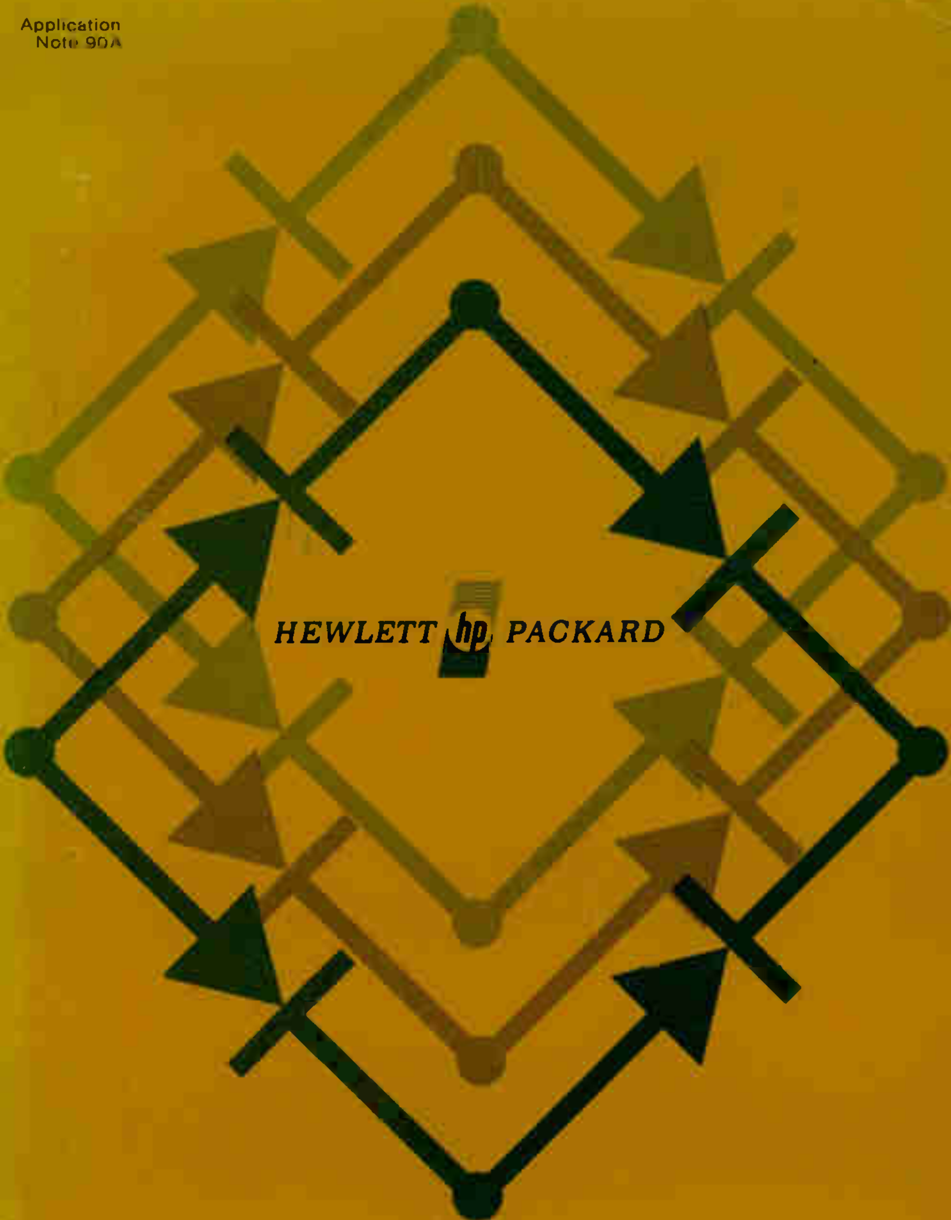
Application
Note 90A



DC POWER SUPPLY HANDBOOK

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DC POWER SUPPLY HANDBOOK

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INTRODUCTION

Regulated power supplies employ engineering techniques drawn from the latest advances in many disciplines such as: low-level, high-power, and wide-band amplification techniques; operational amplifier and feedback principles; pulse circuit techniques; and the constantly expanding frontiers of solid state component development.

The full benefits of the engineering that has gone into the modern regulated power supply cannot be realized unless the user first recognizes the inherent versatility and high performance capabilities, and second, understands how to apply these features. This handbook is designed to aid that understanding by providing complete information on the operation, performance, and connection of regulated power supplies.

The handbook is divided into six main sections: Definitions, Principles of Operation, AC and Load Connections, Remote Programming, Output Voltage and Current Ratings, and Performance Measurements. Each section contains answers to many of the questions commonly asked by users, like:

- What is meant by auto-tracking operation?
- What is the difference between a constant voltage/constant current power supply and a constant voltage/current limit supply?
- When should remote sensing at the load be used?
- How can ground loops in multiple loads be avoided?
- What factors affect programming speed?
- What are the techniques for measuring power supply performance?

In summary, this is a book written not for the theorist, but for the user attempting to solve both traditional and unusual application problems of regulated power supplies.

CONTENTS

DEFINITIONS

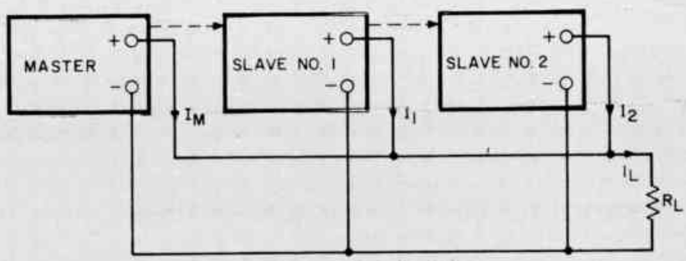
AMBIENT TEMPERATURE

The room temperature or temperature of the air surrounding the power supply.

AUTOMATIC (AUTO) PARALLEL OPERATION

A master-slave parallel connection of the outputs of two or more 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 identical supplies may be connected in Auto-Parallel; in certain cases, however, supplies of the same series are capable of mixed Auto-Parallel operation.

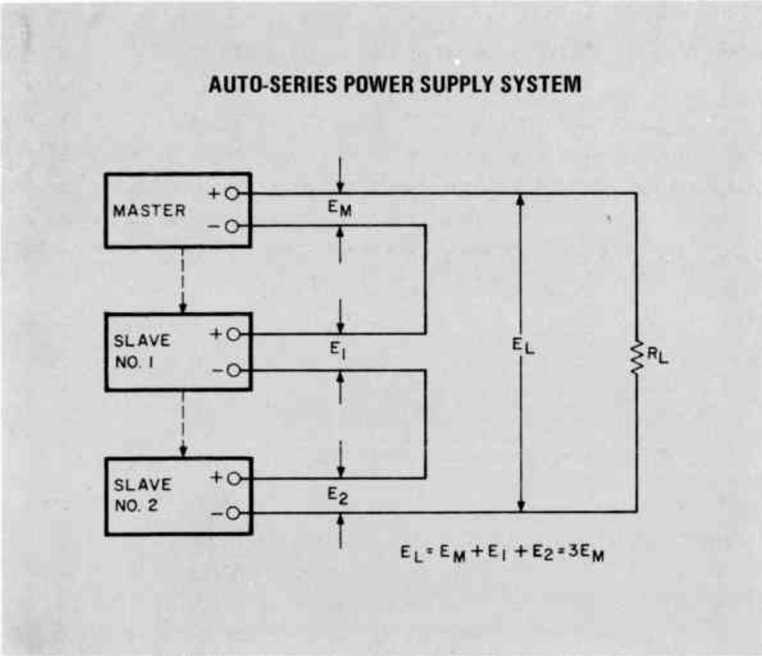
AUTO-PARALLEL POWER SUPPLY SYSTEM



$I_L = I_M + I_1 + I_2 = 3I_M$

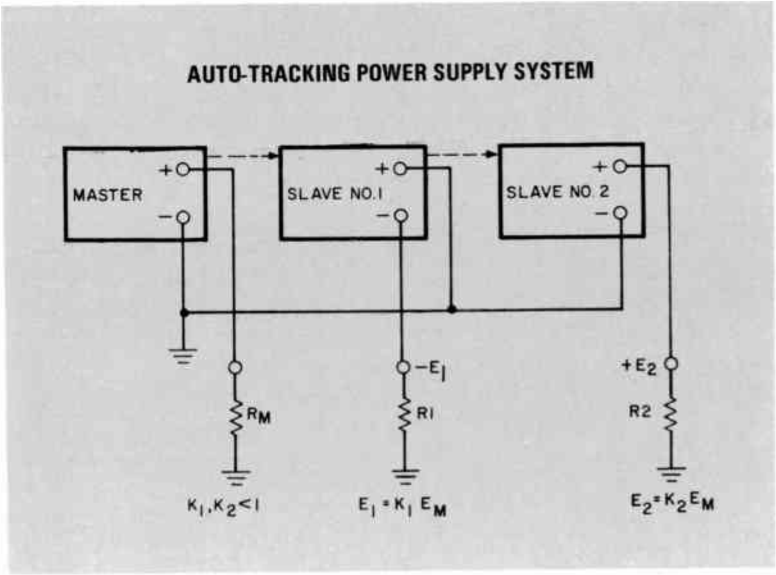
AUTOMATIC (AUTO) SERIES OPERATION

A master-slave series connection of the outputs of two or more 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. Different power supplies may be connected in Auto-Series without restriction, provided that each slave is capable of Auto-Series operation.



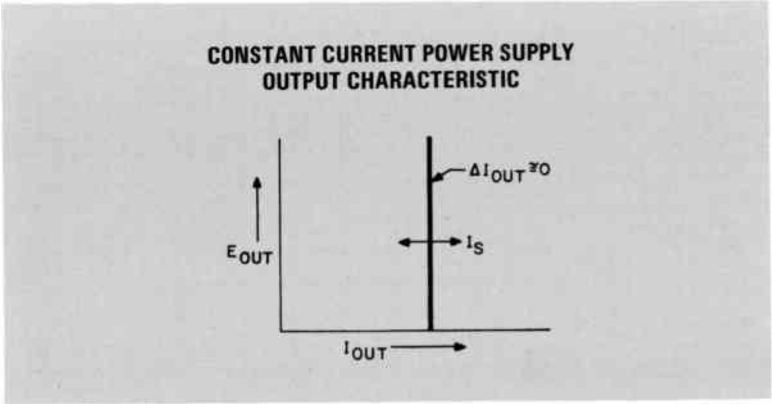
AUTOMATIC (AUTO) TRACKING OPERATION

A master-slave connection of two or more 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. Auto-Tracking operation is 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.



CONSTANT CURRENT POWER SUPPLY

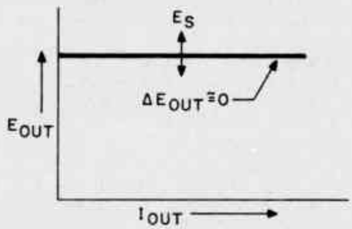
A regulated power supply that acts to maintain its output current constant in spite of changes in load, line, temperature, etc. Thus, for a change in load resistance, the output current remains constant while the output voltage changes by whatever amount necessary to accomplish this.



CONSTANT VOLTAGE POWER SUPPLY

A regulated power supply that acts to maintain its output voltage constant in spite of changes in load, line, temperature, etc. Thus, for a change in load resistance, the output voltage of this type of supply remains constant while the output current changes by whatever amount necessary to accomplish this.

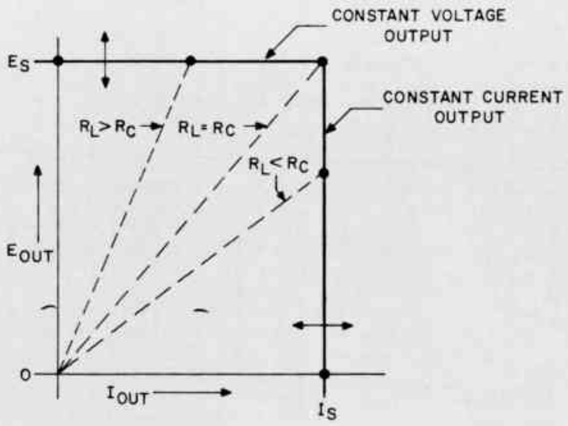
CONSTANT VOLTAGE POWER SUPPLY
OUTPUT CHARACTERISTIC



CONSTANT VOLTAGE/CONSTANT CURRENT (CV/CC) POWER SUPPLY

A power supply that acts as a constant voltage source for compara-

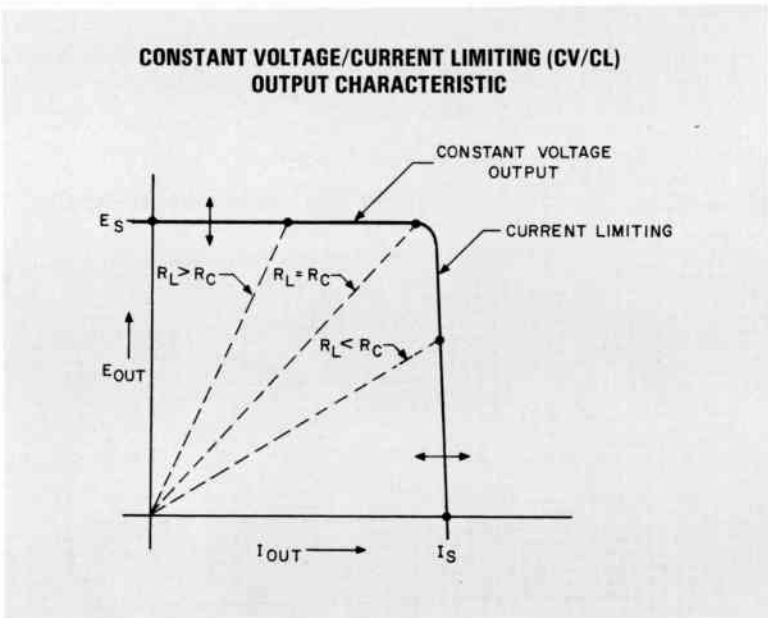
CONSTANT VOLTAGE/CONSTANT CURRENT (CV/CC)
OUTPUT CHARACTERISTIC



tively 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.

CONSTANT VOLTAGE/CURRENT LIMITING (CV/CL) POWER SUPPLY

A supply similar to a CV/CC supply except for less precise regulation at low values of load resistance, i.e., in the constant current or current limiting region of operation.



DRIFT (See Stability)

LINE REGULATION OF A CONSTANT CURRENT POWER SUPPLY

The change in the steady state value of the dc output current due to a change in the input line voltage from low line to high line, or from high line to low line.

LINE REGULATION OF A CONSTANT VOLTAGE POWER SUPPLY

The change in the steady state value of the dc output voltage due to a change in the input line voltage from low line to high line, or from high line to low line.

LOAD REGULATION OF A CONSTANT CURRENT POWER SUPPLY

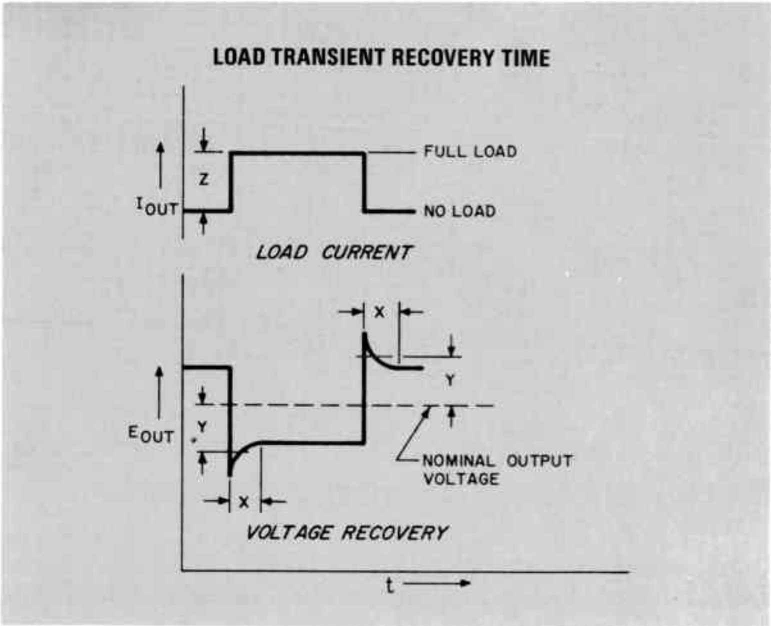
The change in the steady state value of the dc output current due to a change in load resistance from short circuit to a value which results in maximum rated output voltage.

LOAD REGULATION OF A CONSTANT VOLTAGE POWER SUPPLY

The change in the steady state value of dc output voltage due to a change in load resistance from open circuit to a value which results in maximum rated output current.

LOAD 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 return to within a level approximating the normal dc output following a sudden change in load current. More exactly, Load Transient Recovery Time for a CV supply is the time "X" required for the output voltage to recover to, and stay within "Y" millivolts of the nominal output voltage following a "Z" amp step change in load current—where:

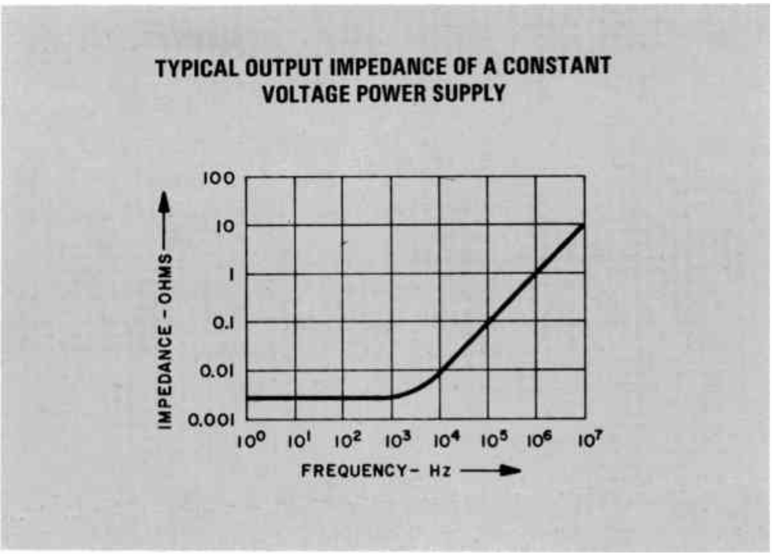
(1) "Y" is specified separately for each model but is generally of the same order as the load regulation specification.

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

(3) "Z" is the specified load current change, typically equal to the full load current rating of the supply.

OUTPUT IMPEDANCE OF A POWER SUPPLY.

At any frequency of load change, $\Delta E_{OUT}/\Delta I_{OUT}$. Strictly speaking, the definition applies only for a sinusoidal load disturbance, unless 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.



OVERVOLTAGE CROWBAR PROTECTION CIRCUIT

A separate circuit that monitors the output of a power supply and rapidly places a low resistance shunt (or "crowbar") across the output terminals of the power supply whenever a preset voltage limit is exceeded, thereby initiating action to reduce the output voltage to a low value.

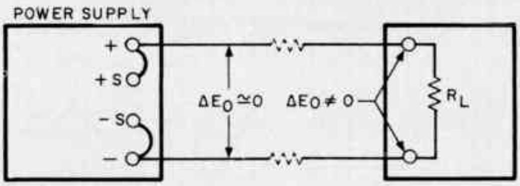
PROGRAMMING SPEED

The time required following the onset of a step change in the programming input for the output to change from an initial value to within a certain band of the newly programmed value. This band is typically specified in millivolts for a well regulated CV supply, and in milliamps for a CC supply.

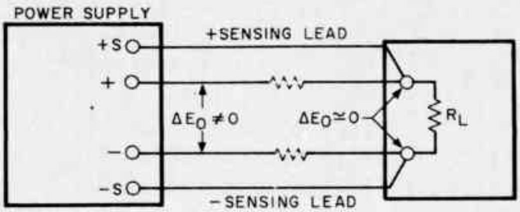
REMOTE ERROR SENSING, OR REMOTE SENSING

A means whereby a constant voltage power supply monitors and regulates its output voltage directly at the *load* terminals (instead of the power supply output terminals). Two low current sensing leads are connected between the load terminals and special sensing terminals located on the power supply, permitting the power supply output voltage to compensate for IR drops in the load leads and achieve optimum regulation at the remote load terminals.

POWER SUPPLY AND LOAD CONNECTED NORMALLY



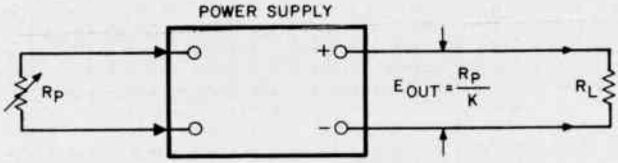
POWER SUPPLY AND LOAD CONNECTED FOR REMOTE SENSING



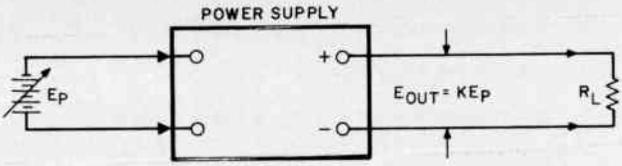
REMOTE PROGRAMMING

Control of the regulated output voltage or current of a power supply 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 page 90.

REMOTE PROGRAMMING USING RESISTANCE CONTROL



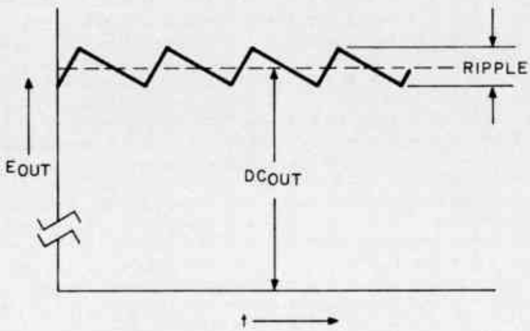
REMOTE PROGRAMMING USING VOLTAGE CONTROL



RIPPLE AND NOISE

The residual ac component which is superimposed on the dc out-

DC OUTPUT OF POWER SUPPLY AND SUPERIMPOSED RIPPLE COMPONENT



put 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 20MHz. Measuring ripple and noise with an instrument that has insufficient bandwidth may conceal high frequency spikes detrimental to the load.

STABILITY

Obviously a misnomer, this term refers to the *instability* in power supply output which occurs in the presence of constant load, constant ac input 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.

TEMPERATURE COEFFICIENT

For a power supply operated at constant load and constant ac input, the maximum permissible 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.

PRINCIPLES OF OPERATION

Electronic power supplies are 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 frequency changers

(2) dc in, dc out—converters and dc regulators

(3) dc in, ac out—inverters

(4) ac in, dc out

This last category 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.

Four basic outputs or modes of operation can be provided by dc output power supplies:

Constant Voltage: Maintains the output *voltage* constant in spite of changes in load, line, or temperature.

Constant Current: Maintains the output *current* constant in spite of changes in load, line, or temperature.

Voltage Limit: Same as Constant Voltage except for less precise regulation characteristics.

Current Limit: Same as Constant Current except for less precise regulation characteristics.

As explained in this section, power supplies are designed to offer these outputs in various combinations for different applications.

CONSTANT VOLTAGE POWER SUPPLY

An ideal constant voltage power supply would have zero output impedance at all frequencies. Thus, as shown in Figure 1, the voltage would remain perfectly constant in spite of any changes in output current demanded by the load.

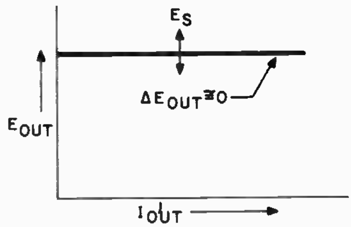


Figure 1. Ideal Constant Voltage Power Supply Output Characteristic

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. A control element is interposed either in shunt or in series with the rectifier and the load device to form a *regulated* power supply. The shunt regulator is less often used than the series regulator, because it must withstand the full output voltage under normal operating conditions and is less efficient for most applications. Figure 2 shows a simplified schematic of a power supply employing a series regulator, or series control element, that acts as a variable resistance connected in series with the load resistor.

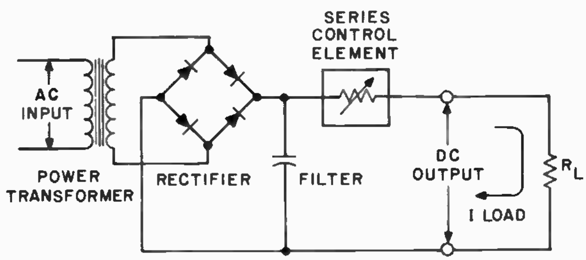


Figure 2. Basic Series Regulated Supply

PRINCIPLES OF OPERATION

Series Regulated Power Supply

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

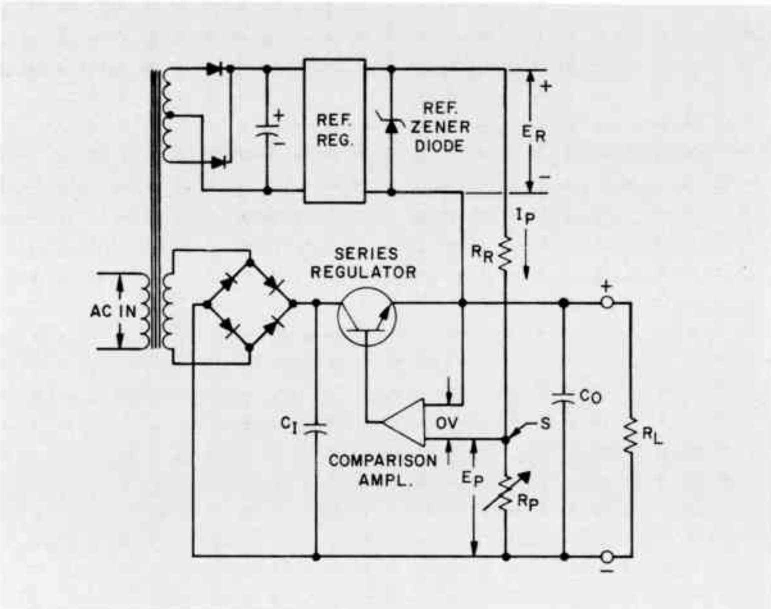


Figure 3. Series Regulated Constant Voltage Power Supply

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 produces an amplified difference (error) signal. This signal is of such a magnitude and polarity as to change the conduction of the series regulator, thereby changing the current through the

*Throughout this Handbook NPN power transistors are employed as series regulating elements and the reference circuit and comparison amplifier are referenced to the positive output circuit (common). The use of PNP series power transistors would necessitate only reversing 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.

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 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, so 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.

The Regulated DC Power Supply—An Operational Amplifier

An operational amplifier (Figure 4) is a high gain dc amplifier that employs shunt negative feedback. The power supply, like an operational amplifier, is also a high gain dc amplifier in which degenerative feedback is arranged so the operational gain is the ratio of two resistors.

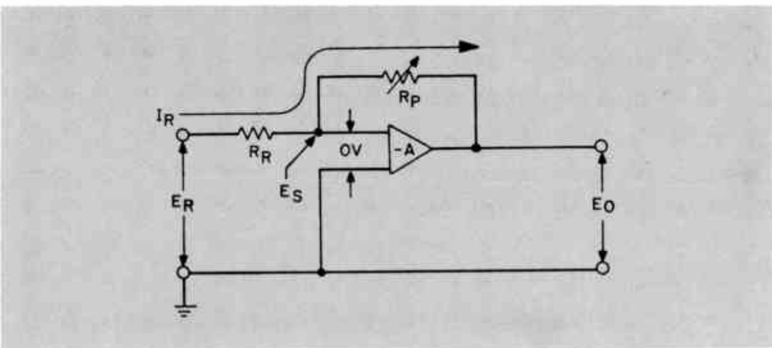


Figure 4. Operational Amplifier

As shown in Figure 4, the input voltage E_R is connected to the summing point via resistor R_R, and the output voltage is fed back to this same summing point through resistor R_P. Since the input impedance is very high, the input current to the amplifier 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, multiplying both sides by $R_R R_P$, we obtain

$$E_R R_P = E_S R_P + E_S R_R - E_0 R_R. \qquad (2)$$

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

$$E_0 = E_S(-A) \qquad (3)$$

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

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

Normally, the operational amplifier gain is very high, commonly 10,000 or more. In equation (4)

If we let $A \longrightarrow \infty$

Then $E_S \longrightarrow 0$ (5)

This important result enables us to say that the two input voltages of the comparison amplifier of Figure 4 (and Figure 3) are held equal by feedback action.

In modern well-regulated power supplies, the summing point voltage E_S is at most a few millivolts. Substituting $E_S = 0$ into equation (1) yields the standard gain expression for the operational amplifier

$$E_0 = -E_R \frac{R_P}{R_R}. \qquad (6)$$

Notice that from equation 6 and Figure 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).

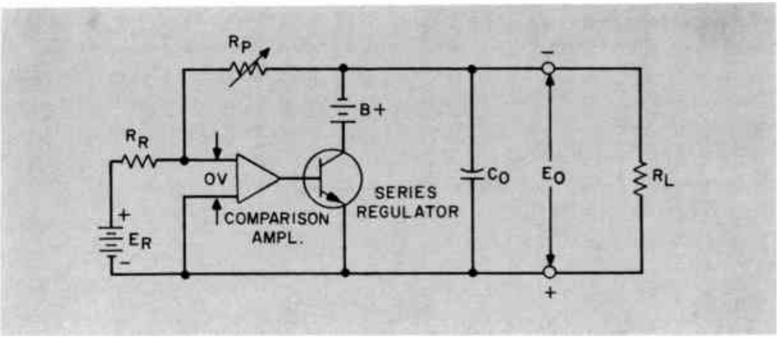


Figure 5. Operational Amplifier with DC Input Signal.

A large electrolytic capacitor is then added across the output terminals of the operational amplifier. 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) is much lower than the impedance of any load that might normally be connected to the amplifier output. Thus, the phase shift through the output terminals is independent of the phase angle of the load applied and depends 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.

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

Replacing the batteries of Figure 5 with rectifiers and a reference zener diode results in the circuit of Figure 6. A point by point comparison of Figures 3 and 6 reveals that they have identical topology —all connections are the same, only the position of the components on the diagram differs!

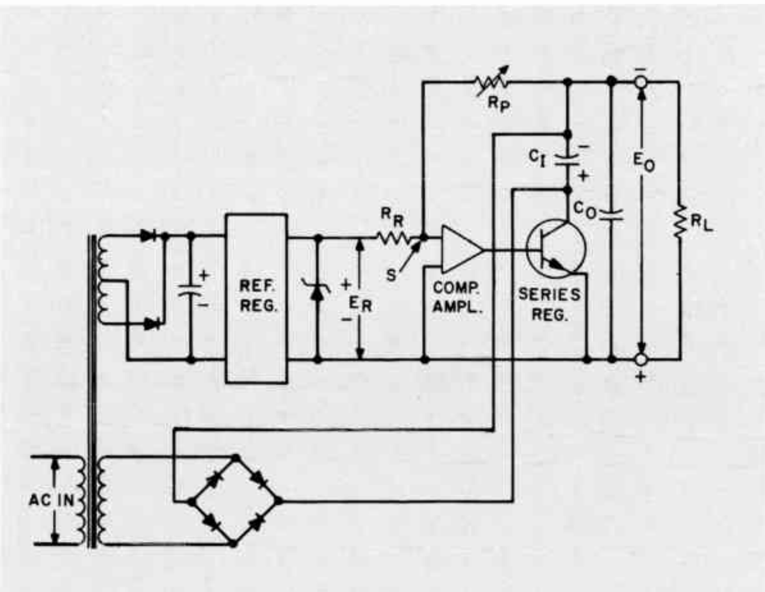


Figure 6. Operational Amplifier Representation of Adjustable CV Power Supply

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	Reference Voltage
Output Signal	Regulated DC
Amplifier	Regulator
Output Stage	Series Regulating Transistor
Bias Power Supply	Rectifier
Gain Control	Output Voltage Control

As a result of the specific method used in transforming an operational amplifier into a power supply, some restrictions are placed on the general behavior of the power supply. The most important of these are:

(1) The large output capacitor C_0 limits the bandwidth.*

(2) The use of a fixed dc input voltage means that the output voltage can only be one polarity, the opposite of the reference polarity. **

(3) The series regulator 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, and 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 any given power supply is suitable for a specific application and what limitations exist.

Variable Transformer Preregulated Power Supply

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

*Special design steps have been added to the design of most HP low voltage supplies to permit a significant reduction in the size of the output capacitor merely by manipulating straps on the rear barrier strip (see page 94).

**In the PS/A Series of Power Supply/Amplifiers this output capacitor is virtually eliminated by using a special feedback design. In addition, PS/A instruments are capable of ac output, conduct current in either direction, and their outputs are continuously variable through zero (see page 50).

resorting to some sort of preregulator in the rectifier path. The purpose of 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, minimizing the power dissipation in the series regulator elements. One of the simplest techniques for accomplishing this is shown in Figure 7. 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.

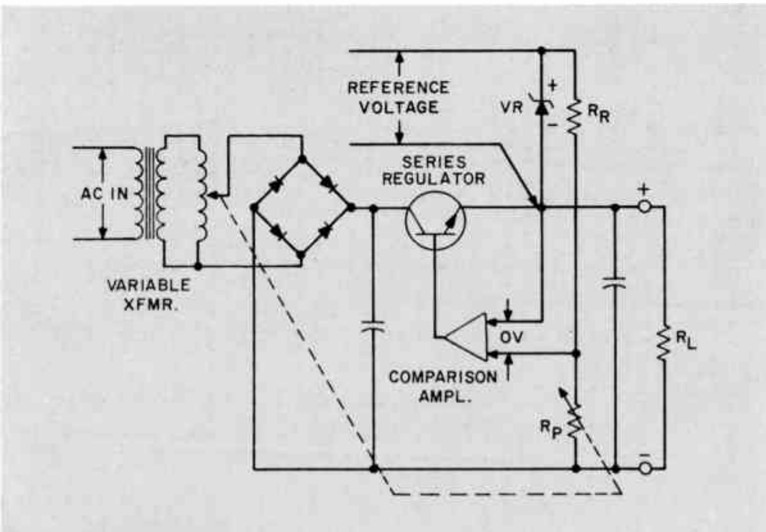


Figure 7. Constant Voltage Supply with Variable Transformer Preregulator

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, just as in a power supply with no preregulator.

SCR Preregulated Power Supply

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 8 shows a typical HP regulated dc power supply utilizing an SCR preregulator.

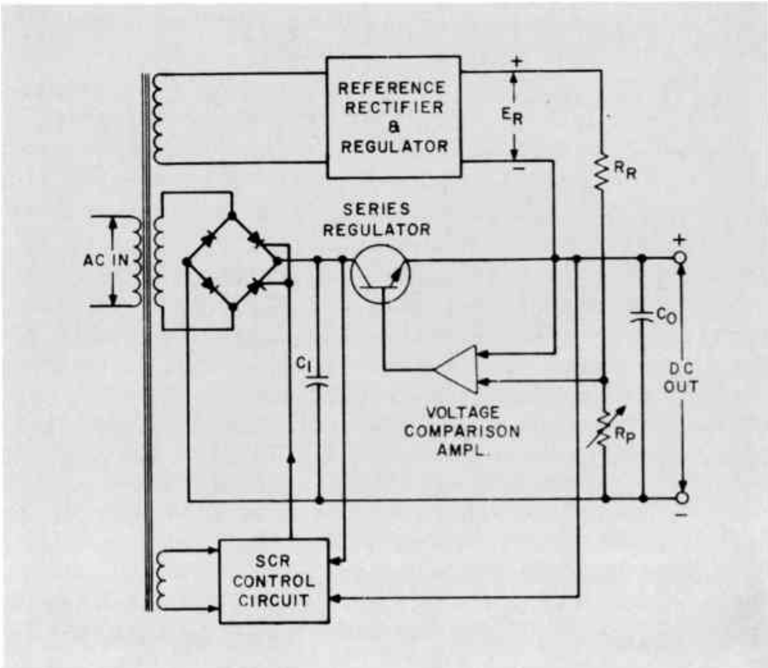


Figure 8. Constant Voltage Power Supply with SCR Preregulator

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.

On some recent preregulator designs, the SCR's are replaced by triacs, which are bidirectional devices. Whenever a gating pulse is received, the triac conducts current in a direction that is dependent on the polarity of the voltage across it.

Triacs are usually connected in series with one side of the input transformer primary, while SCR's are included in two arms of the bridge rectifier as shown in Figure 8. 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 imposed by the dc output voltage and current of the supply.

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 and hold the voltage drop across the series regulator constant in spite of changes in load current, output voltage, and input line voltage. The final burden of providing the precise *output* voltage regulation rests with a series regulator.

The reaction time of an HP SCR control circuit is much faster than conventional SCR or magamp circuits. 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 Hz input). The use of large electrolytic capacitors across the rectifier output allows only a small voltage change to occur during any 8 millisecond interval. Using this pre-regulator technique, the series regulator elements drop a relatively low voltage, without any risk of transient drop-out and loss of regulation due to changes in load or line. The use of this type of SCR pre-regulator results in a power supply having unusually high efficiency and reliability, since the power dissipated in the series regulator is held to a very small value.

The leakage inductance of the power transformer acts as a small filter choke in series with the SCRs. This inductance slows the in-rush current after firing, thus reducing the peak current through the SCRs, and improving their reliability. Since this inductance reduces the high frequency content of the energy flow through the SCRs, RFI effects are suppressed.

SCR Regulated Power Supply

In many applications the highly regulated performance capability of a series-regulated transistor power supply is not required. For medium and high power requirements, SCR circuit techniques permit the design of power supplies that are economical and yet have efficiency and performance characteristics superior to that obtainable from magamp supplies. Figure 9 illustrates a typical Hewlett Packard SCR regulated supply that is variable continuously down to zero volts and achieves excellent line transient immunity.

The SCR control circuit receives its input from the voltage comparison amplifier. The control circuit 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 SCR preregulator supplies, the 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.

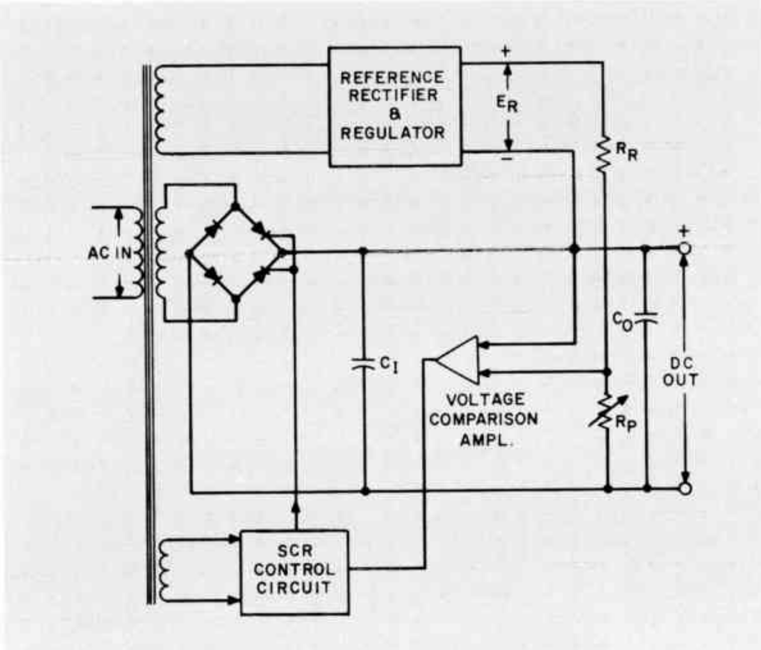


Figure 9. SCR Regulated Power Supply

"Piggy-Back" Regulator Design

Normal series or SCR regulated circuit techniques are not suitable for all-semiconductor, short-circuit-proof power supplies with outputs greater than 300 volts. Shorting the output terminals would place the rectifier voltage (more than 300 volts) across the series regulator transistors. Utilizing a sufficient number of high voltage series transistors to achieve output of several thousand volts would be too costly and unreliable. Even the preregulator circuit of Figure 8 is not suitable for a higher voltage supply, because a shorted output causes the rectifier capacitor to discharge through the series regulator, and the energy stored in this capacitor is more than adequate to destroy the power transistors in the regulator.

High voltage HP supplies utilize a circuit technique that 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 10, the basic technique consists of placing a well-regulated low voltage power supply in series with a less-well-regulated high voltage supply. 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 by adjusting the voltage across its series regulator to maintain the total output voltage at a constant level.

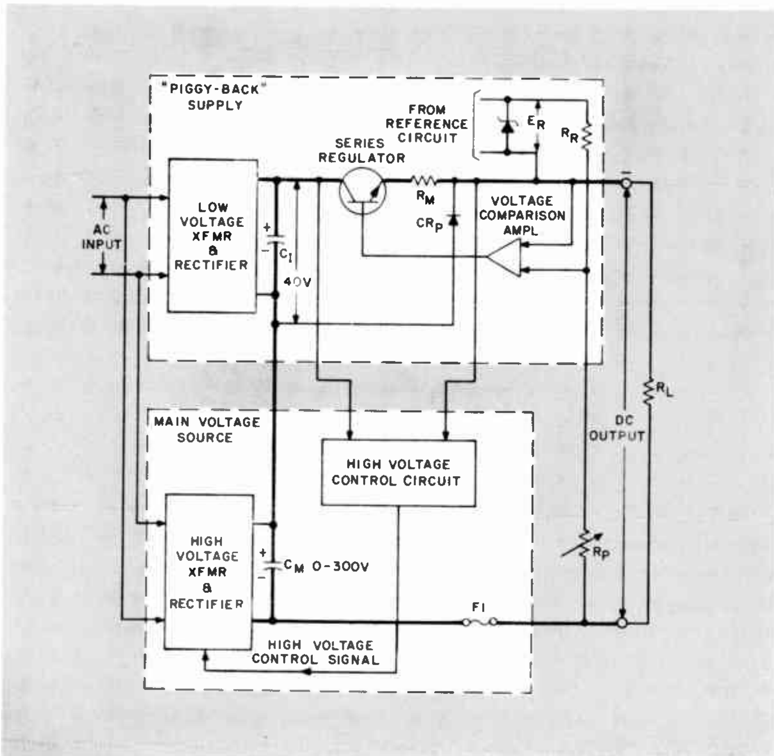


Figure 10. "Piggy-back" Power Supply

As an illustrative example assume that the low voltage rectifier supplying the series transistor of the "piggy-back" supply develops approximately 40 volts, and 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 would be 320 volts; 20 volts from the "piggy-back" supply and 300 volts from the main source. Thus, the series regulator of the "piggy-back" supply would have a ±20 volt range available for accomplishing the dynamic changes necessary to compensate for the output voltage variations of the main source.

Short-circuit protection for the series regulator in the "piggy-back" supply (Figure 10) is provided by diode CR_P which, if the output terminals are shorted, provides a discharge path for rectifier capacitor C_M. Since CR_P prevents the output of the "piggy-back" supply from ever reversing polarity, the series regulator will never be called upon to withstand a voltage greater than the 40 volts from its own rectifier.

Fuse F1 is included so that the path between the output terminals and the rectifying elements of the main voltage source will be opened under overload conditions, to protect the rectifiers and transformer.

The high voltage control circuit does not derive its input control signal from the total voltage across the load resistor or the voltage across the terminals of the high voltage supply itself. Instead, the control circuit monitors the voltage across the combination series regulator and current monitoring resistor and maintains this voltage drop at approximately 20 volts, leaving approximately 20 volts across the output terminals of the "piggy-back" supply.

Hewlett-Packard supplies may use any of three basic methods of controlling the high voltage output of the Main Voltage Source: (1) the control signal from the High Voltage Control Circuit fires SCRs in the rectifier circuit to vary the dc output, (2) the control signal varies the coupling of the high voltage input transformer to adjust the ac input to the rectifiers or (3) the control signal pulse modulates the input to the rectifier to vary the dc output.

CONSTANT CURRENT POWER SUPPLY

The ideal constant current power supply exhibits an infinite output impedance (zero output admittance) at all frequencies. Thus, as Figure 11 indicates, the ideal constant current power supply would accommodate a load resistance change by altering its output voltage by just the amount necessary to maintain its output current at a constant value.

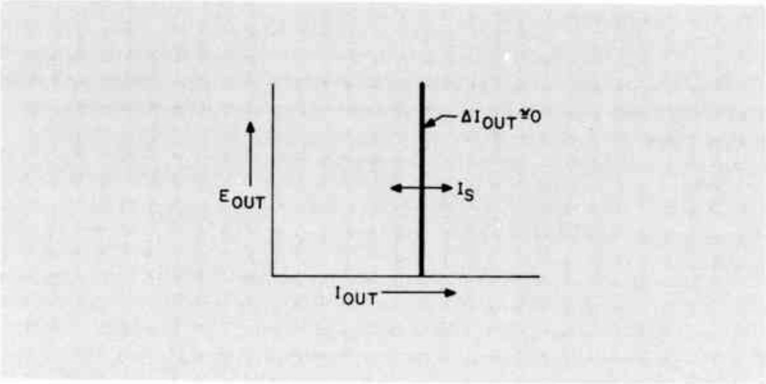


Figure 11. Ideal Constant Current Power Supply Output Characteristic

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

The following paragraphs describe the current feedback loop generally employed in HP Constant Voltage/Constant Current supplies. This particular approach to constant current, while sufficiently effective for most applications, has limitations caused by its simplified nature. For example, although output capacitor C_O minimizes output ripple and improves feedback stability, it also increases the programming response time and decreases the output impedance of the supply; a decrease in output impedance inherently results in degradation of regulation at low values of output current.

If precise regulation, rapid programming, and high output impedance are required, improvements on the basic feedback loop are necessary as described under Precision DC Constant Current Source on page 43.

Figure 12 illustrates the elements constituting a basic constant current power supply. Many of these elements are identical to those found in a constant voltage supply. The feedback loop acts continuously to keep the two inputs to the comparison amplifier equal. The inputs are the voltage drop across the front panel current control and the IR drop developed by load current I_L flowing through current monitoring resistor R_M. If the two voltages are momentarily unequal, then the comparison amplifier output changes the conduction of the series regulator, which in turn corrects the load current and voltage drop across R_M until the error voltage at the comparison amplifier input is reduced to zero. Momentary unbalances at the comparison amplifier are caused by adjustment of current control R_Q or 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 corrected.

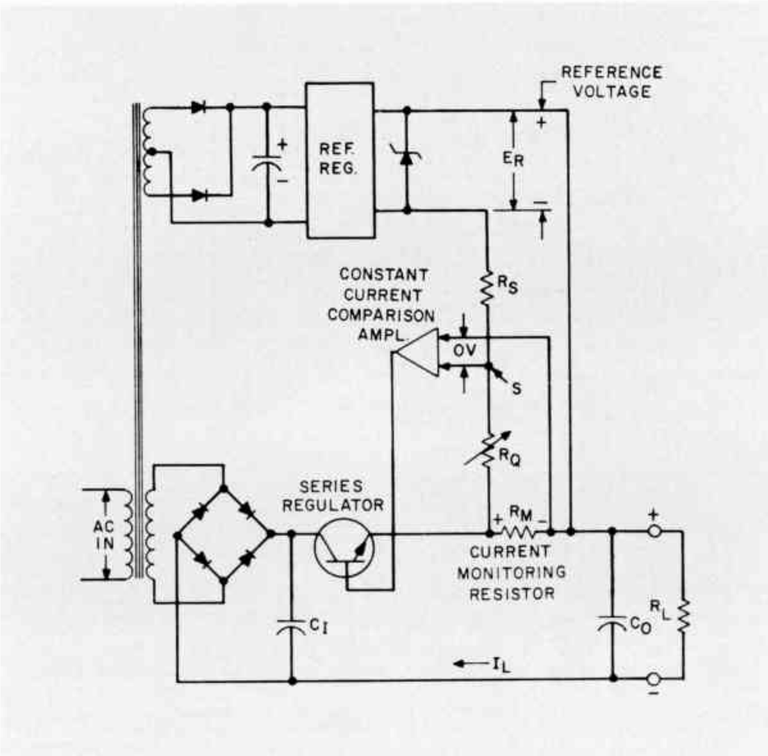


Figure 12. Constant Current Power Supply

CONSTANT VOLTAGE/CONSTANT CURRENT (CV/CC) POWER SUPPLY

The many common elements in the constant voltage power supply (Figure 3) and the constant current power supply (Figure 12) suggest combining these two circuit principles in one supply as illustrated in Figure 13. Fortunately, most of the expensive, high power elements are common to both the constant voltage and constant current circuit configurations. Only low-level circuitry need be added to a constant voltage power supply for dual-purpose use as a constant current source. Because of its unusual versatility and inherent output protection features, many HP supplies employ this CV/CC circuit technique.

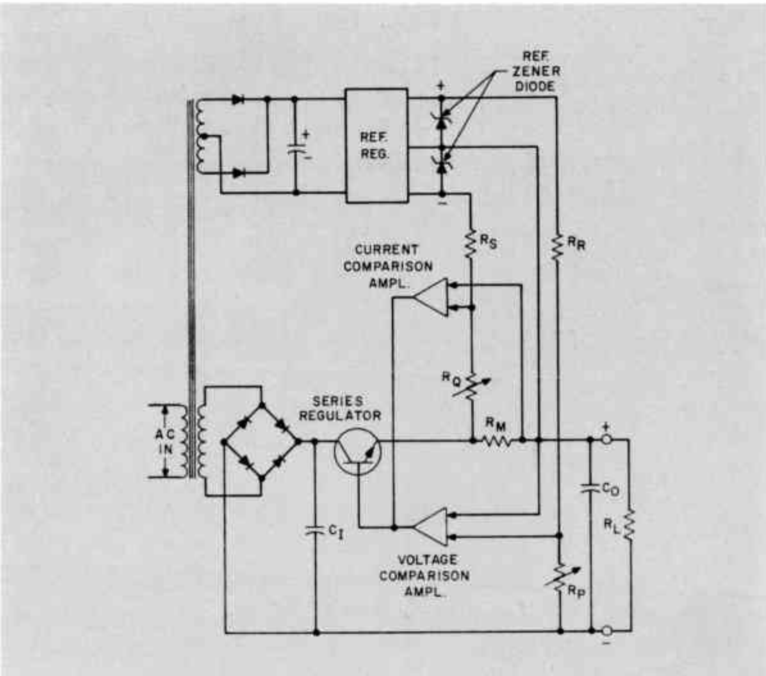


Figure 13. Constant Voltage/Constant Current (CV/CC) Power Supply

Two comparison amplifiers are included in a CV/CC supply for controlling output voltage and current. The constant voltage amplifier approaches zero output impedance by varying the output *current* whenever the load resistance changes, while the constant current amplifier approaches infinite output impedance by varying 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 or a constant current supply—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.

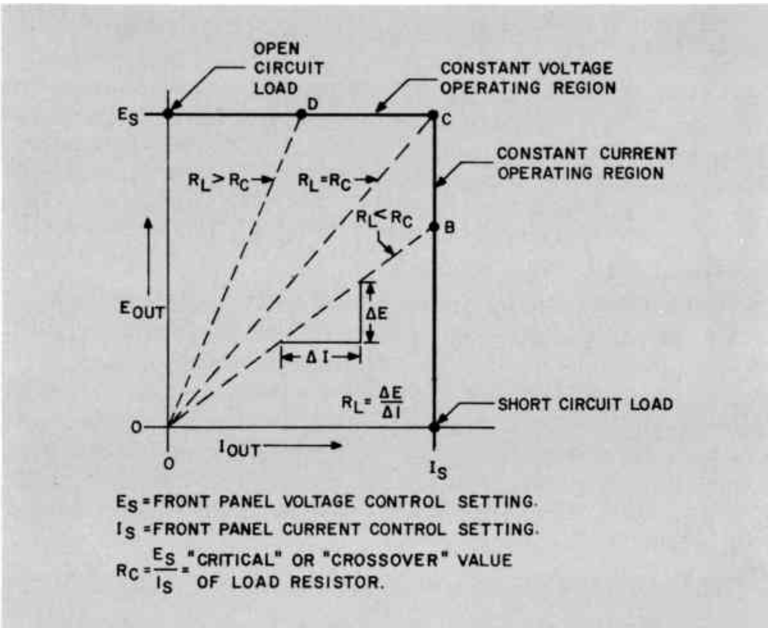


Figure 14. Operating Locus of a CV/CC Power Supply

Figure 14 illustrates the output characteristic of an ideal 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 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 $E_{OUT} = 0$.

By gradually changing the load resistance from a short circuit to an open circuit the operating locus of Figure 14 will be traversed in the opposite direction.

Full protection against any overload condition is inherent in the Constant Voltage/Constant Current design principle because all load conditions cause an output that lies somewhere on the operating locus of Figure 14. For either 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.

The slope of the line connecting the origin with any operating point on the locus of Figure 14 is proportional to the value of load resistance connected to the output terminals of the supply. The "critical" or "crossover" value of load resistance is defined as $R_C = E_S/I_S$, and adjustment of the front panel voltage and current controls permits the "crossover" resistance 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.

CONSTANT VOLTAGE/CURRENT LIMITING (CV/CL) SUPPLY

The difference between a CV/CC power supply and a CV/CL power supply is one of degree. Because a current limiting supply uses fewer stages of gain in the current regulating feedback loop, the regulation in the region of current limiting operation is less precise than in constant current operation. Thus, the current limiting portion of the locus of Figure 15 slopes more than the current operating region for a CV/CC power supply (Figure 14).

CV/CL supplies 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 customarily 3% to 5% of the current rating of the power supply.

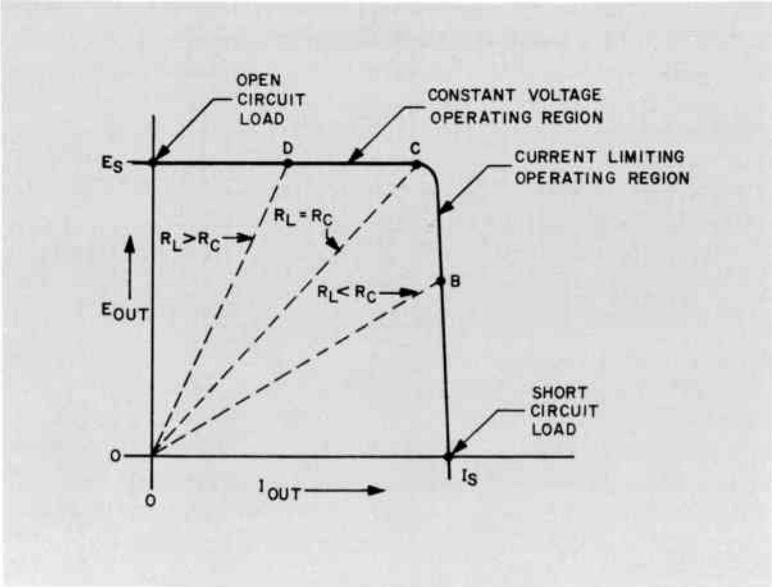


Figure 15. Operating Locus of a CV/CL Power Supply

DETAILED CIRCUIT DISCUSSION

Regulated dc power supplies, regardless of their regulating method, employ some similar basic circuits, such as the reference circuit, comparison amplifier, and others. An in-depth discussion of these circuits is included in the following paragraphs.

Reference Circuit

In all HP power supplies the reference voltage is developed across a reference zener diode that has a low ac impedance and temperature coefficient. This reference zener diode is in turn controlled by a reference regulator assuring reference voltage immunity against line voltage changes and other disturbances. The reference regulator is a low-power closed-loop auxiliary supply designed to maintain the operating current through a reference zener diode constant. In addition, reference circuits used in HP power supplies also provide the necessary bias voltages for use at various points throughout the regulator circuit.

Nearly all reference circuits for supplies employing NPN power transistors are referred to the positive output; and for supplies using

PNP power transistors the reverse is true. Figure 16 is a simplified schematic of a positive common reference circuit.

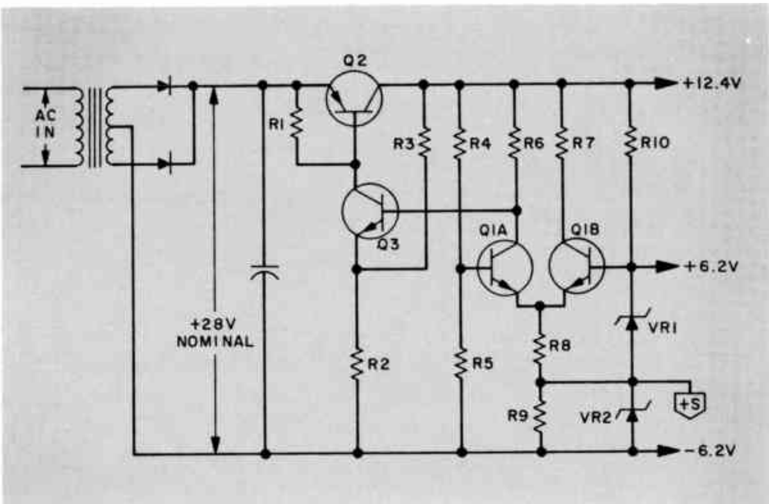


Figure 16. Simplified Reference Circuit

This reference circuit is actually a small closed loop regulator employing Q2 as the series regulating element and Q1 as the comparison amplifier. VR1 and VR2 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 V regulated output.

Comparison Amplifier Circuit

This circuit 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. The emitter-to-base voltage of normal transistors varies approximately 2mV per degree Centigrade. Such voltage variations in the input amplifier stage would produce a proportional change in the 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.

The effect of the comparison amplifier in 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 17A. If we regard the positive output terminal as circuit common, then the negative output terminal and the summing point "S" become instantaneously more negative. Therefore, the collector of Q1A becomes 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 bases of Q1A and Q1B is reduced to zero.

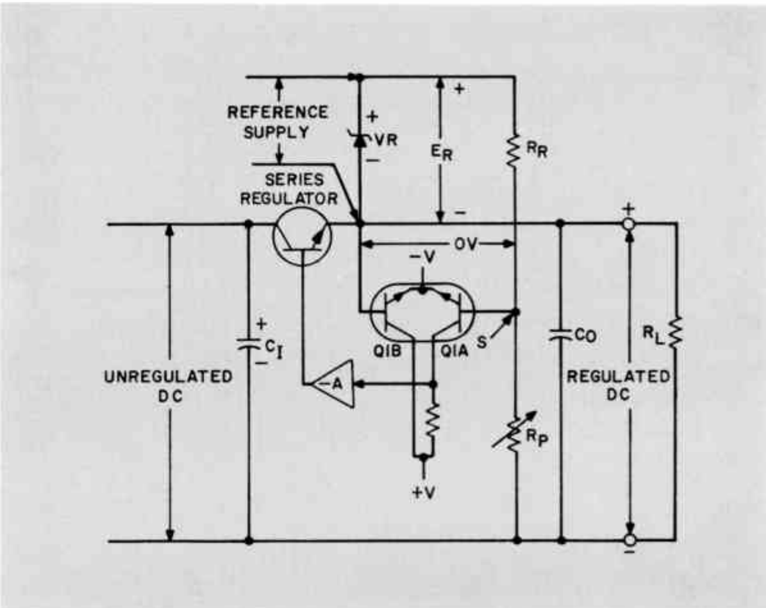


Figure 17A. Constant Voltage Regulator with Simplified Comparison Circuit

Because any change in the resistance value of R_R or R_P will cause a change in the output voltage, wire-wound elements with a very low temperature coefficient are used. To avoid thermal fluctuations these resistors are operated at a power dissipation level considerably less than their rating so that their surface temperature will not be significantly higher than ambient.

Figure 17B shows several refinements Hewlett-Packard typically includes in comparison circuits to improve performance and reliability. Capacitor C1 improves the regulator performance with regard to ripple and other ac disturbances; diodes CR1 and CR2 limit the maximum voltage that can be impressed on the base of Q1A. Normally there are 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 CR1 or CR2 to conduct, thereby preventing the burn-out of transistor Q1A. Resistor R3 is added to balance the I_{CO} effects of the bases of Q1A and Q1B, and is nominally equal to the resistance seen by the base of Q1A. Variable resistor R4 provides one method of adding positive feedback within the regulator loop as discussed in the following paragraphs.

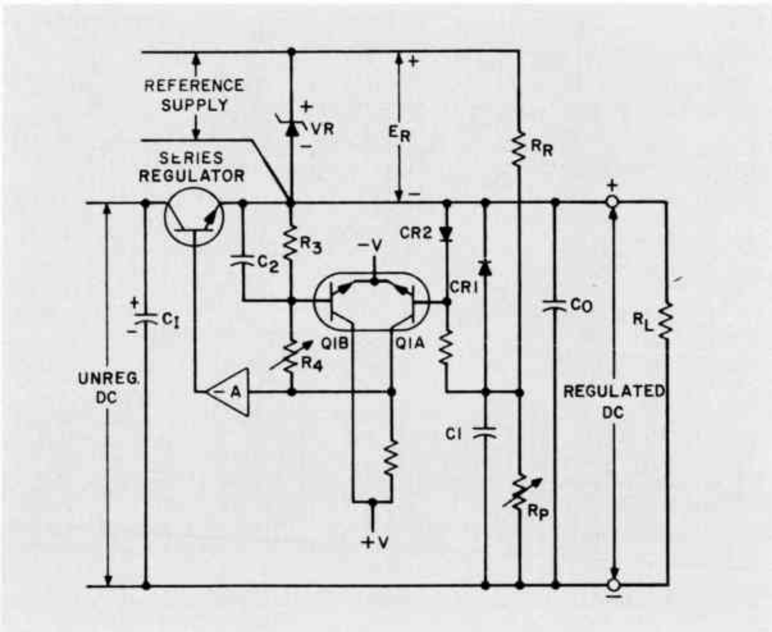


Figure 17B. Constant Voltage Regulator with Improved Comparison Circuit

Zero Output Impedance

As mentioned previously, the ideal constant voltage power supply would have a zero output impedance at all frequencies. This would result in constant 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; however, the circuit shown in Figure 17B does approach zero output impedance at zero frequency (dc).

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.

The term 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:

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

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

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

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

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:

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

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 17B shows one method of adding positive feedback to a power supply regulator to obtain zero output impedance. Control R4 furnishes the local positive feedback from the collector of Q1A to the base of Q1B. Adjustment of this control enhances the gain of the comparison amplifier and permits the power supply to retain its static output voltage constant in spite of a no load to full load change in load current.

Series Regulator Circuitry

All previous circuits described have included only a single series transistor; however, it is obvious that a single series transistor has an adequate power capability only for the smallest power supply. Using several 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 18A 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 18B illustrates the circuit principle of a two transistor series regulator employing a shunt resistor R5 around the second series transistor. With any moderate amount of load current the circuit of Figure 18B will attempt to maintain approximately 2 volts across transistor Q_A. With a proper choice of R5 the maximum power 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 18A—the excess power is dissipated by power resistor R5.

Furthermore, the operation of this circuit assures that transistors Q_A and Q_B are not required to dissipate maximum power simultaneously. Thus, a heat sink for both transistors will have a maximum temperature rise associated with the heat dissipated by one, not two, power transistors.

The circuit of Figure 18B has the advantage of performing a pre-regulating 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.

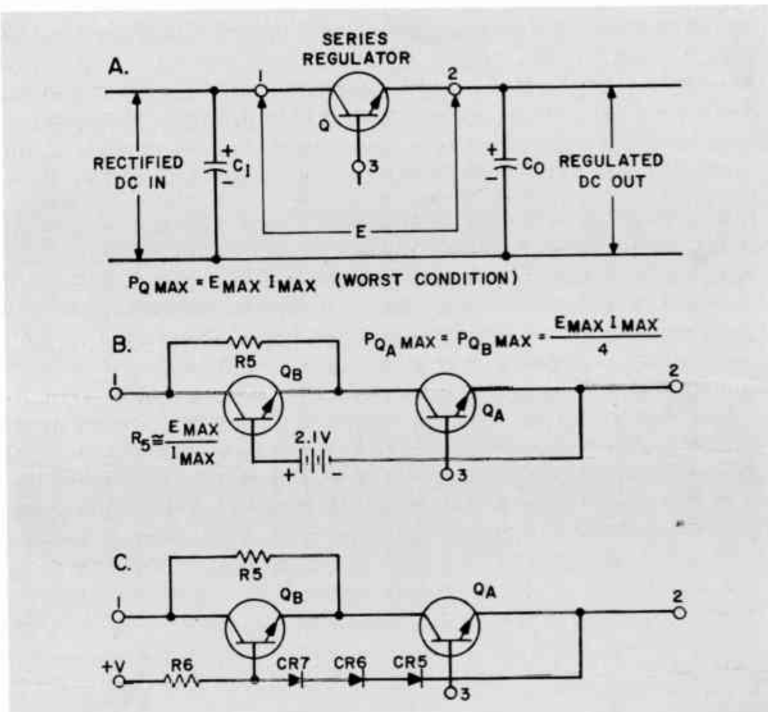


Figure 18. Series Regulator Circuits

Figure 18C 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 18B. Resistor R6 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 18C; 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.

Multiple Range Meter Circuit

Many HP supplies employ a multiple range meter circuit that allows a single front-panel meter to indicate either the output voltage or current in one of two ranges. A meter switch selects 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 the maximum voltage and current ratings, respectively. Figure 19 shows 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 appears across voltage divider R1, R2 and R3, and 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 R3 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 is sufficiently high to avoid loading the shunt resistance. For low values of output current, the meter switch is set to the lower current range (Y/10 AMPS position) switching resistors R2 and R3 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 from the current monitoring resistor, because the meter has a relatively poor temperature coefficient (of the order of 4000 ppm/°C). This 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 degrades the overall constant current temperature coefficient of the supply. The meter amplifier has an additional current limiting feature for protecting 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.

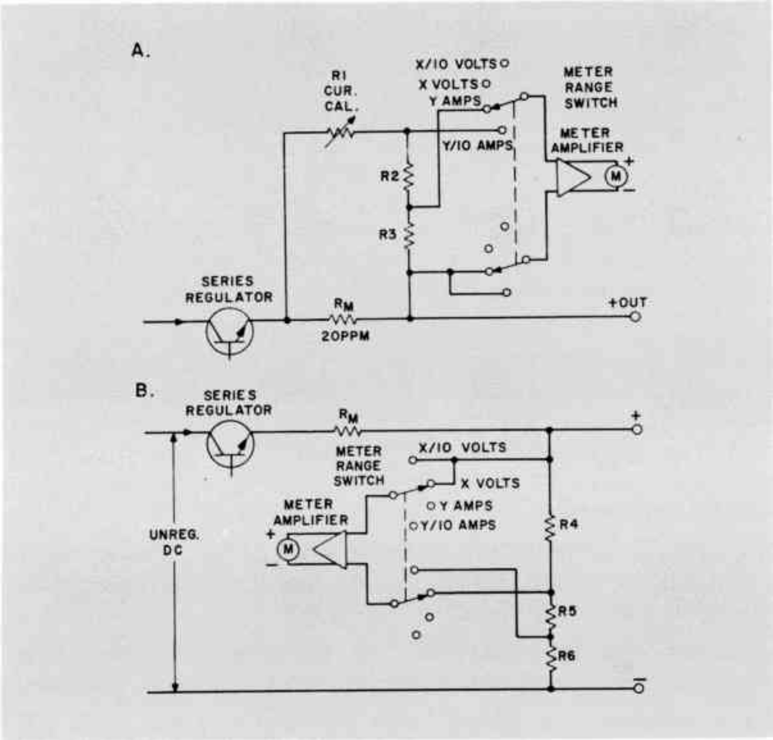


Figure 19. Multiple Range Meter Circuit

Figure 19B shows the meter connections for 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 R4 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 R4 and R5) is applied to the meter amplifier.

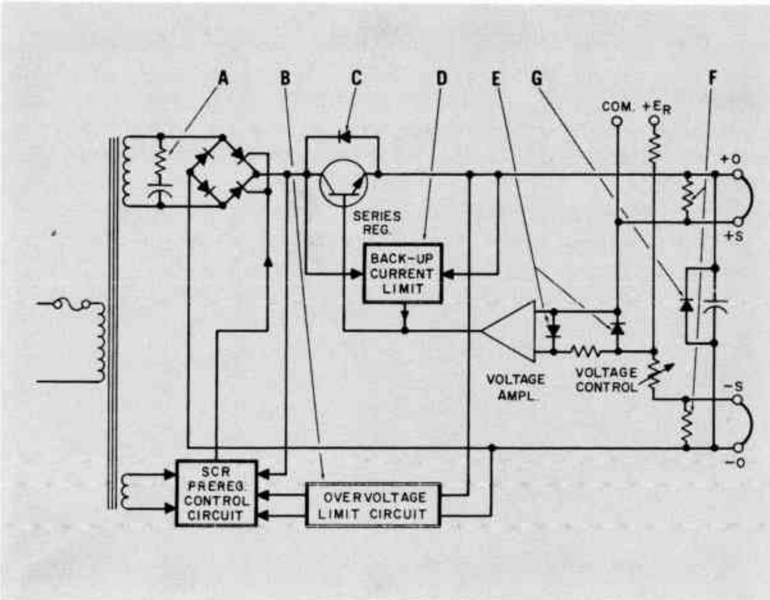


Figure 20. Power Supply Protection Circuits

Protection Circuits

Many different methods may be employed to protect a power supply and its load. The following paragraphs describe protection circuits commonly used in HP supplies. (Figure 20).

A. ***Rectifier Damping Network*** —This RC network protects other elements in the supply against short-duration input line transients.

B. ***Preregulator Overvoltage Limit***-By monitoring the output voltage of the supply this circuit turns off the preregulator when excessively high output voltage is being delivered to the load. Thus, protection for both the load and other elements in the supply is provided.

C. ***Series Regulator Diode*** —This diode protects the series regulator against any reverse voltage which may be delivered by an active load or parallel power supply.

D. ***Back-Up Current Limit*** —This circuit protects against excessive output current in the event of a failure of the primary current limit circuit or in case the voltage across the series regulator becomes excessive.

E. ***Amplifier Input Clamp Diodes***—By limiting the maximum input to the amplifier to ±0.7 volts, these diodes protect the comparison amplifier against excessive voltage excursions.

F. ***Sensing Protection Resistors***-These resistors protect the load from receiving full rectifier voltage if the remote sensing leads are accidentally open-circuited.

G. ***Output Diode*** —This diode protects the components in the power supply against reverse output voltage which might be generated by an active load or series connected power supply.

Overvoltage Crowbar Circuit– The crowbar circuit is connected across the output terminals, and provides protection against any output overvoltage condition which might occur because of operator error or failure within the power supply or load. Because of its importance the crowbar circuit is discussed in more depth below and on the following three pages.

Overcurrent and Overvoltage Protection –All HP semiconductor supplies are short-circuit-proof and can operate under any current overload condition indefinitely without risk of internal damage. Moreover, overvoltage protection is also available if required during constant current operation. CV/CC and CV/CL automatic crossover circuitry (see pages 26 and 28 respectively) is ideal for these purposes since it allows the user to select the maximum safe current or voltage for the particular load device.

Turn-On Overshoot Protection-This circuit consists of a long time-constant RC network connected to the base of the series regulator transistor. When the supply is first turned on, this RC circuit biases the series regulator off until the reference circuits stabilize.

Overvoltage Crowbar Circuit Details

A crowbar monitors the output voltage to protect against an operator error or power supply malfunction that could destroy the load. It guarantees that the power supply voltage across the load will never exceed a preset limit. This guarantee is necessary because of the extreme voltage sensitivity of present-day semiconductor devices—an overvoltage condition of only a few volts is destructive to low level IC's.

The basic elements used in most crowbars are: some method of sensing the output voltage, an SCR that will short the output, and a circuit that will reliably trigger the SCR.

The sense circuit can be a simple bridge or voltage divider network that compares the output voltage to some internal crowbar reference voltage. The best trigger circuit is the one which turns the SCR on the fastest. The fastest SCR turn-on is accomplished by a fast rise-time pulse circuit such as a blocking oscillator or Schmidt trigger.

The Hewlett-Packard crowbar, illustrated in Figure 21A, compares the output voltage with a reference voltage +V. The overvoltage potentiometer adjusts the reference voltage on the comparison amplifier and sets the voltage level at which the crowbar will activate. Normally the overvoltage control is located on the front panel and can be adjusted from approximately 2 volts to 20% above the maximum output voltage of the power supply.

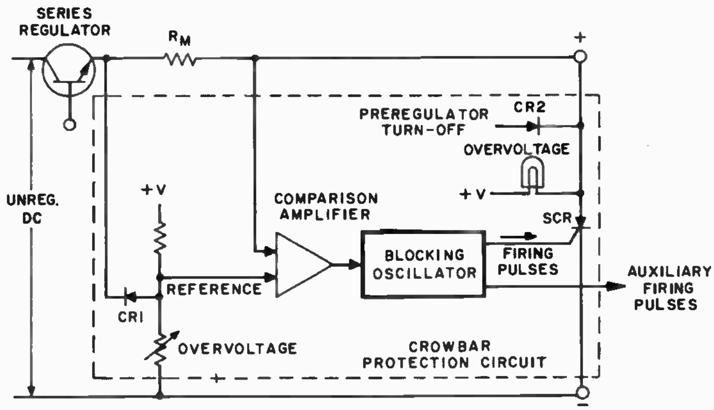


Figure 21A. Typical Crowbar Overvoltage Protection Circuit

When the output voltage exceeds the reference, the comparison amplifier triggers the blocking oscillator which then sends firing pulses to the SCR. When the SCR fires, it places a very low impedance across the output, reducing the voltage to near-zero.

Several beneficial features are included in most HP crowbar circuits:

1. An overvoltage indicator lights when the SCR fires; the lamp conducts a holding current to prevent the SCR from oscillating on and off.
2. The crowbar circuit creates an extra current path during normal operation of the supply, thus changing the current that flows through the current monitoring resistor. Diode CR1 keeps this extra current at a fixed level for which compensation can then be made in the constant current comparator circuit.
3. In preregulated supplies the crowbar turns off the preregulator circuit when the SCR fires, reducing the voltage drop across the series regulator.
4. An auxiliary winding is included on the blocking oscillator transformer for connection to an additional crowbar. Tandem crowbar operation is available for coincident firing of all crowbars in a system.

Crowbar Response Time

There are three time delays that place a practical limit on how fast crowbars can react. In order of decreasing magnitude, they are:

(1) The typical SCR turn-on time (from 1μsec to around 50μsec);

(2) The reaction time of the trigger circuit; and

(3) The time delay associated with the crowbar voltage-sensing circuit. Since only a fraction of the output voltage is compared with an internal crowbar reference voltage, the voltage sensing circuit incorporates a large voltage divider which combines with discrete and stray capacitance in the sensing circuit to form an RC delay network.

If the output voltage is rising relatively slowly there will be essentially no time delay of types (2) and (3). The SCR will be triggered within a fraction of a microsecond after the relatively slow-rising output voltage crosses the trip level, and the only noticeable time delay will be the turn-on time of the SCR. If, on the other hand, the output voltage waveform approaches a step, the sense circuit will not follow the fast rising wavefront and an added time delay (type 3) will result. For a step that is only a few millivolts above the trip level, this time delay can be as much as a few microseconds; but as the magnitude of the step increases, the sense circuit charges faster and the delay decreases.

In practice, it is unrealistic to specify either the time delay or the maximum overvoltage as shown in Figure 21B, because they vary according to operating levels, load and line impedances, and the exact failure mode. Instead Hewlett-Packard specifies the overvoltage margin, which is "the minimum crowbar trip setting above the desired operating output voltage to prevent false crowbar tripping".

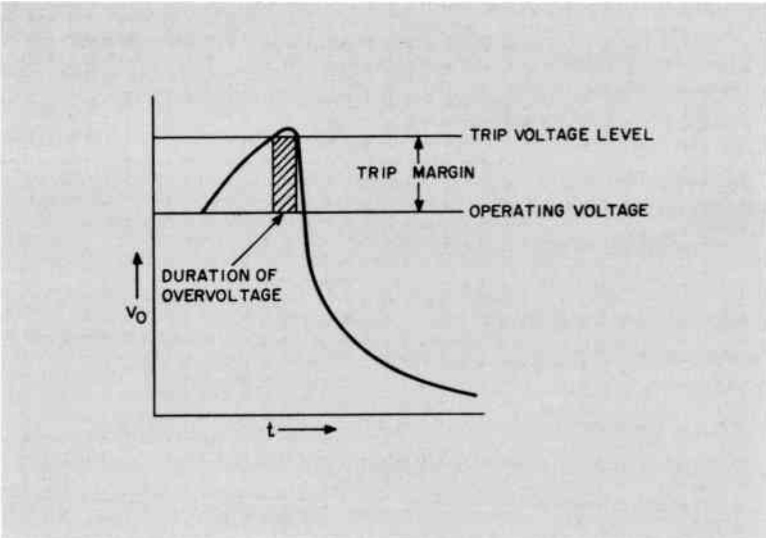


Figure 21B. Crowbar Response

HIGH PERFORMANCE POWER SUPPLIES

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.

High Stability DC Power Supply.

The STB supplies are Constant Voltage/Current Limiting type, similar to those described on page 28, 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 with 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% accuracy.

Precision DC Constant Current Source

The concepts and circuits used in *basic* constant current power supplies are discussed on page 23. This section is devoted to the refinements necessary to upgrade a basic constant current supply to a *precision* class, with characteristics that more closely approach an ideal current source.

An ideal current source is a current generator that has infinite internal impedance. It provides any voltage necessary to deliver a constant current to a load, regardless of the size of the load impedance. It will supply this same current to a short circuit, and in the case of an open circuit it will attempt to supply an infinite voltage (see Figure 22).

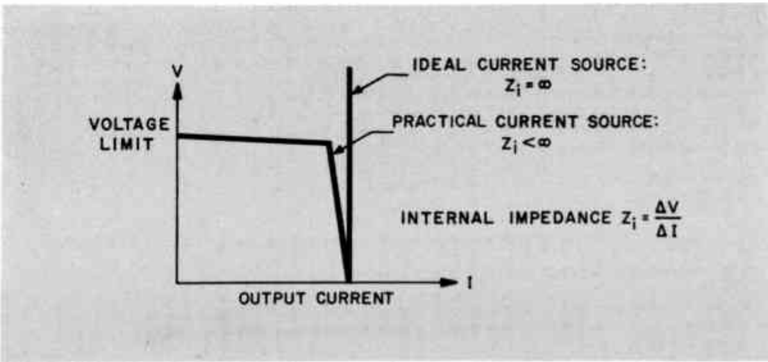


Figure 22. An Ideal Current Source

In practical current sources, neither infinite internal impedance nor infinite output voltages are possible. In fact, if the current source is to be used as a test instrument, it should have a control for limiting its maximum output voltage, so its load will be protected against the application of excessive potentials. Its output impedance should be as high as possible, of course, and should remain high with increasing frequency to limit current transients in rapidly changing loads. A capacitor across the output terminals should be avoided, since it will lower the output impedance, store energy which can result in undesirable current transients, and decrease the programming speed.

One approach to the design of a current source is to add a high series resistance to an ordinary voltage source. However, it is difficult to achieve good current regulation with this design.

Typical applications for current sources call for output impedances of a few megohms to a few hundred megohms and currents of tens or hundreds of milliamperes. This means the source voltage would have to be tens of kilovolts or more. Such a high-voltage supply will cause noise problems, will be difficult to modulate or to program rapidly, will be dangerous, very large, and will waste considerable power.

Electronic current regulation is a much more tractable way to obtain high output impedance, although there are still design problems, such as leakage.

Leakage Versus Regulation

The current regulation of a current source, as seen at the load, is degraded by any impedance in parallel with the load. If I_O is the current generated by the source, I_L is load current, Z_L is load impedance, and Z_S is the total impedance shunting Z_L, then

$$I_L = \frac{I_O Z_S}{Z_L + Z_S}$$

When the output impedance of the current source is high, then even very small leakage currents can become significant (see Figure 23). Such things as the input impedance of a voltmeter measuring the load voltage, the insulation resistances of wiring and terminal blocks, and the surface leakage currents between conductors on printed-circuit boards will all take current away from the load, unless special design precautions are used.

CCB Current Sources

In the Hewlett-Packard CCB Current Sources, leakage at the output terminals is negligible, owing to a combination of techniques, including guarding, shielding, and physical isolation. Feedback regulation makes the output impedance high (3.3 to 10,000 megohms), and there is no output capacitor to lower the output impedance or store energy. Low leakage and high output impedance result in precise current regulation.

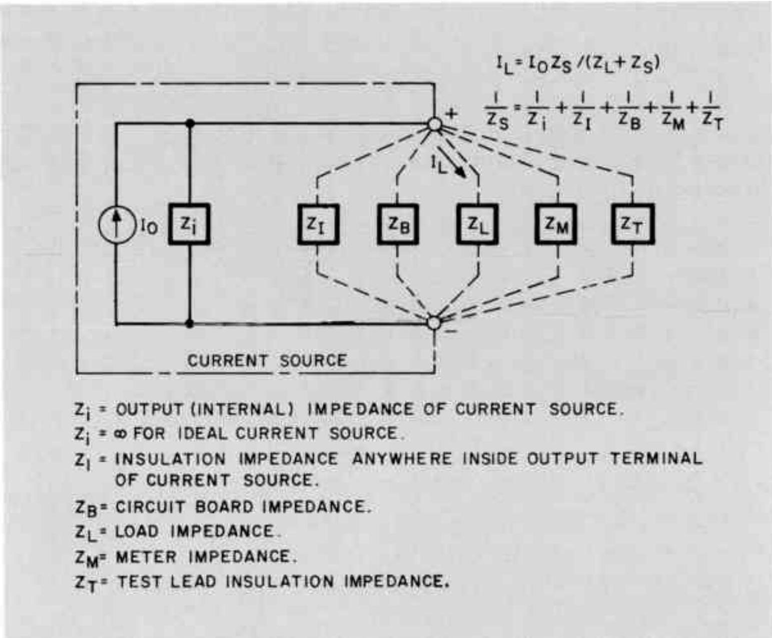


Figure 23. Impedances Shunting the Load Degrade Current Regulation

As shown in Figure 24, the CCB design includes three key sections which determine its unique regulating properties—the Programming/Guard Amplifier, the Main Current Regulator, and the Voltage Limit Circuit.

The Programming/Guard Amplifier is an independent, variable constant voltage source, whose output voltage E_G is linearly dependent upon the setting of R_Q, being equal to $E_S R_Q/R_S$. The guard aspects of this circuit are discussed in detail later; it is sufficient to note here that this circuit permits linear output current control while facilitating the common point connection at the *inboard* side of the current monitoring resistor.

The Programming/Guard Amplifier provides the programming voltage E_G for the Main Current Regulator; this dc voltage, which is negative with respect to circuit common, is applied to one of the inputs of the differential Current Comparison Amplifier. The other input of this differential amplifier is connected to the current monitoring resistor R_M. The Current Comparison Amplifier continuously compares the voltage drop across the current monitoring resistor ($I_O R_M$) with the programming voltage (E_G). If these voltages are momentarily unequal due to a load disturbance or a change in the output current control setting, this error voltage is amplified and applied to the series regulator transistors, altering the current conducted through them and forcing the voltage drop $I_O R_M$ to once again equal E_G.

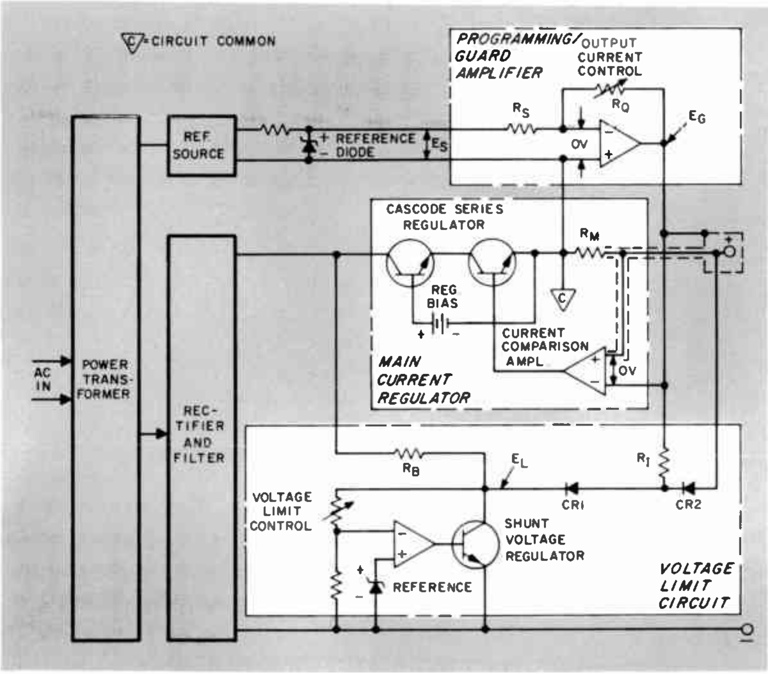


Figure 24. CCB Current Source Block Diagram

The output current is related to the programming voltage and reference voltage by the relationship

$$I_O = \frac{E_G}{R_M} = \frac{E_S}{R_M} \cdot \frac{R_Q}{R_S}$$

As this equation suggests, R_M is a critical component and is selected to have low noise, low temperature coefficient, and low inductance.

Its ohmic value is large enough to give an adequate current monitoring voltage, yet small enough to minimize its temperature rise (and the resulting resistance change) caused by its own power dissipation.

Returning to the *guard* duties of the Programming/Guard Amplifier, the output of this amplifier (E_G) is connected to a guard conductor which surrounds the positive output terminal, the current monitoring resistor, and the (+) input to the Current Comparison Amplifier. Since E_G is held at the same potential as the positive output terminal by the Main Current Regulator, no leakage current flows from the positive output terminals (or any of the internal circuit elements connected to it). The leakage currents that would normally flow from the positive output circuitry flow instead from the guard conductor, whose current is supplied by the Programming/Guard Amplifier. Notice that since the Programming/Guard Amplifier is a low impedance source referenced to (C), any leakage current fed by the guard originates from circuit common via this amplifier, bypassing R_M —only the output current flows through R_M . In this way leakage current flowing directly between the supply's two output terminals is eliminated, and precise load regulation is obtained.

The Programming/Guard amplifier output may also be used as a convenient point to connect indicating meters, since the current to drive these meters will not affect the regulated output current, I_O.

The Voltage Limit Circuit is designed to eliminate dangerous high-voltage or high-current transients that might occur under certain load conditions. For example, when the load is suddenly removed from an ordinary constant-current power supply, the output voltage attempts to rise to the raw supply voltage of the instrument, which can be hundreds of volts. Or, when the load is suddenly reconnected to a supply operating in the voltage limit mode, a high-current transient can occur if the current regulator saturates while the instrument is still in voltage limit.

The Voltage Limit Circuit in CCB Current Sources virtually eliminates voltage or current overshoots and undershoots when going in and out of voltage limit, without adding any significant leakage path across the output terminals.

Normally, when voltage limiting action is not occurring, the setting of the Voltage Limit Control establishes across the Shunt Voltage Regulator a preset voltage limit E_L which is higher than the positive output voltage and its twin, the guard voltage E_G. Since there is zero volts across the series combination of isolation diode CR2 and resistor R_I (5 kilohms or less), no current flows through them, and the potential E_G is also present at their junction, thus back-biasing isolation diode CR1. (Any small leakage through back-biased diode CR1 flows through R_I and the output of the Programming/Guard Amplifier, but does not flow into CR2 or the positive output terminal). The Shunt Voltage Regulator conducts a "standby" current through shunt regulator bias resistor R_B; this current insures that the Shunt Voltage Regulator is operating in its linear region, ready to react quickly when voltage limiting action is required, thus preventing crossover transients.

If the output voltage exceeds the preset voltage limit value, CR1 and CR2 conduct, and the Shunt Voltage Regulator conducts a portion of the current which otherwise would flow to the load, thus clamping the output voltage to the preset limit value.

Even during voltage limiting action, E_G continues to be maintained at a value equal to the potential at the positive output terminal; both guarding action and the normal control action of the Main Current Regulator continue, minimizing any output transients which might tend to occur when the output transfers from voltage limiting to its normal output current mode.

High Output Impedance.—The high output impedance of CCB Current Sources is a result of several factors, both electrical and mechanical. The series-regulator transistors are in a cascode configuration, which inherently has a high output impedance. Since the open-loop gain of the error amplifier is high, the closed-loop output impedance is greatly increased by feedback.

Output capacitors have been eliminated—and although the output impedance falls off with frequency because of the necessary gain and phase compensation in the amplifier circuits, it is much higher than it would be if a capacitor were connected across the output terminals.

The importance of low output capacitance should not be underestimated. Excessive output capacitance would cause the output impedance of the current source to fall off with increasing frequency, producing undesirable transients in rapidly changing loads. Large capacitors store large amounts of energy which, if discharged suddenly through the load, may cause damage; negative-resistance devices are particularly susceptible to this kind of damage. Finally, an output capacitor would slow down the response of the current source to changes in the external programming signal.

In the interest of keeping the output impedance high, the impedances of internal leakage paths have been made as high as possible by careful mechanical design and hygienic construction techniques. Leakage, both internal and external, is further reduced by guarding the positive output terminal.

Guarding.—In addition to eliminating leakage currents, as described on page 47, the guard can also be used to measure the output voltage without drawing current away from the load. Connecting a voltmeter between the negative output terminal and the positive output terminal will lower the output impedance, but a voltmeter connected between the negative output terminal and the guard has no effect on the output impedance. The meter still measures the output voltage because the guard is at the same potential as the positive output terminal. The front-panel voltmeter is internally connected to guard; and if greater accuracy is needed, a voltmeter can be connected externally.

Unlike other guards, such as those used on digital voltmeters, the guard in the CCB Current Source is active and internally referenced to the positive terminal. For this reason the guard is labeled "(+) meter" on the front panel, and *must not be connected to either output terminal, since this interferes with the closed loop performance.*

Transformer Shielding Eliminates Ripple.—The CCB Current Sources meet their low ripple specifications regardless of which output terminal, if either, is connected to earth ground. High-gain current regulation is one reason for the low ripple. Another is special shielding to keep ac voltages in the power transformer from being coupled into the output via the capacitance between the transformer windings and the output or ground.

One potential source of ripple current is capacitive coupling between the primary winding and the negative output terminal. In the CCB Current Sources, this problem is eliminated by enclosing the primary winding in an electrostatic shield which is connected to earth ground. A second source of ripple current is capacitive coupling between the secondary winding and ground. To keep this current from affecting the output, the secondary winding is enclosed in an electrostatic shield which is connected to the negative output terminal. This causes the ripple current generated by the secondary winding to be confined to a closed loop inside the instrument.

Power Supply/Amplifier Design *

In many applications a power supply is required that has faster programming speed than standard power supply designs (see page 94 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 (page 14). 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.

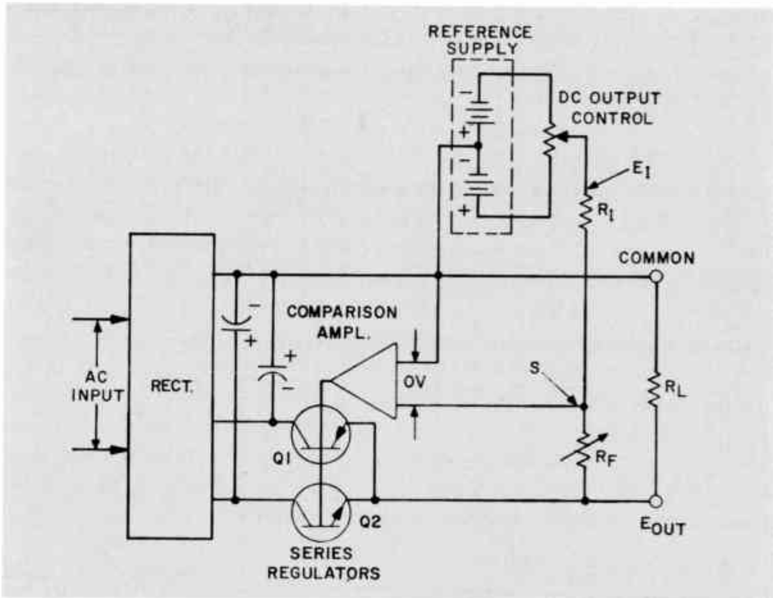


Figure 25. Power Supply/Amplifier Drawn as a Power Supply

Figure 25 shows a simplified representation of this instrument drawn as a power supply. Two series transistors are used in a complementary configuration, where one transistor is connected to a negative rectifier and the other to a positive rectifier. These transistors in turn are controlled by the normal comparison amplifier;

*Application Note 82 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 sales office.

however, 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 26 shows the same circuit redrawn as an amplifier. Transistors Q1 and Q2 are arranged in a single ended push-pull configuration, and the operational amplifier aspects are more readily suggested by the configuration shown. In Figure 26 an external signal input has been substituted for the internal reference supply shown in Figure 25.

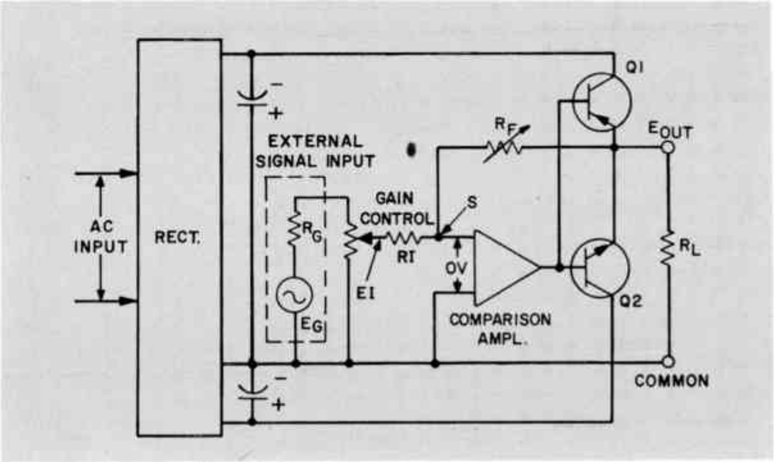


Figure 26. Power Supply/Amplifier Drawn as an Amplifier

Not shown in either diagram are the circuit details of a special output sensing circuit which ensures feedback stability regardless of the phase 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 with 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 on page 108, thus making the instrument useful as a resistance or voltage controlled constant current output power supply or amplifier.

DIGITALLY CONTROLLED POWER SUPPLIES

Digitally controlled power supplies are designed specifically for use in modern automated systems which require power supplies capable of being programmed by a computer or other digital source. Although tailor-made for computer-based automatic test systems, the digitally controlled power supply (DCPS) is useful wherever digital signals must be converted to analog form with speed, accuracy, and a minimum of system interface complication.

Figure 27 is a simplified block diagram showing a typical DCPS manufactured by HP. The unit consists basically of a digital-to-analog (D/A) converter followed by a bi-polar power amplifier.

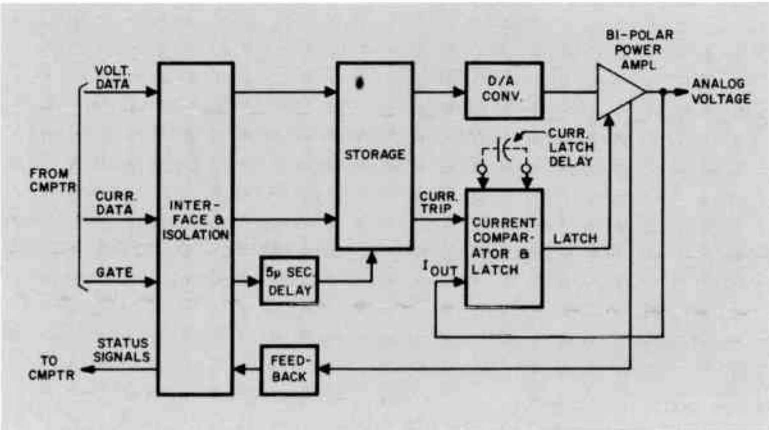


Figure 27. Digitally Controlled Power Supply Block Diagram.

Additional circuits are also included to facilitate operation within the systems environment. The additional circuitry performs interface, isolation, storage, overcurrent protection, and status feedback functions as explained in subsequent paragraphs.

Interface and Isolation

Each input and output signal, to and from the DCPS, passes through interface and isolation circuits. Interface circuits are designed to match the DCPS to a variety of computers or other digital sources. Isolation circuits isolate the digital input from the analog output voltage allowing the output to be floated if desired. Isolation also prevents troublesome loops between the output ground and computer ground and prohibits potentially destructive current surges which could occur if some point in the load circuit were inadvertently grounded.

Storage

The digital voltage and current programming input data are transferred into integrated-circuit storage buffers upon receipt of the storage pulse from the computer. Once the data is stored, the computer can perform other tasks without the need for maintaining the input data. This increases computer operating efficiency and even allows "party-line" operation where one set of data lines can be used to program several DCPS's.

The storage capability also minimizes voltage programming overshoots or undershoots by ensuring that all voltage program inputs reach the D/A converter simultaneously. The gate pulse is delayed 5-μsec from the arrival of the input data to allow time for all input lines to settle.

If the programming source does not normally generate gate signals, the storage circuits can be bypassed by means of a switch on the DCPS. The voltage program data now passes directly into the D/A converter as soon as received from the isolation circuits, but without the benefit of storage.

D/A Converter

The heart of the DCPS is the D/A converter. This bi-polar, high-speed circuit converts the digital voltage programming inputs into an analog reference signal which drives the precision power amplifier. The reference output signal is either positive or negative in accordance with the polarity of the input number.

Bipolar Power Amplifier

The accurate reference signal from the D/A converter goes directly to the power amplifier. To preserve the accuracy of the input signal, large amounts of negative feedback are used in the amplifier circuits. The amplifier can be programmed either side of, or through, zero without "notch" effects or the use of polarity switches.

The power amplifier has a self-contained voltage limit circuit which prevents the output voltage from exceeding 110% of rating despite possible programming errors. It also contains a "gross" current limit circuit which prevents the output current from exceeding 110%

(maximum) of the rated output current. This circuit provides back-up protection for the programmable overcurrent circuits.

Overcurrent Protection

Both the load and the DCPS are protected against overcurrent conditions by a current comparator and latch circuit. When activated, this circuit sends a latch signal to the power amplifier which shuts off the output stages and reduces the output current to under 10% of the current rating. The current latch trip point can be programmed, by three external current latch program bits, to one of eight values ranging from 2% to 100% of the output current rating. The current latch bits from storage are first converted to a corresponding analog reference value within the current comparator and latch circuit. Next, this reference value is compared with a sample of the output current (I_{OUT}). If the output current equals or exceeds this reference value, a current overload condition exists. Approximately 5 μsec after a current overload is detected; a latch signal is generated to reduce the output current. Should the load require a heavy initial current, the delay period between overload and latch can be extended up to 2msec by adding an external capacitor.

The current latch trip point can also be set by manual switches on the DCPS instead of by the external current latch program bits.

Status Feedback

Three feedback lines are available to furnish continuous status information to the computer. A flag line informs the computer when new voltage programming data is being processed by the DCPS. Current overload and latch lines are activated if the DCPS experiences a current overload or latch condition.

AC AND LOAD CONNECTIONS

Modern power supplies are flexible, high-performance instruments designed to deliver a constant or controlled output with a maximum of reliability and control versatility. In many cases, however, the user inadvertently degrades this performance capability by making improper wiring connections to the input or output. At best, this can result in excessive output ripple, a tendency toward oscillation, poor load and line regulation, and unnecessary degradation of stability, temperature coefficient, and transient recovery specifications. At worst, the result can be power supply failure and potential shock hazards.

Careful attention to the guidelines presented in this section will improve the safety and usefulness of power supplies. As a general rule, the guidelines should be followed in the sequence given, e.g., dc distribution terminals must be considered before common or ground connections.

The following checklist is included for quick reference to the most important rules in connecting dc power supplies; these rules are repeated with greater detail on the pages indicated.

CHECKLIST FOR AC AND LOAD CONNECTIONS

Each rule should be followed in the sequence indicated.

AC Power Input Connections

Page

1. The ac, acc and third wire safety ground continuity should be retained without accidental interchange from ac power outlet to the power supply input terminals 57
2. An autotransformer (or isolation transformer) connected between the ac power source and the power supply input terminals should be rated for at least 200% of the maximum rms current required by the power supply 58
3. The autotransformer common terminal should be connected to the acc (not ac) terminals of both the power supply and the input power line 58

AC POWER INPUT CONNECTIONS

The ac, acc and third wire safety ground continuity should be retained without accidental interchange from ac power outlet to the power supply input terminals.

Accidental interchanging of ac and safety ground leads may result in the power supply chassis being elevated to an ac potential equal to the line input voltage. This could result in a potentially lethal shock hazard, if the chassis is *not* grounded; or blown fuses, if the chassis *is* grounded.

If ac and acc are accidentally interchanged, the power supply switches and fuses are thereby placed in series with the ground side of the power line instead of the hot side—if the power supply ac line switch is turned off or the fuse opens, the hot side of the power line will be connected to exposed components within the power supply.

Accidental interchanging of acc and ground leads places the chassis at the acc potential giving rise to circulating ground currents flowing through the power supply chassis and other associated ground return paths—the result is often excessive power supply output ripple and malfunction of associated instruments.

Autotransformers

An autotransformer (or isolation transformer) connected between the ac power source and the power supply input terminals should be rated for at least 200% of the maximum rms current required by the power supply. Because a power supply input circuit does not draw current continuously, the input current wave is not sinusoidal, and the peak-to-rms ratio is generally greater than $\sqrt{2}$, and can be as high as two or more at full output. To avoid autotransformer saturation and consequent limiting of peak input current, the autotransformer must have a rating higher than suggested by the power supply's rms input current. Failure to follow this precaution may result in the power supply not meeting its specifications at full output voltage and current.

The autotransformer common terminal should be connected to the acc (not ac) terminals of both the power supply and the input power line. If acc is not connected to the common terminal of the autotransformer, the input acc terminal of the power supply will have a higher than normal ac voltage connected to it, contributing to a shock hazard and, in some cases, greater output ripple.

Line Regulators

Most ac input line regulators should not be used with well-regulated power supplies without first checking with the power supply manufacturer. Such regulators tend to increase the impedance of the line in a resonant fashion, and can cause malfunctioning of power supplies particularly if they employ SCR or switching type regulators or pre-regulators. Moreover, since the control action of the most common line voltage regulators is accompanied by a change in the output waveshape, their advantage in providing a constant rms input to a power supply is small. Often these waveshape changes are just as effective in causing output voltage changes of the power supply as the original uncorrected line voltage amplitude changes.

Input AC Wire Rating

When connecting ac to a power supply, it is necessary to use a wire size which is rated to carry at least the maximum power supply input current. In addition, a check should be made to determine whether a still larger wire size will be required to retain a sufficiently low impedance from the service outlet to the power supply input terminals, particularly if a long cable is involved.

As an extreme example, many power supplies would fail to function properly if the IZ drop in the input cable approached 10% of the line voltage, even though the wire size had an adequate *current* rating, and even though the voltage at the power supply terminals was not below the rated input range specified by the manufacturer.

As a general guideline, input cables should employ wire size sufficient to insure that the IZ drop at maximum rated power supply input current will not exceed 1% of the nominal line voltage.

LOAD CONNECTIONS FOR ONE POWER SUPPLY

The simplest (and most common) example of improper load wiring is illustrated in Figure 28. Each load sees a power supply voltage which is dependent upon the current drawn by the other loads and the IZ drops they cause in some portion of the load leads. Since most power supply loads draw a current which varies with time, a time-varying interaction among the loads results. In some cases this interaction can be ignored, but in most applications the resulting noise, pulse coupling, or tendency toward inter-load oscillation is undesirable and often unacceptable.

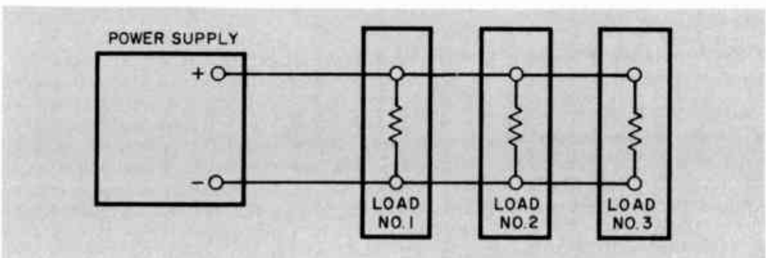


Figure 28. Improper Load Connections

DC Distribution Terminals

A single pair of terminals are designated as the positive and negative "DC Distribution Terminals" (DT's). These two terminals may be the power supply output, the B+ at the load, or a separate pair of terminals established expressly for distribution. Proper location of the DT's results in improved over-all performance and reduced mutual coupling effects between separate loads using the same power supply. If remote sensing is not used, locate the DT's as close as possible to the power supply output terminals—optimum performance will result when the power supply output terminals themselves are used as the DT's. (See Figure 29).

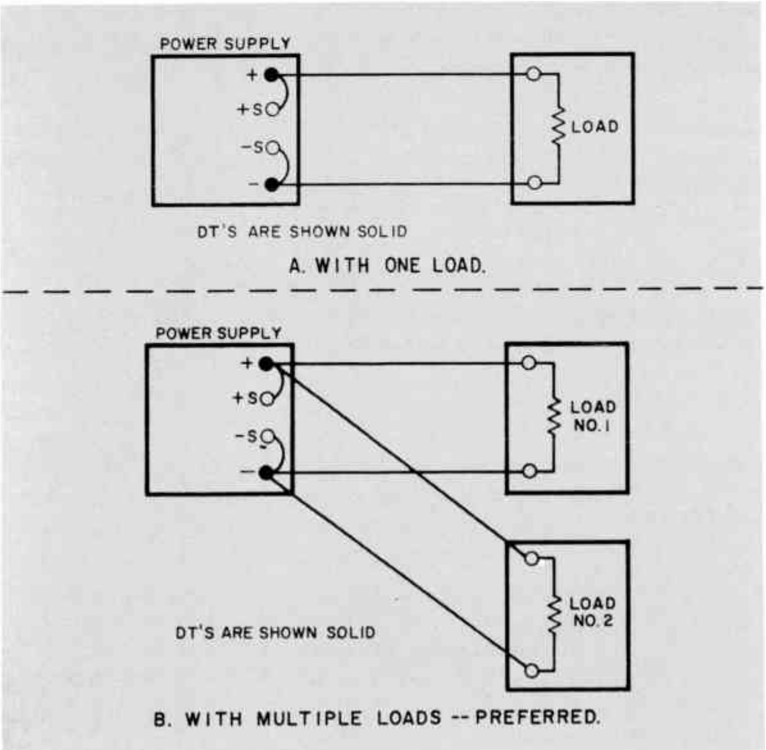


Figure 29. Location of DC Distribution Terminals without Remote Sensing

If remote sensing is employed, the DT's should be located as close as possible to the load terminals—sensing leads should then be connected from the power supply sensing terminals to the DT's (see Figure 30). (See Page 74 for further details on remote sensing.)

One pair of wires should be connected directly from the power supply output terminals to the DT's, and a separate pair of leads from the DT's to each load. There should be no direct connection from one load to another, except by way of the DC Distribution Terminals.

Although for clarity the diagrams show the load and sensing leads as straight lines, some immunity against pick-up from stray magnetic fields is obtained by twisting each pair of (+) and (−) load leads. In addition, all sensing leads should be shielded.

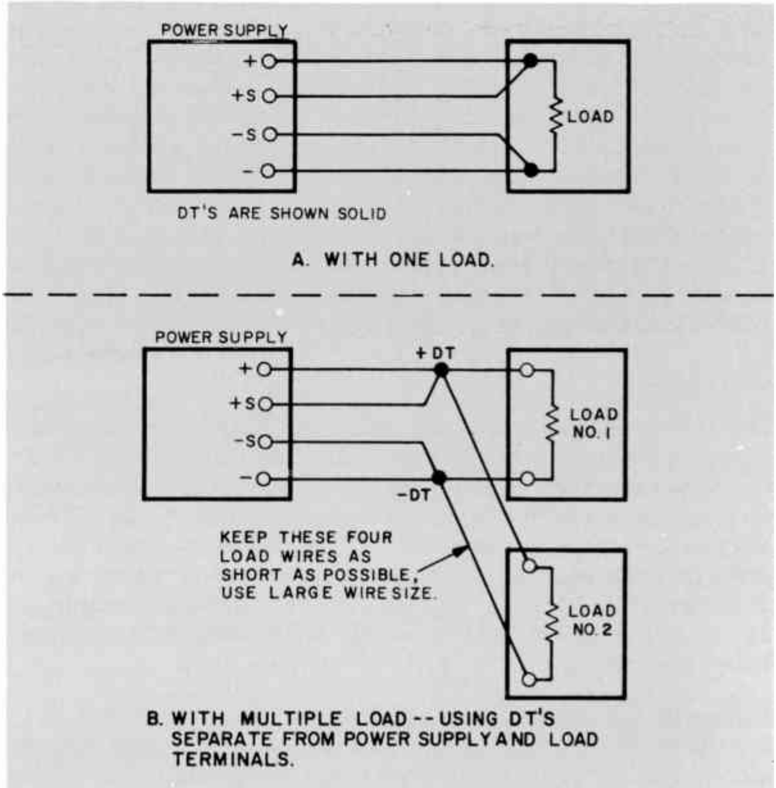


Figure 30. Location of DC Distribution Terminals with Remote Sensing

Load Wire Rating

As an absolute minimum, each load wire must be of sufficient size to carry the power supply output current which would flow if the associated load terminals were short circuited. However, impedance and coupling considerations usually dictate the use of load current wires larger than required simply to satisfy current rating requirements.

Power supplies and load wires are usually thought of in terms of their schematic equivalents—the battery symbol and line connections. The simplistic circuit models which these symbols imply are adequate for many purposes, but more exact models must be used when evaluating the regulation properties of a power supply connected to its load(s).

The battery symbol represents an ideal constant voltage source with perfect regulation and zero output impedance at all frequencies, but every regulated power supply has some small output impedance at low frequencies, and a much higher output impedance at high frequencies. Thus a more exact circuit model for a power supply includes an equivalent source resistance and inductance as shown in Figure 31. R_S is the power supply output impedance at dc, and is found by dividing the load regulation by the current rating; for example, a power supply which has a load regulation of 10mV for a full load change of 10 amps has an equivalent R_S of 1 milliohm, a typical value. Similarly, a power supply with an output impedance of 0.2 ohms at 100kHz and 2 ohms at 1 MHz has an equivalent high frequency output inductance L_S of 0.3μH—again a value typical of high performance power supplies.

The connecting lines on a schematic represent *ideal* connection between two points, but the physical wires used to connect any two terminals (such as power supply and load) are characterized by distributed resistance, inductance, and capacitance. For determining necessary load wire sizes, it is usually sufficient to consider only the equivalent lumped constant series resistance and inductance (L_O, L1, L2 . . . and R_O, R1, R2 . . .). Given the wire size and length, these lumped equivalents can be determined from wire tables and charts.

In general, the power supply performance degradation seen at the load terminals becomes significant whenever the wire size and length result in a load wire impedance comparable to or greater than the equivalent power supply output impedance. With one load, this degradation can be evaluated by comparing $2R_O$ with R_S, and $2L_O$ with L_S. The total impedance seen by the load is $Z_T = (R_S + 2R_O) + j\omega\ (L_S + 2L_O)$, and the variation of the dc load voltage caused by a sinusoidal variation of load current is $E_{ac} = I_{ac}\ Z_T$. If load current variations are more pulse- or step-shaped than sinusoidal, then the resulting load voltage "spike" will have a magnitude of $e_L = L_T$ (di/dt), where $L_T = L_S + 2L_O$, and di/dt is the maximum rate of change of load current.

If these calculations indicate that the resulting variations in dc voltage provided to the load are greater than desired, then shorter and/or larger load leads are required.

With multiple loads (Figure 31B), it is necessary to consider separately the common or mutual impedance seen by the loads, $(R_S + 2R_O) + j\omega\ (L_S + 2L_O)$, and the added impedance seen by each load individually, 2(R1 + jω L1), 2(R2 + jωL2), etc. Remember that the *mutual* impedance presents an opportunity for a variation of *one* load current to cause a dc voltage variation at *another* load. If the loads are pulse or digital circuits, false triggering may result. Similarly, if one load is the output stage of a high gain amplifier, and another load contains low level stages feeding the same signal path, unintentional feedback may occur via this mutual impedance, with resulting amplifier oscillation.

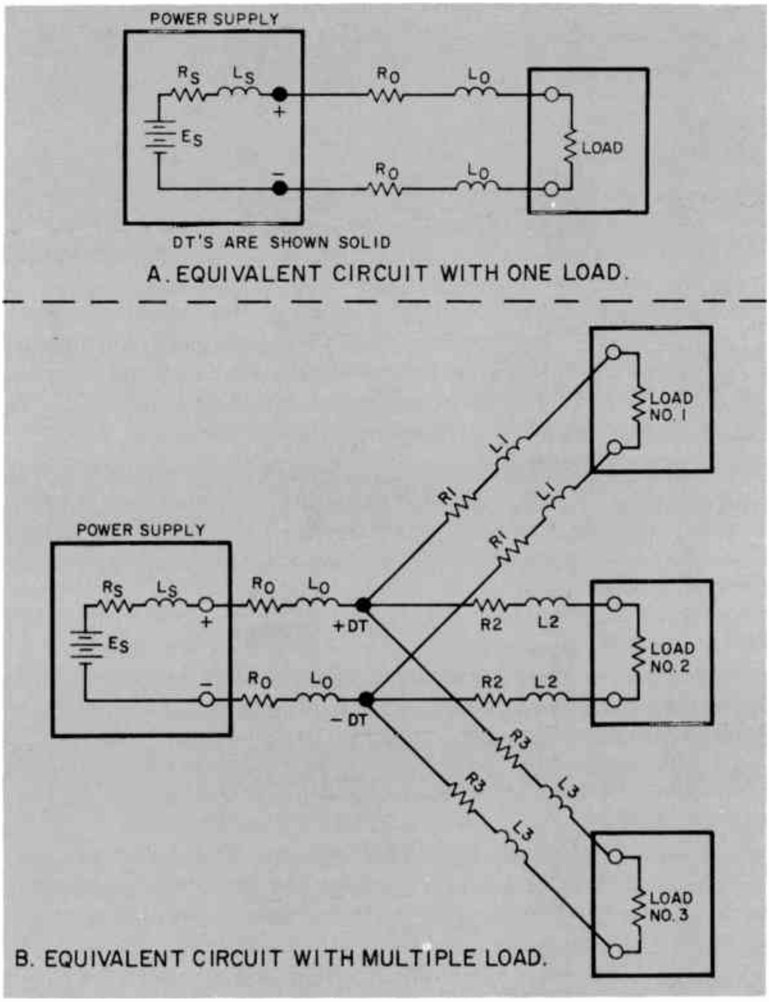


Figure 31. Power Supply and Load Wiring Equivalent Circuits.

Connecting remote sensing to the load terminals of Figure 31A or the DT's of Figure 31B has the effect of reducing R_0 by a factor equal to the loop gain of the power supply regulator, usually of the order of 10^3, 10^4, or 10^5. However, remote sensing does not in general alter the effective value of L_0 seen by the load, since L_0 predominates at frequencies above the bandwidth of the power supply regulator.

Since remote sensing affords little or no reduction in the effective load wiring impedance at high frequencies, some amount of capacitive load decoupling is sometimes desirable, particularly when multiple loads are connected to a power supply.

Load Decoupling

A local decoupling capacitor, if required, should be connected across each pair of load and distribution terminals. This reduces the high frequency impedance seen by any individual load looking back toward the power supply, and reduces high frequency mutual coupling effects between loads fed from the same supply. The use of load decoupling capacitors is most often employed with multiple loads drawing pulse currents with short rise times. Without local decoupling these current changes can cause spikes which travel down the load distribution wires and falsely trigger one of the other loads.

To be effective, the high frequency impedance of local decoupling capacitors C_0, C1, C2, and C3 (Figure 32) must be lower than the impedance of wires connected to the same load. Thus a decoupling capacitor must be chosen with care, with full knowledge of its *inductance and effective series resistance*, as well as its capacitance. Moreover, it is imperative that the *shortest possible leads* be used to connect local decoupling capacitors *directly to the load and DT* terminals (*not* to other points along the dc wiring path) so that the wiring impedance between the capacitor and its connection point is minimized.

Ground Loops

This is the most persistent, subtle, difficult-to-analyze, and generally troublesome problem connected with power supply wiring. The origins of ground loop problems are so diverse that empirical solutions are frequently resorted to. Nevertheless, a little extra thought and care will reduce, and in most cases eliminate, the need for an empirical approach.

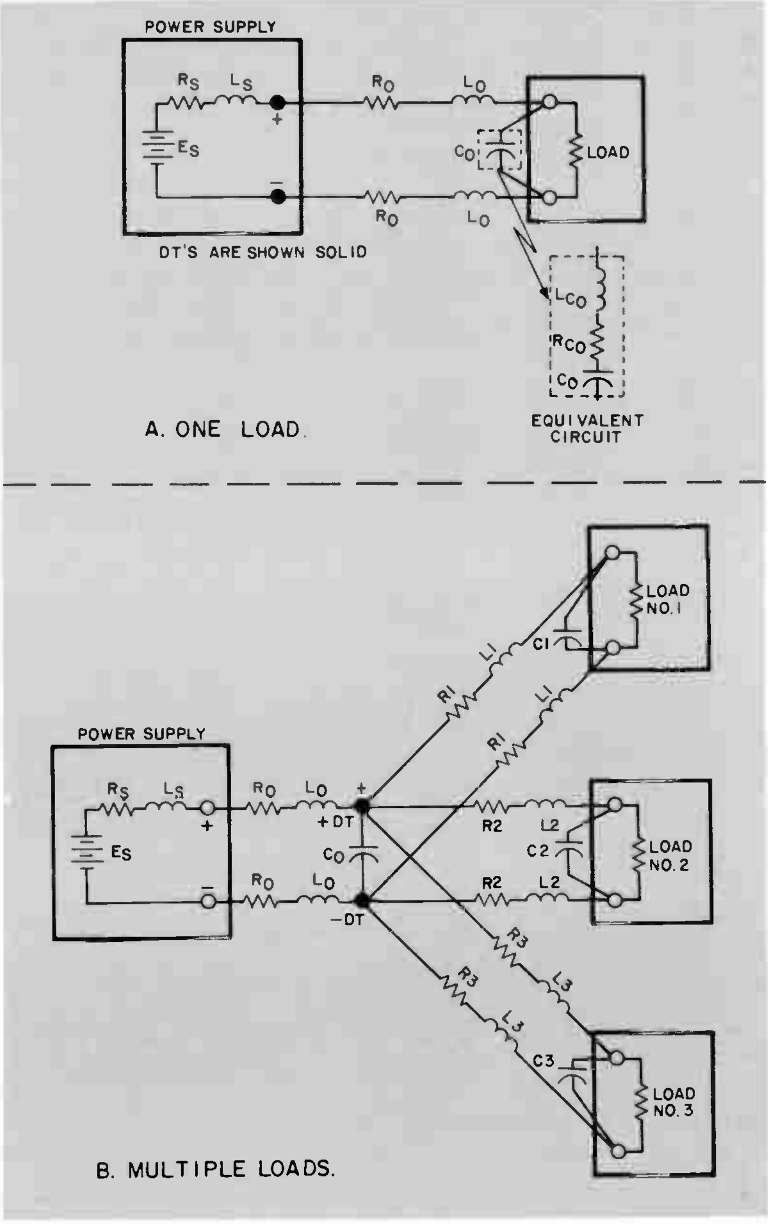


Figure 32. Local Decoupling Capacitors

The ideal concept of a single "quiet" ground potential is a snare and a delusion. No two ground points have exactly the same potential. The potential differences in many cases are small, but even a difference of a fraction of a volt in two ground potentials will cause amperes of current to flow through a complete ground loop (any circuit with more than one ground point).

To avoid ground loop problems, there must be *only one ground return point in a power supply system* (the power supply and all its loads, and all other power supplies connected to the same loads). However, the selection of the best DC Ground Point is dependent upon the nature and complexity of the load and the dc wiring, and there are practical problems in large systems which tend to force compromises with the ideal grounding concept.

For example, a rack mounted system consisting of separately mounted power supplies and loads generally has multiple ground connections—each instrument usually has its own chassis tied to the third "Safety Ground" lead of its power cord, and the rack is often connected by a separate wire to "Safety Ground" (the cold

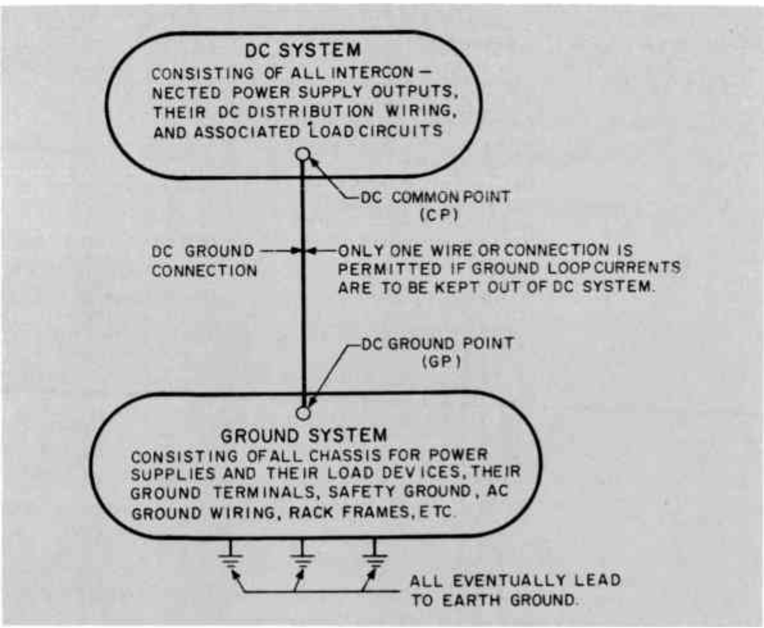


Figure 33. Isolating Ground Loop Paths from DC System

water pipe). With the instrument panels fastened to the rack frame, circulating ground currents are inevitable. However, as long as these ground currents are confined to the "Ground System" and do not flow through any portion of the power supply dc distribution wiring, the effect on system performance is probably negligible. To repeat, *separating the dc distribution circuits from any conductive paths in common with ground currents will in general reduce or eliminate ground loop problems.*

The only way to avoid such common paths is to connect the dc distribution system to ground with only one wire. Figure 33 illustrates this concept. DC (and signal) currents circulate within the DC System, while ground loop currents circulate within the Ground System.

Providing there is only one connection between the two systems, the ground loop currents do not affect the power supply dc output and load circuits.

Notice that any magnetic coupling between the DC System and Ground System, or any capacitive leakage from the DC System to ground can provide a return path enabling additional ground loop current to link both the DC System and Ground System.

DC Common

One of the DC Distribution Terminals should be designated as the "DC Common Point" (CP). There should be only one DC Common Point per DC System. If the supply is to be used as a positive source, then the minus DC Distribution Terminal is the DC Common Point; if it is to be a negative source, then the plus DT is the CP. Here are some additional suggestions for selecting the best DC Common Point for five different classes of loads:

a. Single Isolated Load—Select either the positive or negative DC Distribution Terminal as the DC Common Point. A single isolated load exists when a power supply is connected to only one load, and that load circuit has no internal connections to the chassis or ground. If the power supply output terminals are to be used as the DC Distribution Terminals, then the DC Common Point will be either the positive or negative power supply output terminal (Figure 34A). On the other hand, if remote sensing is to be employed and the load terminals will serve as the DT's, then either the positive or negative load terminal is designated as the CP (Figure 34B).

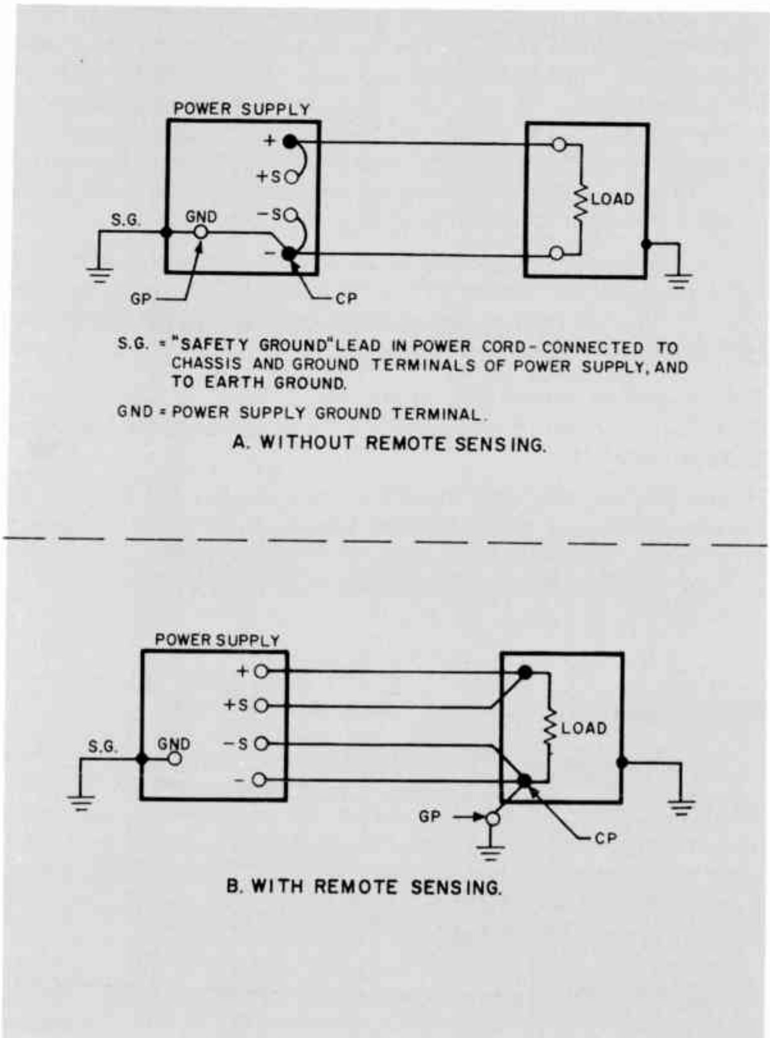


Figure 34. Preferred Ground Connections for Single Isolated Load

b. Multiple Ungrounded Loads—Select the positive or negative DC Distribution Terminal as the DC Common Point. This alternative is applicable when there are two or more separate loads with separate pairs of load leads, and none of the load circuits has internal connections to chassis or ground (Figure 35).

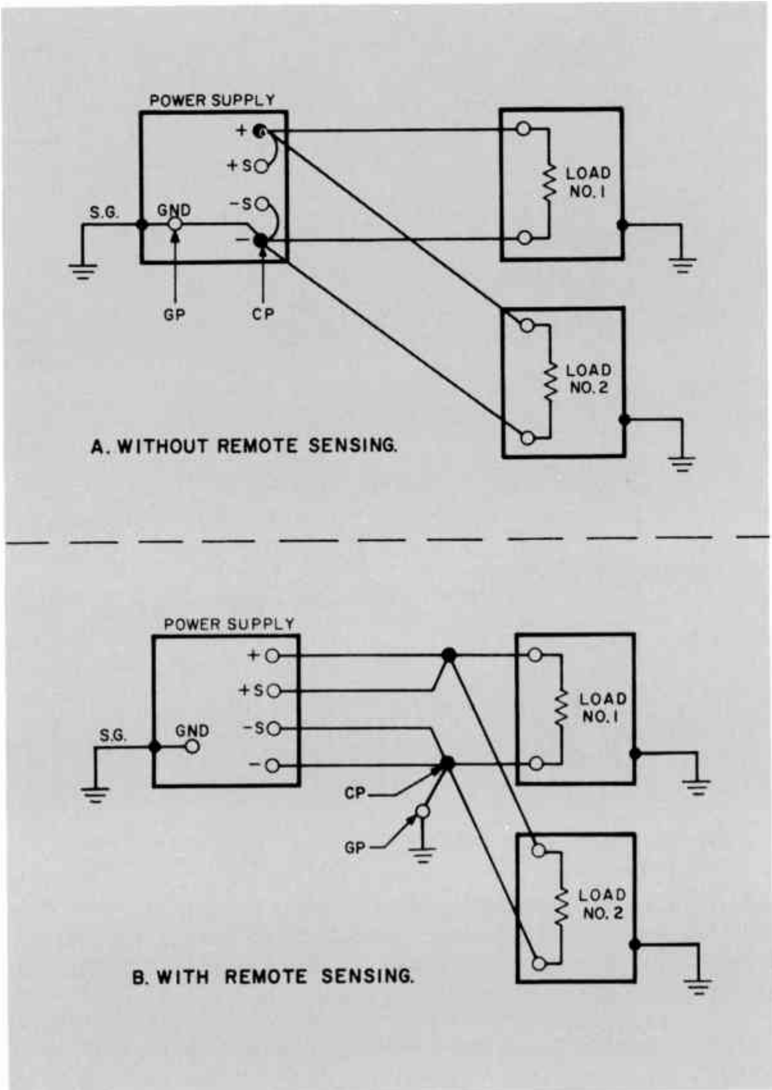


Figure 35. Preferred Ground Connections for Multiple Loads, All Isolated

c. Single Grounded Load—The load terminals of the grounded load must be designated as the DT's and the grounded terminal of the load is necessarily the CP (Figure 36).

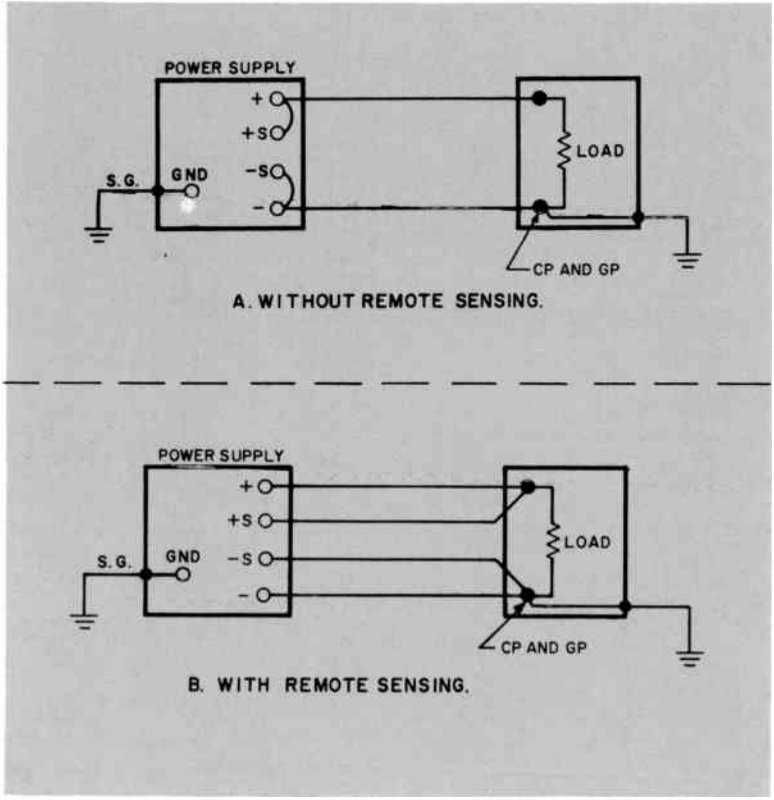


Figure 36. Preferred Ground Connections for Single Grounded Loads

This method of CP selection is followed when there is only one load and it has an essential (internal) connection to ground or chassis—or when there are multiple loads and only one has an internal connection to ground or chassis (Figure 37).

d. Multiple Loads, Two or More of Which are Individually Grounded —This is an undesirable situation and must be eliminated if at all possible. Ground loop currents circulating through the dc and load wiring can not be avoided as long as separate loads connected to the same power supply (or dc system) have separate ground returns (Figure 38).

One solution is to break the circuit connection to ground in all of

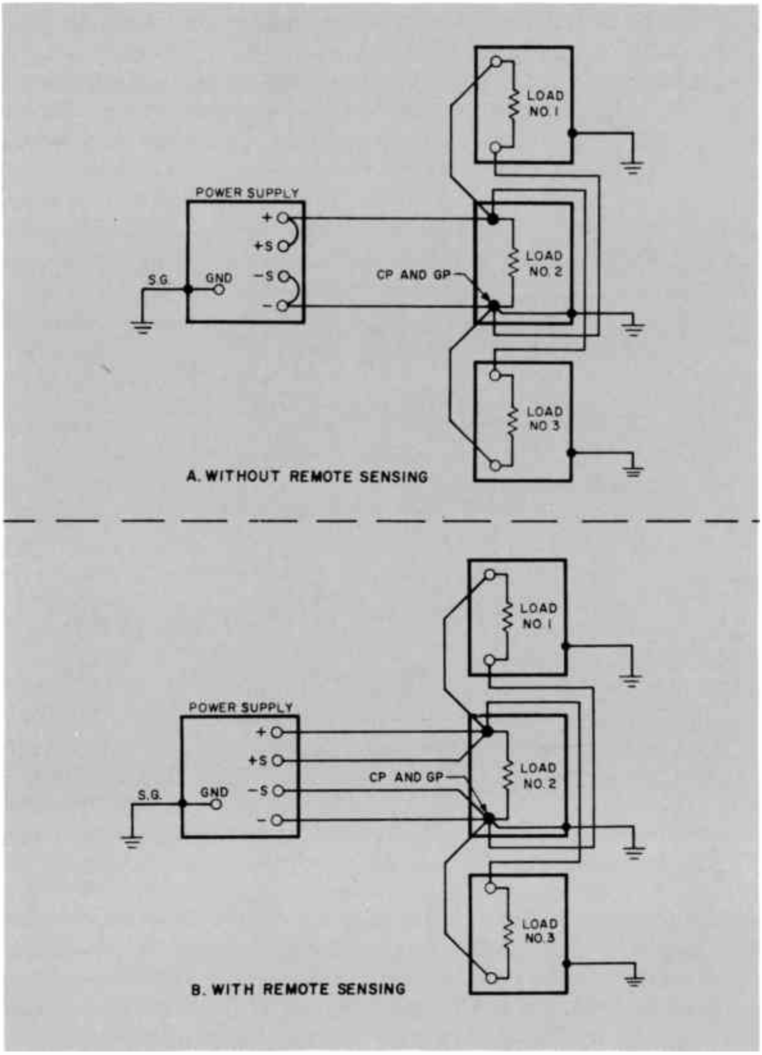


Figure 37. Ground Connections for Multiple Loads, One Grounded

the loads and then select the DC Common Point following alternative (b) on page 68, or break the circuit connection to ground in all but one of the loads and treat as in (c). In other cases the only satisfactory solution is to increase the number of power supplies, operating each grounded load from its own separate supply, and treating each combination of power supply and load as in (c). However, in this case any conductive path remaining between the loads may degrade load performance, and any conductive path between power supplies (except via their respective load grounds) will probably degrade both power supply and load performance.

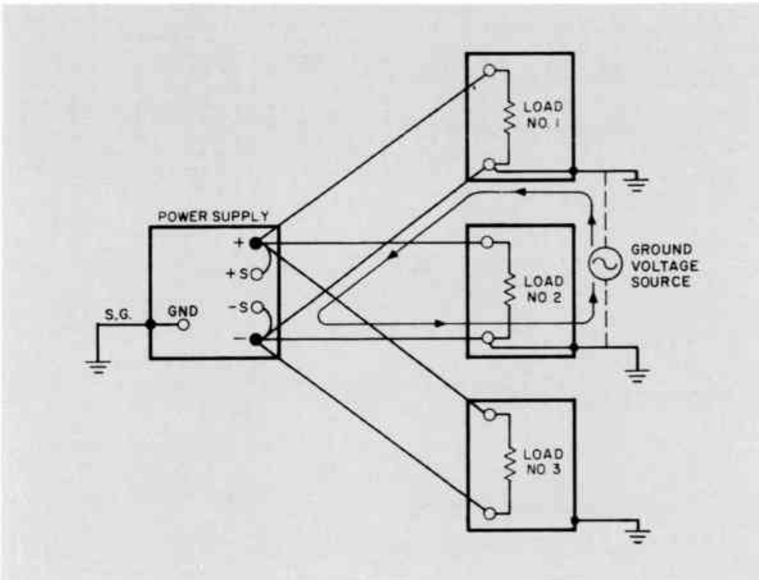


Figure 38. Ground Connections for Multiple Loads, Two or More Grounded

e. Load System Floated at a DC Potential Above Ground—In some applications it is necessary to operate the power supply output at a fixed voltage above (or below) ground potential. In these cases it is usually advantageous to designate a DC Common Point using whichever of the preceding four alternatives is appropriate, just as though conductive grounding would be employed. Then this DC Common Point should be "shorted" to the DC Ground Point through a 1μF capacitor (Figure 39).

In some special applications, however, (e.g., bridge load circuits) neither conductive nor capacitive grounding of the dc load distribution system is appropriate, since such grounding would also short out the desired output signal being generated by the bridge.

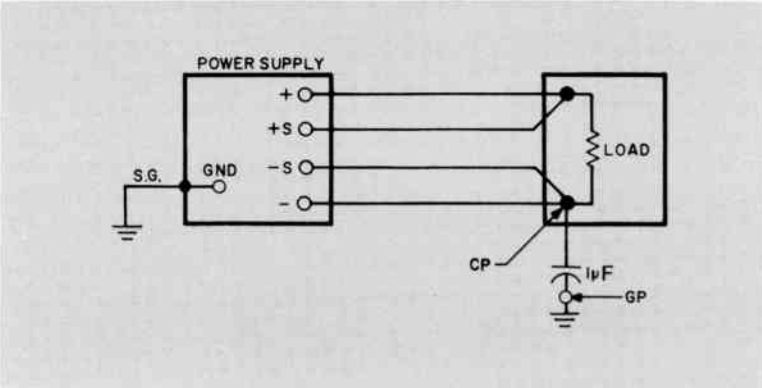


Figure 39. Floating Load

DC Ground Point

The terminal which is connected to ground should be designated as the DC Ground Point (GP). The GP may be any single terminal, existing or added, which is conductively connected to "Safety Ground" of the building wiring system and then eventually to earth ground. It may, for example, be the separate ground terminal located on one of the power supplies or loads in a system, or it may be a special system ground terminal, bus, or plane established expressly for ground connection purposes.

The CP should be connected to the GP as shown in Figures 34 through 37 (unless one load is already grounded), making certain there is only one conductive path between these two points. This connection should be as short as reasonable, and the wire size used should be such that the total impedance from the DC Common Point to the DC Ground Point is not large compared with the impedance from the GP to earth ground. Braided leads are sometimes used to further reduce the high frequency component of this ground lead impedance.

Sometimes the impedance between the CP and the GP is minimized by using a single terminal or bar for both. In these cases, care should be taken that all DC System connections are made at *one* end of the terminal or bar, and any Ground System connection at the other, so that the DC and Ground System currents are not intertwined.

When checking for unintentional paths from dc to ground, be sure that any straps or wires between power supply output and ground terminals have been removed (unless, of course, this is the single desired connection between the CP and the GP).

Remote Error Sensing (Constant Voltage Operation Only)

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 40). 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—usually by an amount proportional to the impedance of the load leads compared with the output impedance of the power supply.

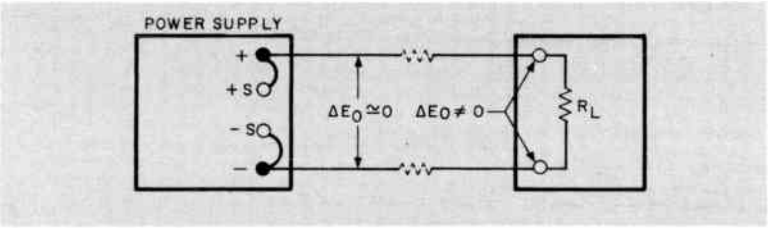


Figure 40. Regulated Power Supply with Local (Normal) Error Sensing

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 a well-regulated 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 at 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 at 30° C with rubber or thermoplastic insulation.

With remote error sensing (Figure 41), 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.

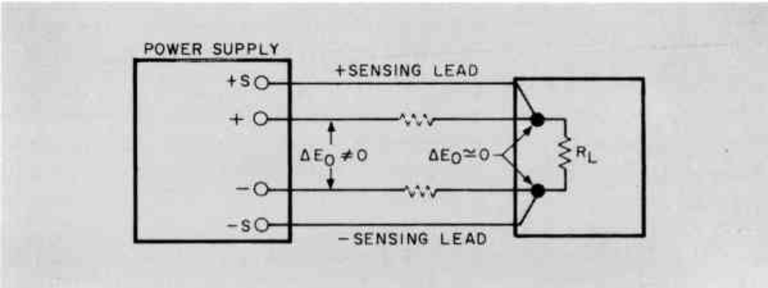


Figure 41. Regulated Power Supply with Remote Error Sensing

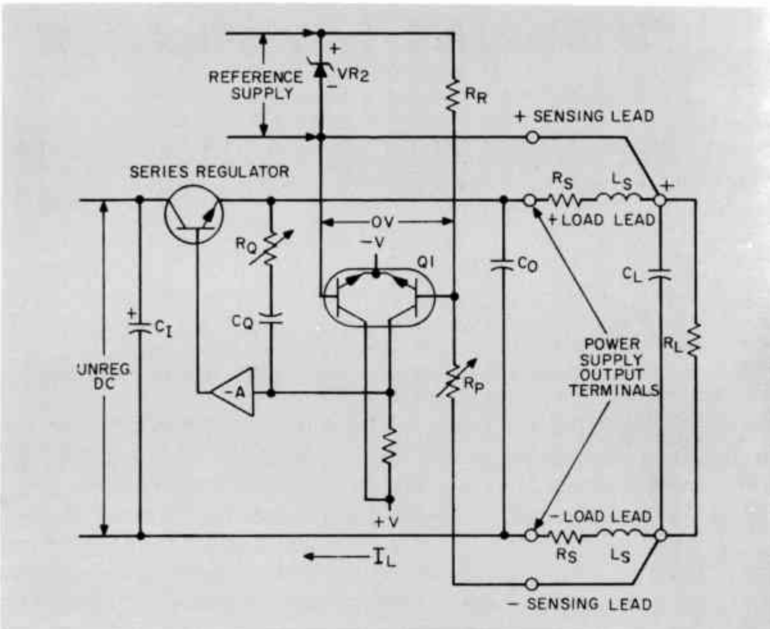


Figure 42. Constant Voltage Regulator with Remote Error Sensing

Figure 42 shows remote sensing connections to the regulator circuit. By comparing Figure 42 with Figure 17A it can be seen that the modifications to a standard design are minor, since remote error sensing simply involves operating the input comparison amplifier Q1 with reference to the load terminals instead of the output terminals of the power supply.

Remote Sensing Connections

Connections between the power supply sensing and output terminals should be removed, and using shielded two-wire cable, the power supply sensing terminals should be connected to the DC Distribution Terminals as shown in Figure 43. Do not use the shield as one of the sensing conductors. Although for clarity the diagram shows the load leads as straight lines, some immunity against pick-up from stray magnetic fields is obtained by twisting each pair of (+) and (—) load leads.

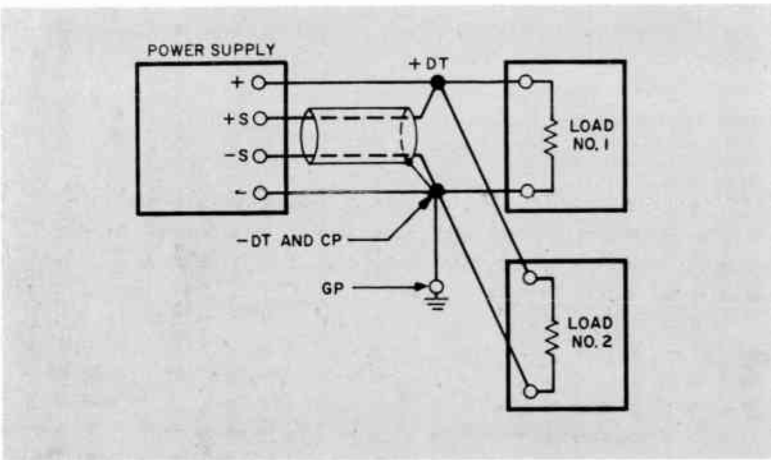


Figure 43. Remote Sensing Connections

Typically, the sensing current is 10mA or less. To insure that the temperature coefficient of the sensing leads will not significantly affect the power supply temperature coefficient and stability specifications, it is necessary to keep the IR drop in the *sensing* conductors less than 20 times the power supply temperature coefficient (stated in millivolts/°C). This requirement is easily met using readily available small size shielded two-wire cable—except in applications involving very long sensing leads or unusually well regulated power supplies with very low TC and stability specifications.

One end of the shield should be connected to the CP and the other end should be left unconnected. In nearly all cases this method of connecting the sensing shield will minimize ripple at the Load Distribution Terminals. However, in rare cases a different ground return point for this shield is preferable—it is important in such cases to experimentally verify that this relative advantage applies under all possible combinations of load and line.

Protecting Against Open Sensing Leads

The possibility of an open remote sensing path, which might occur on a long-term or transient basis, should be avoided. Such open circuit conditions are likely if the remote sensing path includes any relay, switch, or connector contacts; any interruption of the connections between the power supply sensing terminals and the DC Distribution Terminals should be avoided wherever possible.

When a sensing open occurs, the regulator circuit within the supply reacts as though the load voltage were zero—usually, the output voltage corrects this deficiency by climbing rapidly toward the maximum rectifier voltage, a value which is significantly larger than the power supply's maximum rated output voltage. Even if the power supply output circuitry is designed to withstand this extreme, the chances are that the load is not.

To reduce the degree of output overshoot which can result from accidentally opened remote sensing connections, many regulated power supplies include internally wired resistors or small silicon diodes as shown in Figures 44 and 45. If they are not part of the power supply, and if the power supply application involves long sensing leads, sensing paths which include relay, switch, or connector contacts, or any other likely cause of even momentary open-circuits

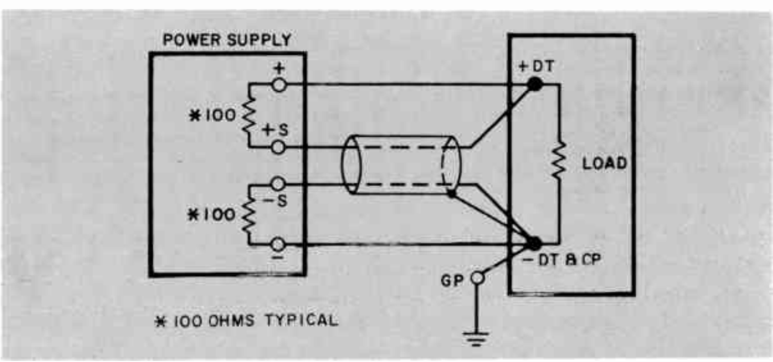


Figure 44. Remote Sensing Protection with Resistors

in the remote sensing paths; then the user should add either resistors or silicon diodes.

If the diode configuration of Figure 45 is employed, operation will be satisfactory up to about 0.5 volts drop in either load lead (between a power supply output terminal and the corresponding DC Distribution Terminal); for greater drops use two or more diodes in series.

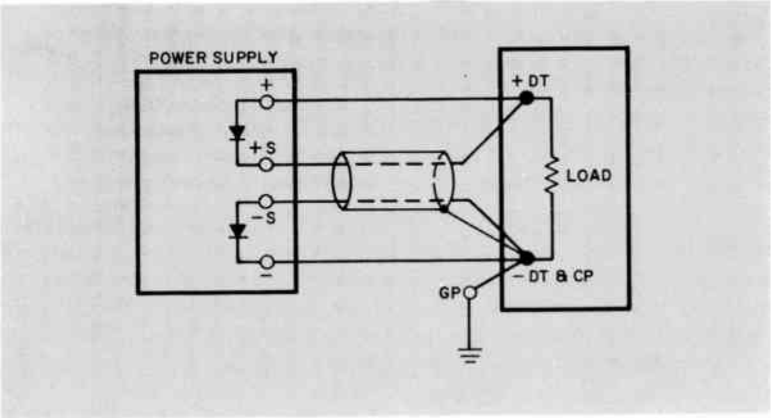


Figure 45. Remote Sensing Protection with Diodes

If the resistor configuration of Figure 44 is included by the manufacturer or added by the user, it may be necessary to check that the power rating of this resistor is adequate, particularly for sizable sensing drops. Remember that the actual dissipation in the remote sensing protection resistors is E_D^2/R, where E_D is the IR drop from either power supply output terminal to the corresponding DT, and R is the ohmic value of the protective resistor.

Load Wire Ratings

The minimum wire size for the load current leads (from the power supply output terminals to the DT's) should be determined. Most well regulated power supplies have an upper limit to the load current IR drop around which remote sensing may be accomplished without losing proper regulation control. This maximum limitation is typically 0.5, 1, or 2 volts, and may apply to the positive, negative, or both the positive and negative output leads—consult the instruction manual or the manufacturer if in doubt concerning the exact limitation applicable to a particular supply.

In addition, it must be remembered that voltage lost in the load leads reduces the voltage available for use at the load. This is usually not significant at high voltages, but a typical 10-volt power supply will only have 6 volts left for load use if 2 volts are dropped in each load lead—remote sensing does not increase the total voltage available from the power supply rectifier and regulator!

Either of these two factors will, in some cases, lead to a wire size selection which is larger than dictated by a consideration of wire current rating or impedance.

Output Oscillation

Check for the possibility of power supply oscillation when connected in the system for remote sensing. Figure 46 illustrates that the impedance of the load leads is included inside the power supply feedback loop. In remote sensing applications involving small or long load wires, there is a tendency for power supply oscillation to occur due to the phase shift and added time delay associated with the load and sensing leads.

Removal of such tendency toward oscillation is usually done empirically. In some cases readjusting a "transient recovery" or "loop stability" control inside the supply will be adequate—in more severe cases the power supply loop equalization may have to be redesigned and tailored for the application.

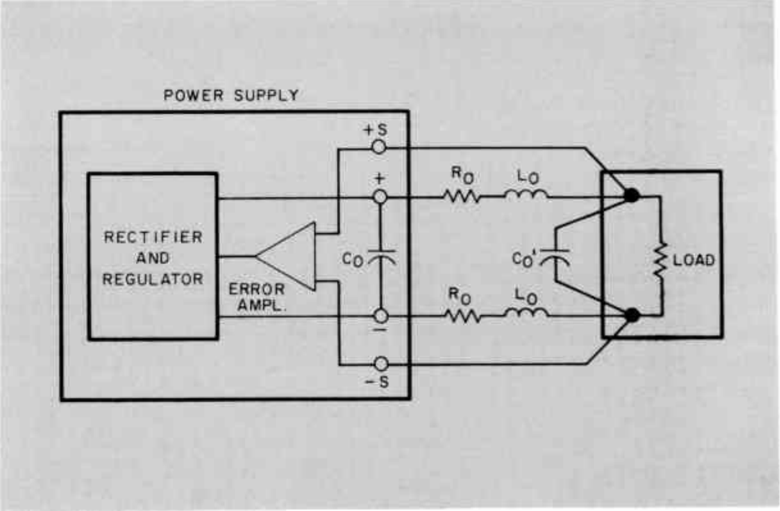


Figure 46. Effect of Load Lead Impedance on Remote Sensing

As suggested on page 64, capacitor C_O' is commonly included in order to suppress load transients and reduce the power supply impedance at the load at high frequencies. However, the capacitor must be chosen with care if power supply oscillation is to be avoided, since any capacitor resonances or other tendency toward high impedance within or near the bandpass of the power supply regulator will reduce loop stability. It is therefore common in extreme remote sensing applications to remove C_O from the power supply and use it as C_O'.

Proper Current Limit Operation

Check for proper current limiting operation while the power supply is connected in the system for remote sensing. With some power supply designs, the resistance of one of the current carrying leads adds to the resistance used for current limit monitoring, thereby reducing the threshold value at which current limiting begins. The current limit value should not change significantly while shorting −S to −OUT and +S to +OUT *at the power supply.* If it does, refer to the instruction manual for corrective adjustments, or contact the manufacturer.

LOAD CONNECTIONS FOR TWO OR MORE POWER SUPPLIES

The extension of the preceding single power supply concepts (pages 59 to 80) to multi-power supply systems (Figure 47) is simple and direct, requiring only the application of the following additional rules.

DC Distribution Terminals

There must be only one point of connection between the dc outputs of any two power supplies in the multiple power supply system —this point must be designated as one of the two DT's for both power supplies.

Thus there are *exactly* (N + 1) DT's in any system, where N is the number of power supplies (excluding the possibility of parallel supplies sharing the same distribution terminals or series power supplies with unused intermediate terminals).

This rule eliminates the possibility of circulating dc currents, while insuring the optimum connection of load and sensing leads (in accordance with DC Distribution Terminals, page 59, and Remote Sensing Connections, page 76), and lays the groundwork for avoiding ground loops.

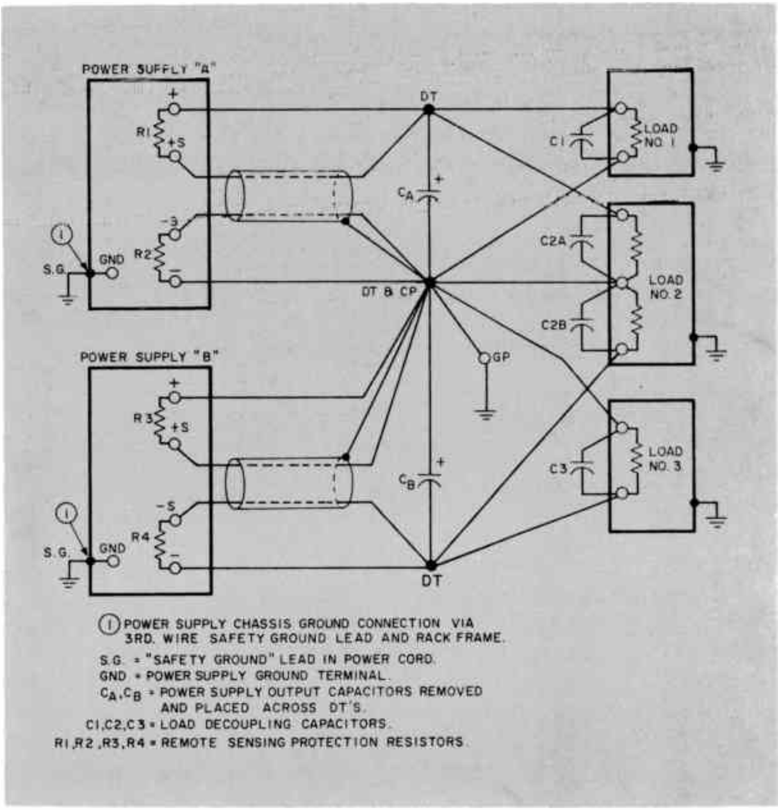


Figure 47. Load Connections for Multiple Power Supplies.

DC Common

One of the (N + 1) DT's determined in accordance with the preceding paragraph is designated as the CP for the system. There can be only one CP per system—it is the DT which is to be held at "Ground" potential. For other constraints affecting the choice of the CP see DC Common starting on page 67.

DC Ground Point

There must be only one GP per multiple power supply system. This rules out the possibility of connecting two grounded loads in the same system. For other notes on designating the GP, refer to DC Ground Point on page 73.

Connect the System CP to the System GP (unless one load is already grounded), making certain there is only one conductive path between these two points for the entire system. This rule also appears on page 73 and is repeated here as a reminder because of the far greater number of possible paths from dc to ground associated with multiple power supply systems. The notes on page 73 are fully applicable to multiple power supply systems.

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.* It 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 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.

Throughout this section, the rules for connecting and operating a power supply with remote programming are underlined. Careful attention to those rules will assure proper remote programming of the power supply.

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

Figure 48 illustrates the essential details of resistance programming of a constant voltage power supply. Note that this differs from the normal constant voltage circuit 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

*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.

substituted. 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.

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 5mA constant current thus resulting in 30 volts across the power supply output terminals.

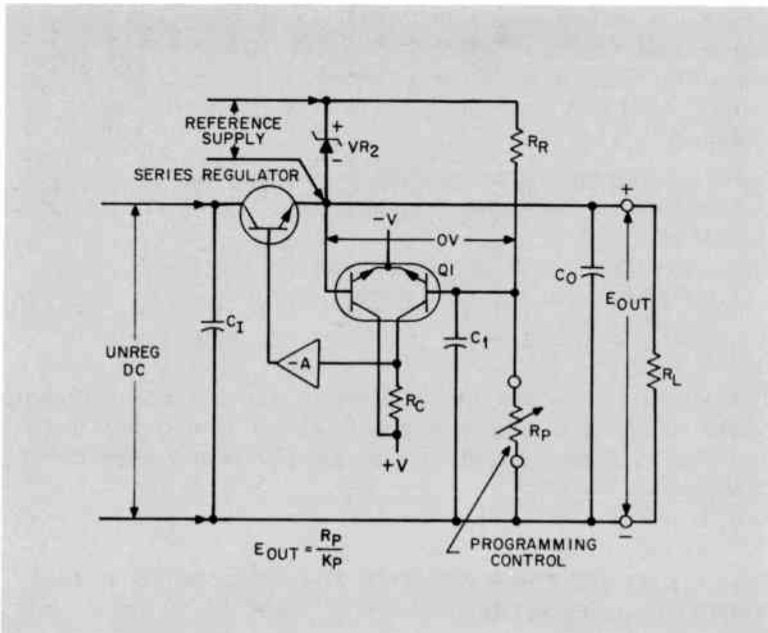


Figure 48. Constant Voltage Supply with Resistance Programming

Remote Programming Connections

Shielded two-wire cable should be used to connect the power supply programming terminals to the remote programming source, following the manufacturer's instructions for connections. The shield should not be used as one of the programming conductors. One end of the shield should be connected to the DC Common Point and the other end of the shield should be left unconnected.

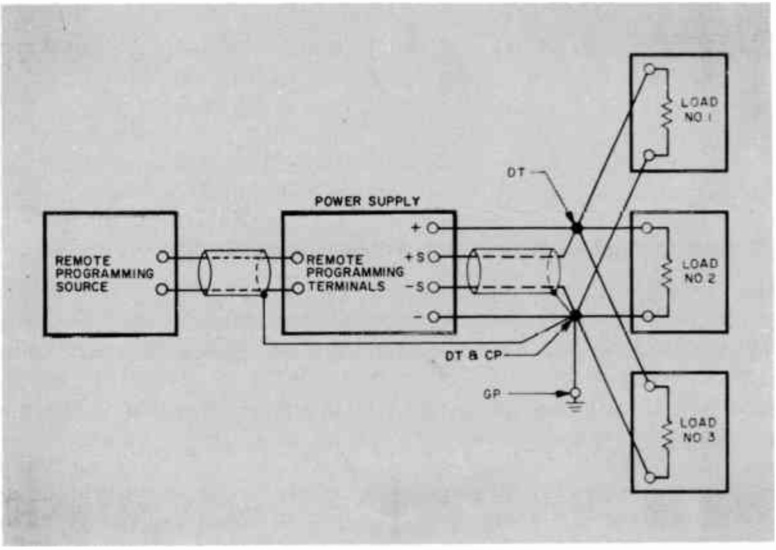


Figure 49. Remote Programming Connections

Output Drift

Check that programming leads and source will not contribute to output drift, noise, etc. 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.

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 wire size of the programming leads must be adequate to withstand any programming surges (consider effects of any large storage capacitors which have to be charged or discharged through the programming leads). The temperature coefficient of very long programming leads may degrade power supply temperature coefficient and stability specifications. This is particularly true if the power supply is exceptionally well regulated, or the programming leads are subjected to considerable ambient temperature changes, or when programming is done with low resistance values.

Protecting Against Momentary Programming Errors

Using remote programming, several different values of fixed output voltage are obtainable 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 50 illustrates several switching techniques that can be used in conjunction with resistance programming.

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 50A is a typical configuration. However, if a break-before-make switch is used in the configuration of Figure 50A, 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 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 should 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 50B, using a make-before-break switch, eliminates both the overshoot and the undershoot problems associated with Figure 50A. When the switch is 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 50B also has one drawback—namely, the output voltage must always be switched in ascending or descending sequence. As Figure 50C shows, however, the same voltage divider can have its tap points returned to the switch contacts in any sequence, permitting output voltage values to be programmed in any desired order without overshoot or undershoot.

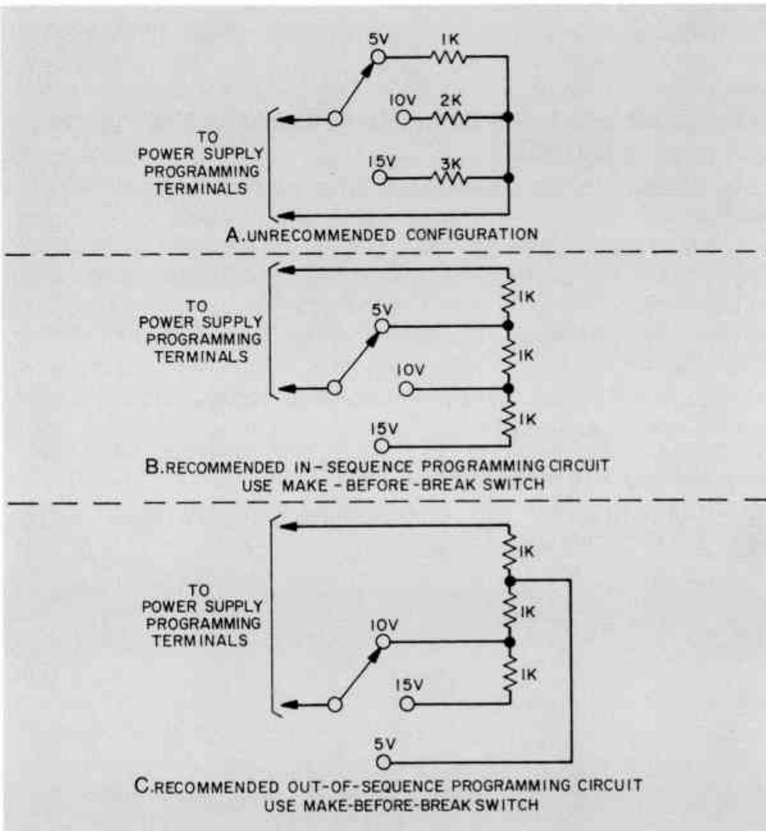


Figure 50. Remote Programming Switching Circuits

Backup Protection for Open Programming Source

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 loads from accidental opening of the remote programming leads, a zener diode should be placed directly across the pow-*

er supply programming terminals. This zener diode is selected to have a breakdown voltage equal to the maximum power supply voltage that 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.

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 remotely programmable supply with an input voltage. Thus, the power supply becomes a low frequency dc amplifier. Remote Programming Speed on page 94 stresses the bandwidth and speed of response of this configuration, whereas this section deals only with the method of control.

Two distinct methods can be employed to voltage program: unity and variable voltage gain.

Programming with Unity Voltage Gain

This method, shown in Figure 51, requires that the external voltage be exactly equal to the desired output voltage.

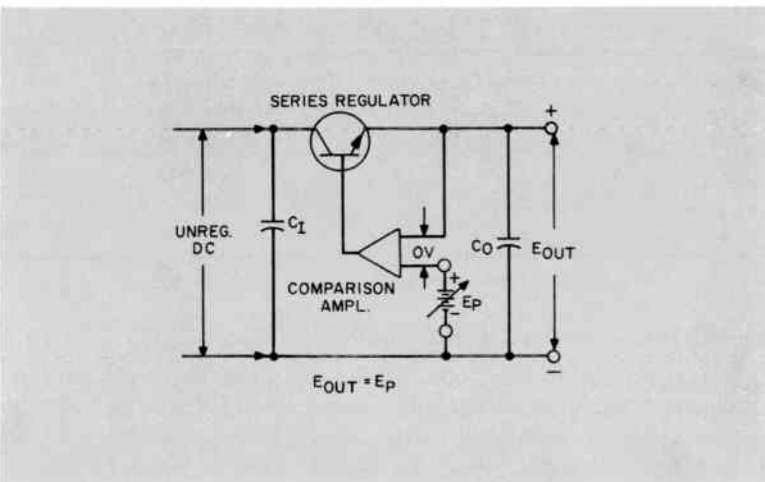


Figure 51. Voltage Programming with Unity Voltage Gain

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.

Programming with Variable Voltage Gain

Figure 52 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 supplies external terminals are available so that the connections shown in Figure 52 can be accomplished without any internal wiring changes. In all HP remotely programmable power supplies the summing point S is made available, and the configuration of Figure 52 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 52, R_P can be selected so that the resulting voltage gain is either less or greater than unity. It is possible to use the front panel control on the supply as the voltage gain control, R_P.

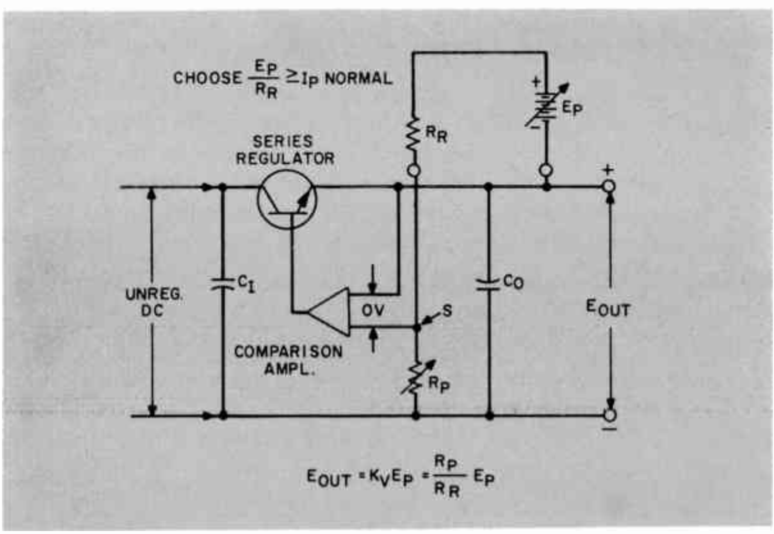


Figure 52. Voltage Programming with Variable Voltage Gain

When programming the output using a remote voltage or current source, the use of a zener diode across the programming terminals will prevent the power supply output from exceeding a predetermined limit, even though the programming source may provide an excessively high input command. The relationship between the zener diode and the output limit value depends upon the power supply design and the programming connection, but in any case can be determined by considering the power supply as equivalent to an operational amplifier. The zener diode must have a current rating equal to or greater than the largest current which the remote programming source can provide—in some cases the power rating of the zener diode can be reduced by employing a fixed resistance in series with the programming path.

In situations where only low programming voltages are being used, forward conducting silicon diodes (0.7V per junction) can be used in place of zener diodes.

CONSTANT CURRENT REMOTE PROGRAMMING

Most of the general principles discussed under Constant Voltage Programming starting on page 83 are also applicable when considering remote programming for constant current supplies. Remote programming of the constant current output of any programmable supply can be accomplished either by:

1. applying a resistance or voltage to the programming 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 on page 108.

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.

Method 1 has one important disadvantage: the normal current limiting protection, which is dependent upon the constant current setting of a CV/CC power supply, is 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 an open circuit will program the power supply to 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 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 resistor can only be used if non-linear programming of the output current can be tolerated. 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 on page 94 are applicable in determining the time required for the newly programmed value of constant current to be achieved.

REMOTE PROGRAMMING ACCURACY

Figure 53 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 output, and all other values of programming resistance result in the output voltage predicted by the programming coefficient Kp.

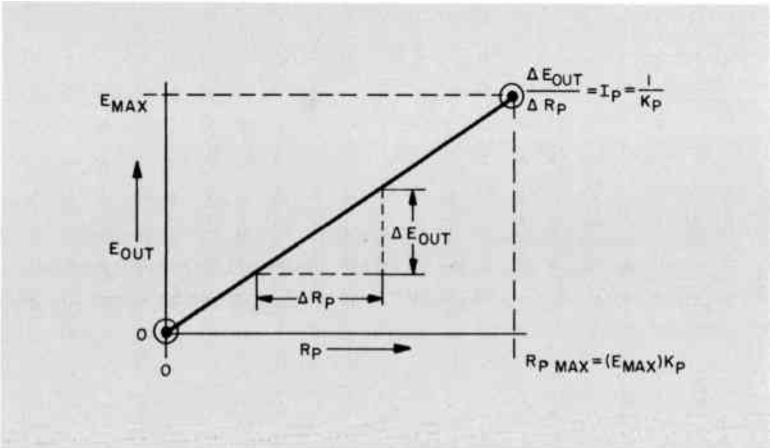


Figure 53. Ideal Remote Programming Characteristics

As Figure 54 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, since by pinpointing 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 zero and maximum output voltage. If these two points are successfully relocated, the graph of Figure 54 can be changed into one closely approximating that shown in Figure 53, which is the characteristic of an ideal supply having perfect programming accuracy.

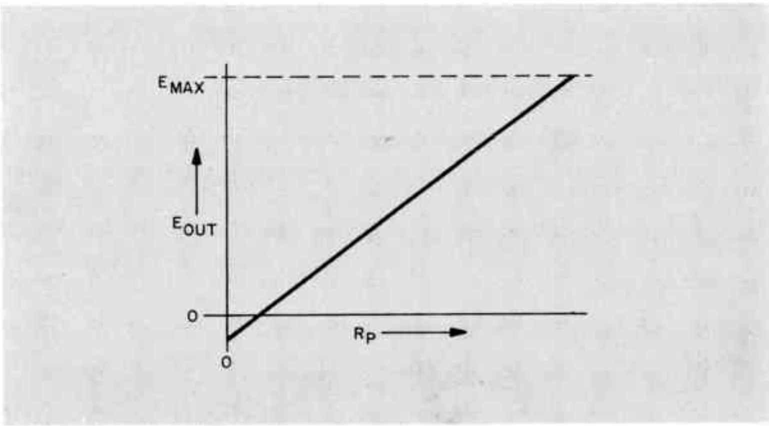


Figure 54. Practical Remote Programming Characteristic

Regardless of the 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 Figure 54 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.

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. Having adjusted this constant current, it may be necessary to readjust 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 53, 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.

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 55. 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_0 and load resistor R_L in parallel. The output therefore rises exponentially with a time constant R_LC_0 toward a voltage level $I_L R_L$, 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 55.

If no load resistor is attached to the power supply output terminals, then the output voltage will rise linearly at a rate of C_0/I_L when programmed upward, and $T_R = C_0(E_2 - E_1)/I_L$, the shortest possible up-programming time.

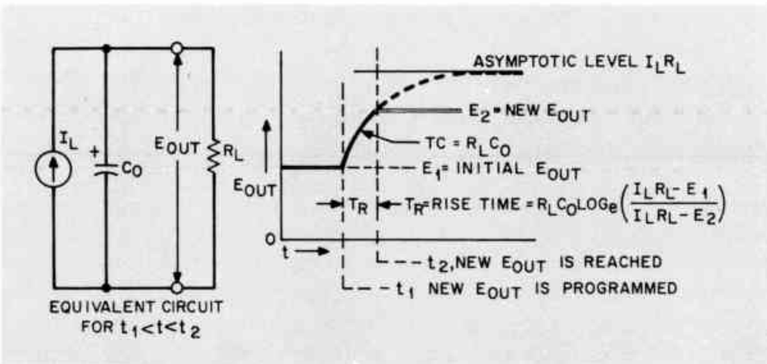


Figure 55. Speed of Response—Programming Up

Figure 56 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 $R_L C_O$, and stops falling when it reaches the new output voltage which has been demanded.

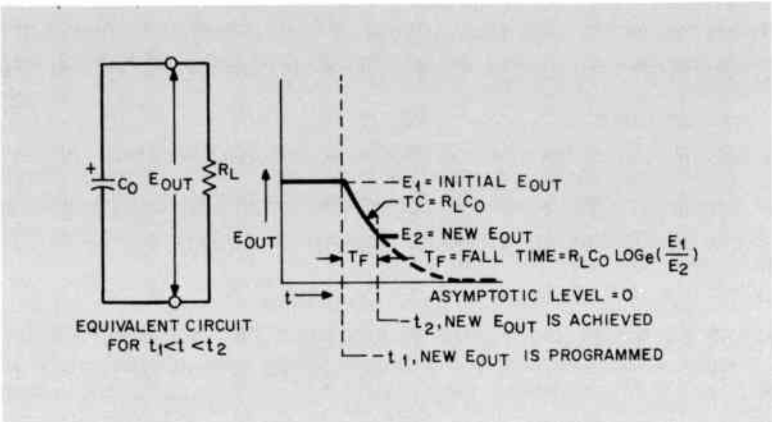


Figure 56. Speed of Response—Programming Down

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 internal bleed paths 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 readjustment of the transient recovery control 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 48 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 many 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 in the order of 1 ms.

High performance power supply/amplifiers provide 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 on page 50 and in Application Note 82.

Supplies using SCR preregulator circuits cannot in general be expected to respond as rapidly as shown in Figures 55 and 56, 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.

OUTPUT VOLTAGE AND CURRENT RATINGS

DUTY CYCLE LOADING

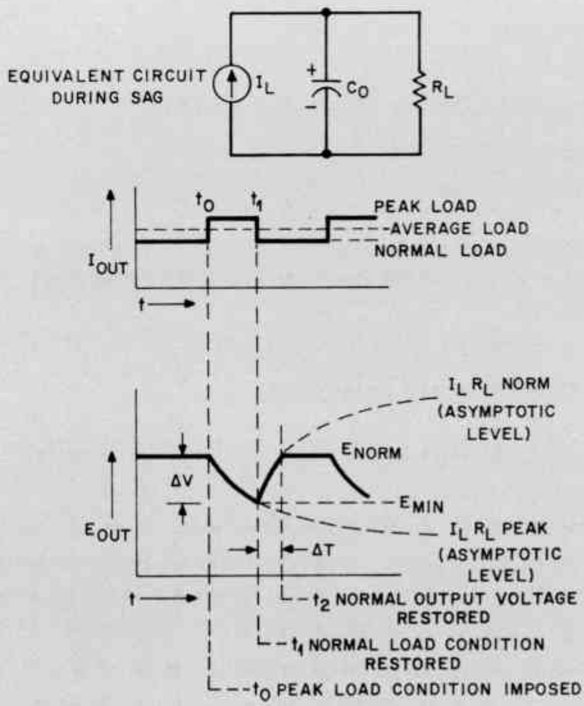
In some applications the load current varies periodically from a minimum to a maximum value. At first it might seem that a regulated power supply having a current rating in excess of the *average* load requirement (but less than the *peak* load value) would be adequate for such applications. However,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

The first question which must be answered when powering a dc load that draws a large current during some portion of its operating cycle is whether (1) the power supply need only *withstand* 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 57 *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 57 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_0 (already charged to E_{NORM}) in parallel with the lowered value of load resistance $R_{L\ PEAK}$. Thus the capacitor begins discharging exponentially toward the final output voltage value which would result if the overload condition were retained, namely $I_L R_{L\ PEAK}$. 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 57. 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 $I_L R_{L\ NORM}$. However, this charging action stops when the voltage level has risen to the normal level, and the regulator changes from the current limit mode to the normal constant voltage mode. Figure 57 also gives the equation for the time required for this voltage recovery following the removal of the peak load condition.



VOLTAGE SAG = ΔV = $E_{NORM} - E_{MIN}$

$$= \left(E_{NORM} - I_L R_{L\,PEAK}\right)\left(1 - e^{-\frac{(t_1 - t_O)}{R_L C_O}}\right)$$

SAG RECOVERY TIME = ΔT = $t_2 - t_1$

$$= R_L C_O \log_e \left(\frac{I_L R_{L\,NORM} - E_{MIN}}{I_L R_{L\,NORM} - E_{NORM}}\right)$$

Figure 57. Short-term Overload Equivalent Circuit and Output Voltage

Thus, the equations can be used to evaluate whether the voltage sag and recovery time resulting from an overload condition lie within acceptable limits, 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

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

I_L = The current limit or constant current setting,

C_O = The output capacitor (in farads), and

ΔT = Duration of overload condition (in seconds).

This approximation is pessimistic, since it assumes that the discharge of the output capacitor is linear at the rate of I/C instead of decaying exponentially.

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 58A 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.

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 58B), thus shifting the zero bias level with respect to the load current waveform so that the power supply is only required to *deliver* current.

OUTPUT VOLTAGE AND CURRENT RATINGS

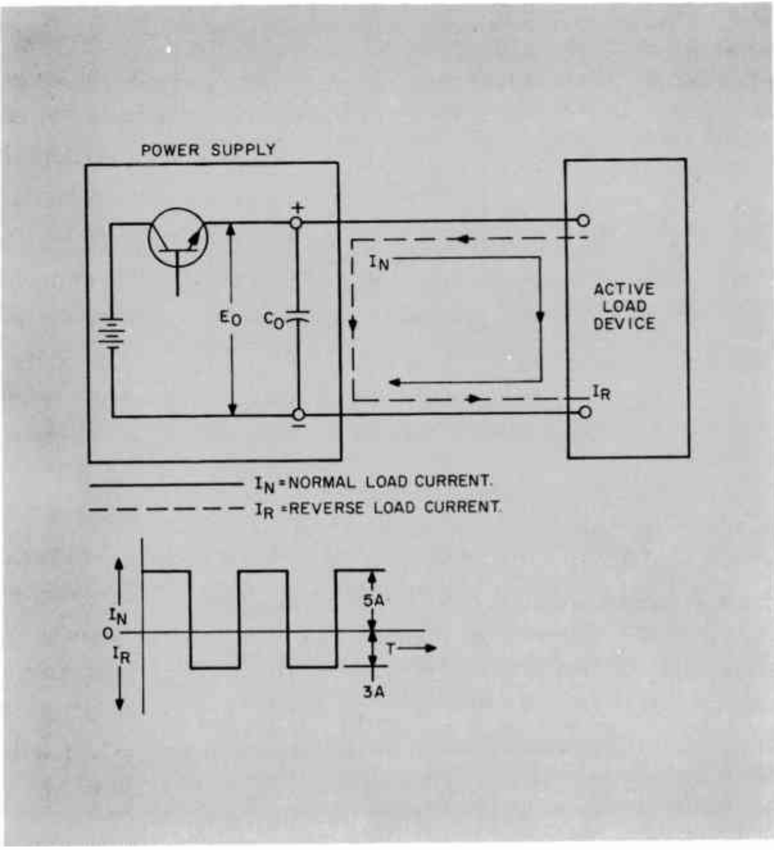


Figure 58A. Reverse Current Loading Problem

In terms of the numerical example shown in Figure 58B, 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 58B, 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.

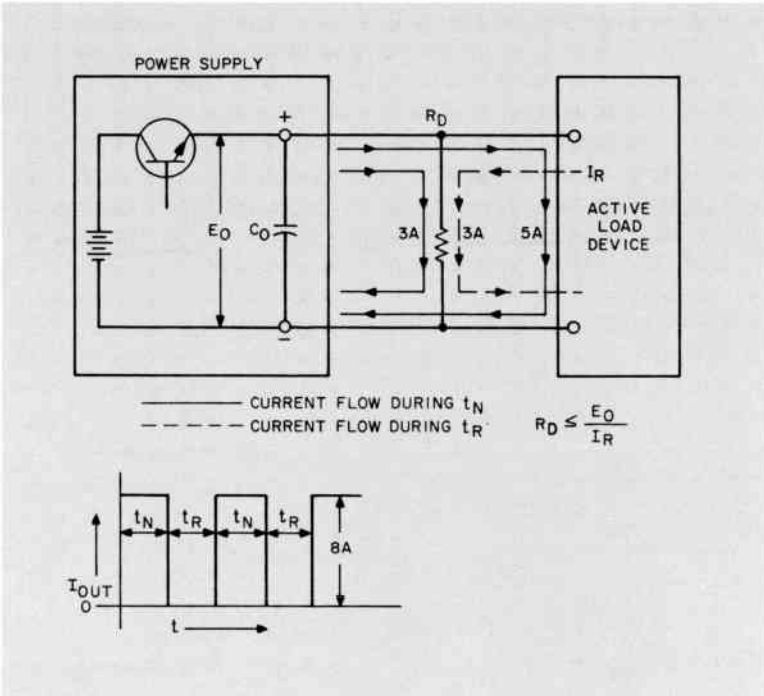


Figure 58B. Reverse Current Loading Solution.

DUAL OUTPUT USING RESISTIVE DIVIDER

Often it is required to use both a positive and negative dc power source having approximately 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 59 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.

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 imbalance can develop. In nearly all cases, a simultaneous need for positive and negative dc voltages necessitates the use of two separate regulated power supplies.

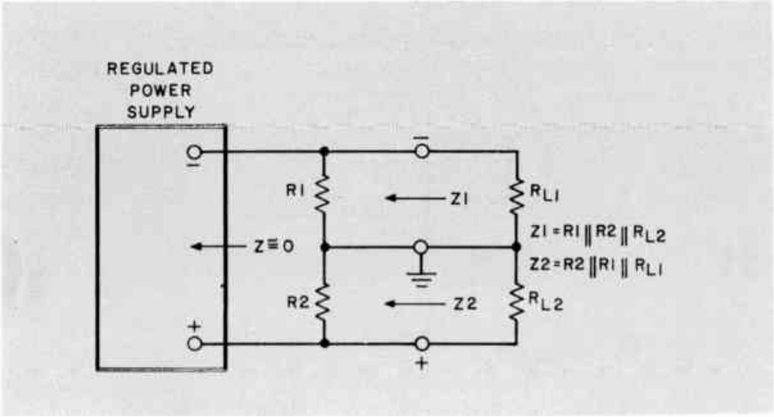


Figure 59. Center-tapped Power Supply Output

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.

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.

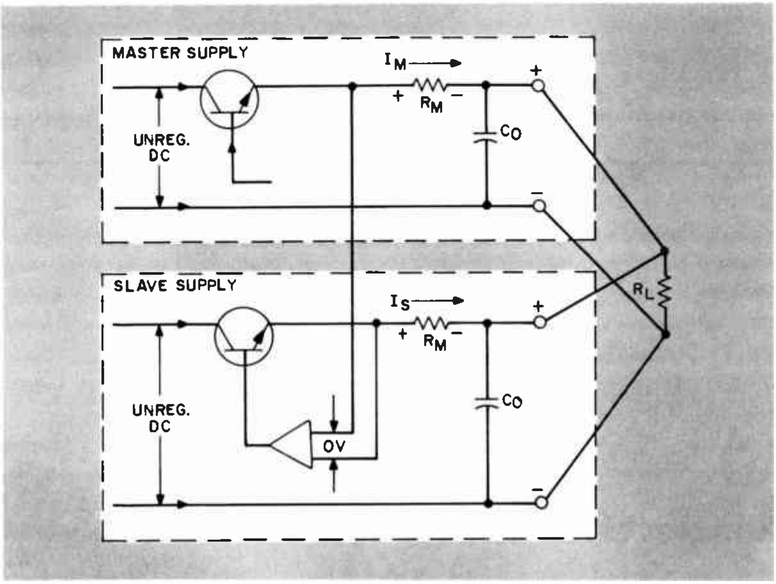


Figure 60. Auto-Parallel Operation of Two Supplies

Figure 60 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.

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.

OUTPUT VOLTAGE AND CURRENT RATINGS

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.

SERIES OPERATION

Series operation of two or more HP power supplies can be accomplished up to 300 volts off ground. 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.

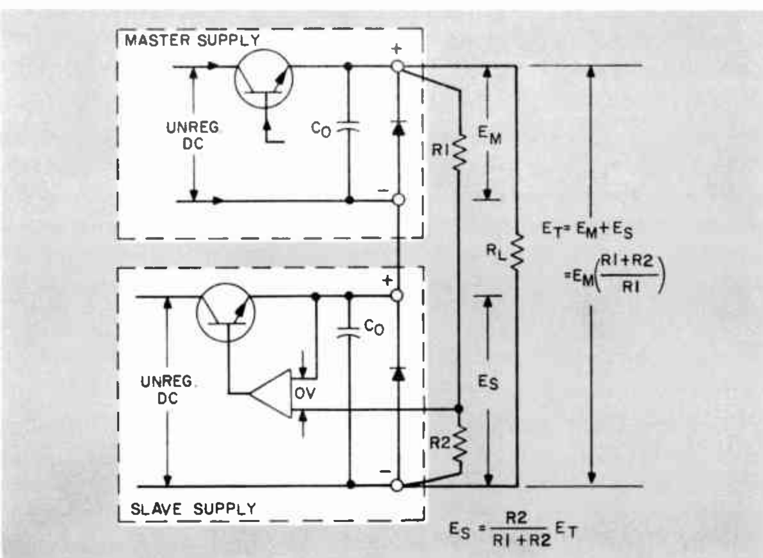


Figure 61. Auto-Series Operation of Two Supplies

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 61 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 (R1and R2) 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 R1 and R2.

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 R1 and R2, 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 R1 to R2.

Since any variation in the resistance value of R1 and R2 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 R1 and R2 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 61 with previous block diagrams for the constant voltage power supply, there is no difference in the circuit location of Resistor R2 and the front panel voltage control normally found in HP power supplies. Thus, Auto-Series operation can be achieved using only one external resistor (R1) 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 analog 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.

AUTO-TRACKING OPERATION

Auto-Tracking or automatic tracking operation of power supplies is similar to Auto-Series operation except that the master and slave

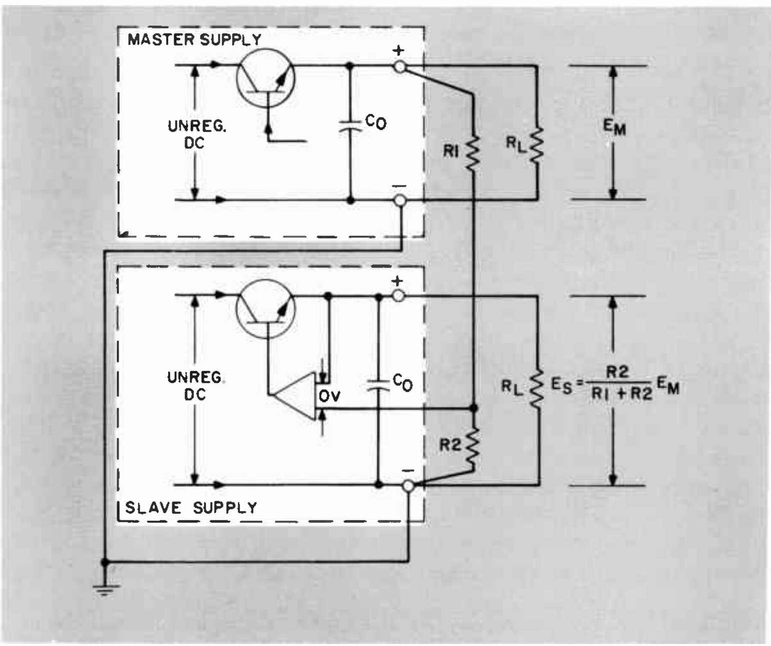


Figure 62. Auto-Tracking of Two Supplies

supplies have the same output polarity with respect to a common bus or ground. Figure 62 shows two supplies connected in Auto-Tracking with their negative output terminals connected together as a common or ground point. A fraction R2/(R1+R2) 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.

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.

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 63 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 remote sensing protection resistor or diode connected inside the supply from −S to −OUT must be removed). Because the proper operation of the 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 $I_T = E/R_M$ will be caused to flow through the current monitoring resistor R_M. The load current I_L consists of the current flowing through the monitoring resistor plus the programming current I_P (normally negligibly small compared to I_T). Both the current through

*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 63 are reversed.

the monitoring resistor and the programming current are held constant by regulator action; thus the net load current is also constant.

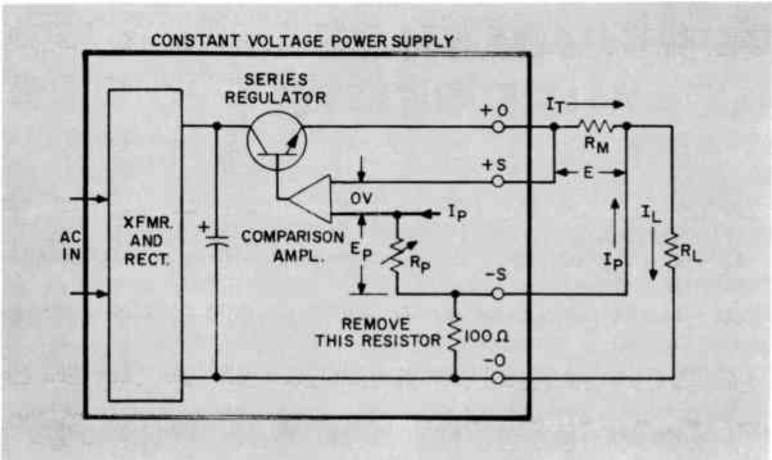


Figure 63. Converting a CV Supply to CC Output

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.

Generally speaking, the constant current performance of a supply connected in the method shown in Figure 63 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.

PERFORMANCE MEASUREMENTS

CONSTANT VOLTAGE POWER SUPPLY MEASUREMENTS

Figure 64 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.

The automatic load switch shown in Figure 64 is used to periodically interrupt the load when measuring transient recovery time. Full details of a suitable load switch and the method of employing it are given later under CV Load Transient Recovery Time on page 120.

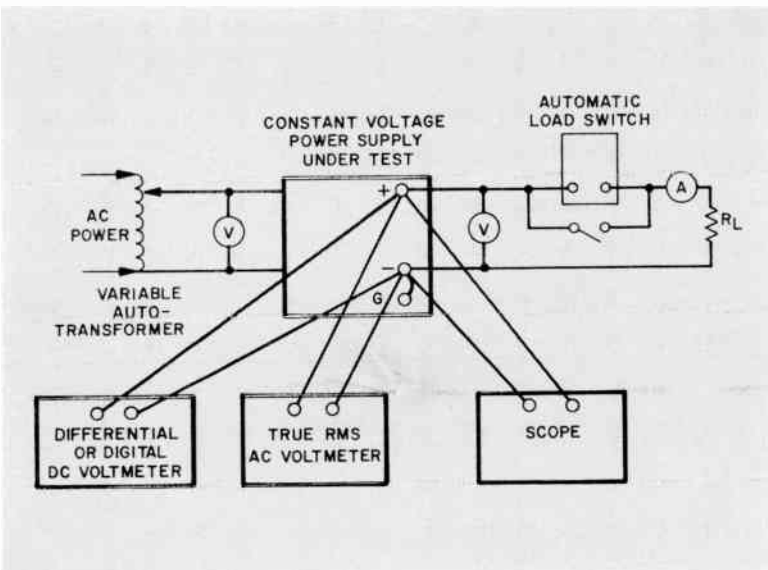


Figure 64. Constant Voltage Measurement Setup

MEASURING INSTRUMENT	NECESSARY CHARACTERISTICS	SUITABLE MODEL NUMBER
Oscilloscope	Minimum bandwith 20 MHz, vertical sensitivity 1 millivolt per centimeter minimum, differential input preferred	HP 180A with 1803A vertical plug-in
Differential or Digital DC Voltmeter	Resolution—1 millivolt or better at voltages up to 300 volts.	HP 3420B HP 3460B
True RMS Voltmeter	Sensitivity 100μvolts full scale. Crest factor 10:1.	HP3400A

Precautions

Measure Performance at Front or Rear Terminals.

Before attaching the load and monitoring devices shown in Figure 64 determine whether the supply is connected for front or rear terminal sensing, because 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 that 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.

Connect Leads to Power Supply Terminals Properly.

Casual clip lead connections will inevitably result in serious measurement errors—in most cases exceeding 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 65A and B. If performance measurements are made at the front terminals (Figure 65A) 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 65B), 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.

Failure to connect the monitoring instrument to the proper points shown in Figure 65 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 using clip leads to connect the load to the power supply terminals and the monitoring instrument to the load 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.

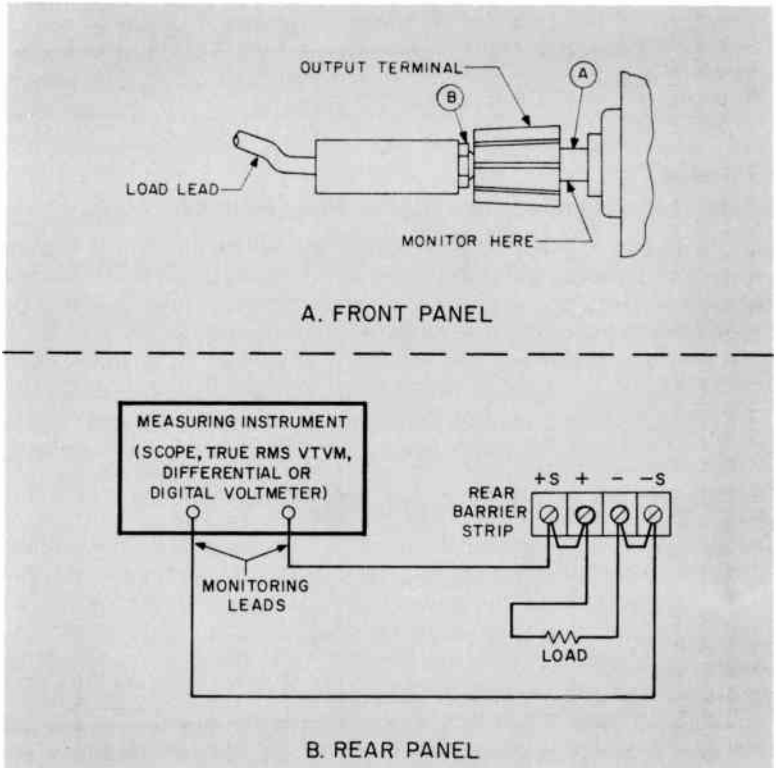


Figure 65. Proper Connections for Monitoring and Load Leads

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 65. This is necessary to avoid the subtle mutual coupling effects that may occur between measuring instruments unless all are returned to the low impedance terminals of the power supply. Twisted pairs or shielded cable should be used to avoid pickup on the measuring leads.

Use an Adequate Load Resistor.

In general, the load resistance and wattage selected should permit operation of the supply at its maximum rated output voltage and current. 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.

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 that the supply will draw. 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.

Check Setup for Pickup and Ground Loop Effects.

Avoid degradation of the measured performance caused by pickup on the measuring leads or by power line frequency components introduced by ground loop paths. Two quick checks will determine if the measurement setup is free of extraneous signals:

(a) Turn off the power supply and observe the CRT for evidence of unwanted signals (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 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 under CV Ripple and Noise on page 115.

Connect AC Voltmeter Properly.

It is important that the ac voltmeter be connected as close 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.

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 operate improperly.

Do Not Use an AC Input Line Regulator

Such regulators tend to increase the impedance of the ac input as explained on page 58.

Further precautions necessary for the proper measurement of specific power supply specifications are given as required in the following paragraphs.

CV Line Regulation

Definition: The change ΔE_{OUT} *in the steady state value of dc output voltage due to a change in ac input voltage over the specified range from low line (e.g. 103.5 volts) to high line (e.g. 126.5 volts) or from high line to low line.*

Actual measurement is accomplished by turning the variable autotransformer (Figure 64) 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 specifications 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 HP power supplies the line regulation specification is not prefixed by "±". Thus the 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.

CV Load Regulation

Definition: The change ΔE_{OUT} *in the steady state value of dc output voltage due to a change in load resistance from open circuit to* *a value that yields maximum rated output current (or vice versa).*

Load regulation is measured by closing or opening the switch in Figure 64 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.

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 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 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 on page 119.

Figure 66A shows an incorrect method of measuring ripple, because a continuous ground loop exists, as illustrated by the dashed line. 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 has a 60 Hz line frequency fundamental, and is magnified by pickup on the unshielded leads interconnecting the power supply and scope. The magnitude of this resulting noise signal can easily be much greater than the true power supply ripple and can completely invalidate the measurement.

The same ground current and pickup problems can exist if an rms voltmeter is substituted in place of the oscilloscope in Figure 66. However, the oscilloscope display, unlike the true rms meter reading, tells the observer immediately whether the fundamental period of the signal displayed is one-half cycle or one full cycle of the ac input. Since the fundamental ripple frequency present on the output of an HP supply is $2f_L$, where f_L is the line frequency (due to full-wave rectification), an oscilloscope display showing a $2f_L$ fundamental component is indicative of a "clean" measurement setup, while the presence of a fundamental frequency f_L usually means that an improved setup will result in a more accurate (and lower) value of measured ripple.

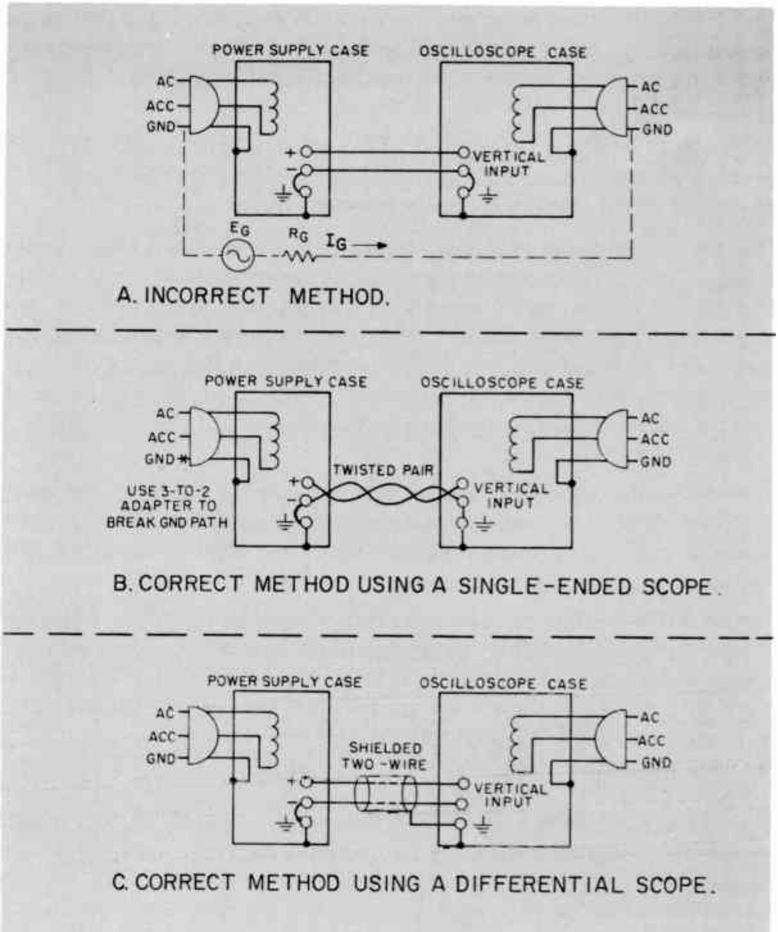


Figure 66. Measurement of Ripple and Noise Output of a CV Supply

Figure 66B 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 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 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 preventing induced noise signals 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. If the ripple magnitude of the "shorted" test approaches the actual ripple measurement, then the measurement results are unreliable.

In most cases, the single-ended scope method of Figure 66B will be adequate to eliminate non-real components of ripple and noise so that a satisfactory measurement may be obtained. However, in more critical cases, or in measurements where both the power supply and the oscilloscope case are 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 66C. If desired, two single-conductor shielded cables may be substituted in place of the shielded two-wire cable.

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 and scope case. Before using a differential input scope in this manner, however, it is imperative that its common mode rejection be verified by shorting together the 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 it 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.

To be absolutely certain that the measurement setup is free from extraneous signals, turn off the power supply and, with the scope connected across +S and −S terminals, ascertain that no signals are present on the CRT. The presence of noise signals under these conditions is indicative of pickup on the leads between the power supply and the scope.

Figure 67 shows the relationship between the peak-to-peak and rms values of three common waveforms. The output ripple of a dc power supply usually approximates the sawtooth of Figure 67B, which is 1/3.464 of the peak-to-peak value displayed on the oscilloscope. The square wave is included in Figure 67 because it has the highest possible peak to rms ratio. Thus, the *rms ripple and noise present on the output terminals of a power supply cannot be greater than 1/2 the peak-to-peak value measured on the oscilloscope.* In most cases, the rms ripple on HP power supplies is between 1/3 and 1/4 of the peak-to-peak value.

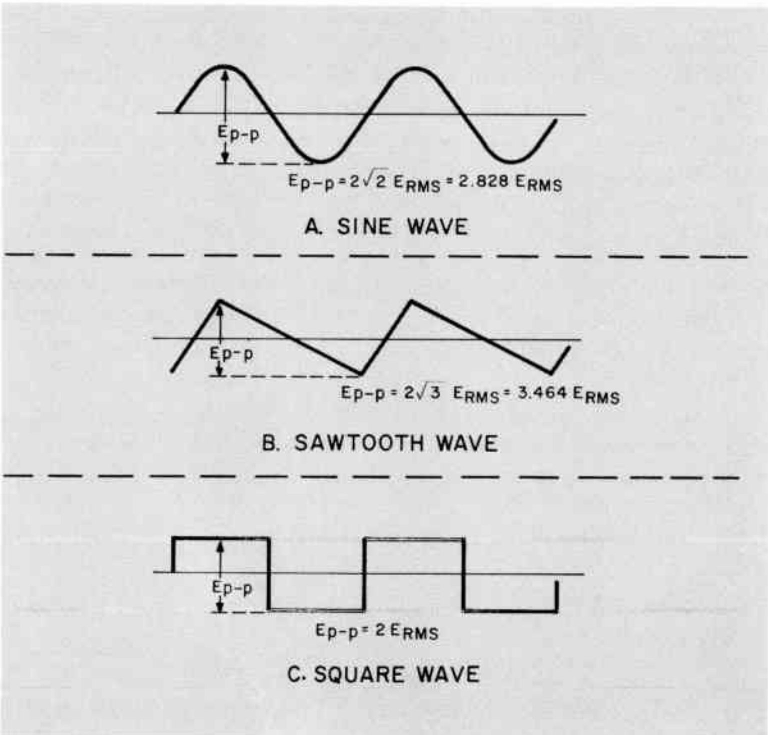


Figure 67. Three Ideal Ripple Waveshapes

Noise Spike Measurements

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

The test setups illustrated in Figures 66A and 66B are generally not acceptable for measuring spikes; a differential oscilloscope is necessary. Furthermore, the measurement concept of Figure 66C must be modified if accurate spike measurement is to be achieved:

1. As shown in Figure 68, 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.

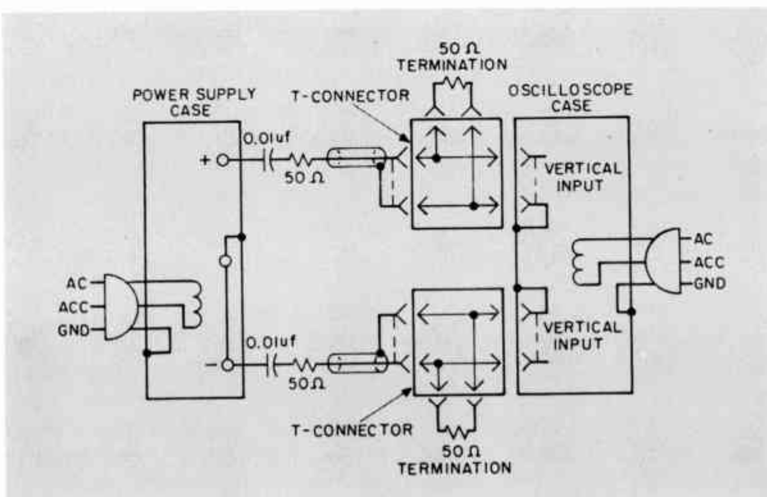


Figure 68. Measurement of Noise Spikes

5. Using the setup in Figure 68, the measured noise spike values must be doubled, because the impedance matching resistors constitute a 2-to-1 attenuator.

The circuit of Figure 68 can also be used for the normal measurement of low frequency ripple and noise, by simply removing the four terminating resistors and the blocking capacitors and substituting a higher gain vertical plug-in in place of the wide-band plug-in required for spike measurements. Notice that with these changes, Figure 68 becomes a two-cable version of Figure 66C.

CV Load Transient Recovery Time

Definition: The time "X" for the output voltage to recover and to stay 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 steady state output voltage before and after the imposed load change.

"Z" is the specified load current change, typically 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.

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 69. The output impedance of any power supply 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, a spike will occur on the output terminals of any power supply.

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 160μV 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.

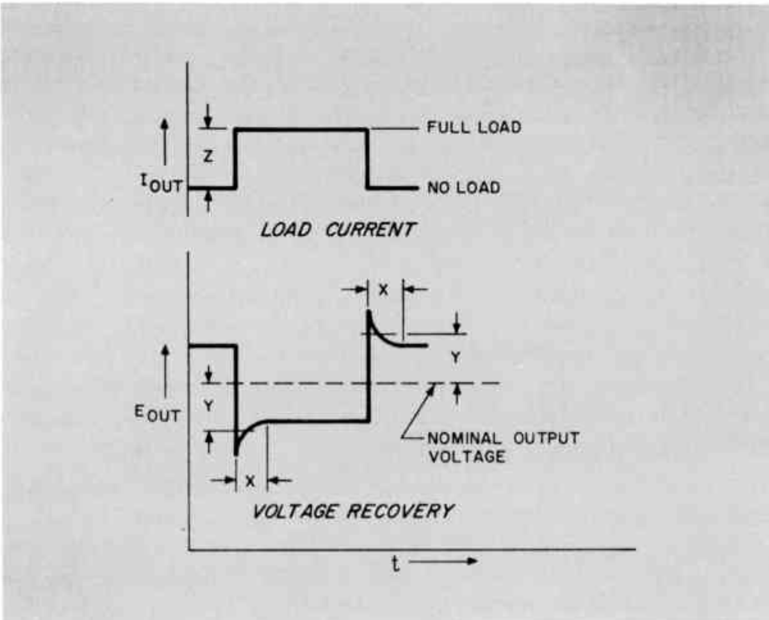


Figure 69. Transient Recovery of a Constant Voltage Power Supply

While an oscilloscope with a bandwidth of the order of 100 kHz 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 wideband 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. Specifying 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, to within 10%, or "all the way."

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 70. When this load switch is connected to a 60 Hz 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 70 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.

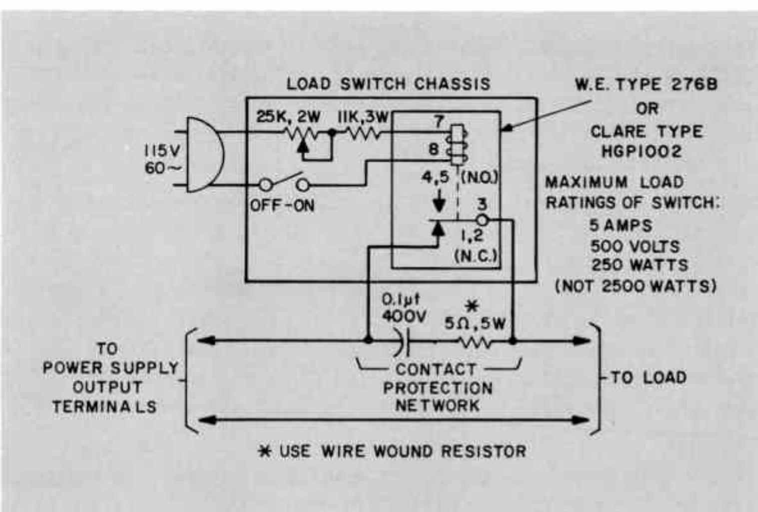


Figure 70. Automatic Load Switch for Measuring Transient Recovery Time

PERFORMANCE MEASUREMENTS

CV Stability

Definition: The change in output voltage for the first eight hours following a 30 minute warm-up period. During the warm-up and measurement interval 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 1/2 hour warm-up period.

Stability measurements are frequently 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."

CV Temperature Coefficient

Definition: The change in output voltage per degree Centigrade change in the ambient temperature following a 30 minute warm-up. During the measurement interval the ac line voltage, load resistance, and output voltage setting are held constant.

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 $0^{o}C$ to $55^{o}C$). 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 $5^{o}C$ 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.

CV Programming Speed

Definition: The time required following the onset of a step change in the programming input for the output to change from an initial value to within a certain band of the newly programmed value. This band is typically specified in millivolts for a well regulated CV supply, and in milliamps for a CC supply.

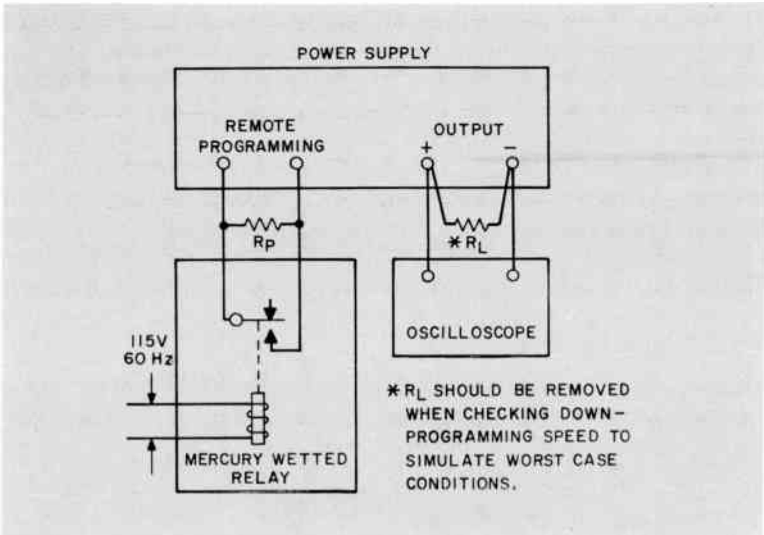


Figure 71. CV Programming Speed Test Setup

This measurement is made by monitoring the output voltage while rapidly changing the remote programming resistance. Up-programming requires that the remote programming resistance (R_P in Figure 71) be varied from zero ohms to a value that will produce maximum rated output voltage, while down-programming involves changing the resistance from the value that produces maximum rated output voltage to zero ohms. As shown on Figure 71, the load resistance R_L is included when checking up-programming and is removed for down-programming. This is done to present the worst possible conditions for programming in each direction. A method for measuring the programming speed of an HP power supply is as follows:

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 each HP Operating and Service Manual.

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 oscillate 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 on page 94.
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/volts) 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. For supplies with programming speeds of less than 8 milliseconds, a mercury-wetted relay (of the type used for checking transient recovery time) can be employed to switch the programming resistance between zero and maximum at a 60 Hz rate. The relay is connected as shown on Figure 71. For supplies with slower programming speeds (above 8 milliseconds) a hand-operated switch must be substituted in place of the mercury-wetted relay across the programming resistance. A dc coupled oscilloscope is connected across the output terminals to allow observation of the one-shot displays.

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

CV Output Impedance

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 is commonly measured only in those cases where the exact value at a particular frequency is of engineering importance; consult the Operating & Service Manual or the factory for further details.

CONSTANT CURRENT POWER SUPPLY MEASUREMENTS

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 72 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_M.

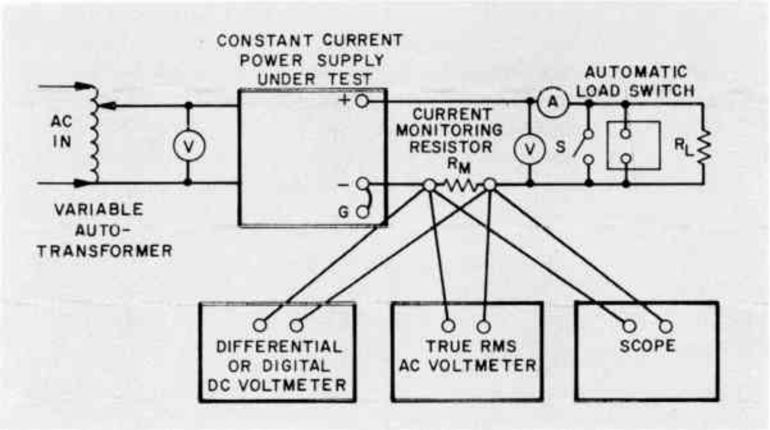


Figure 72. Constant Current Measurement Setup

Many of the precautions listed for the constant voltage measurement setup (page 110) are equally applicable to a constant current setup. In addition, other precautions peculiar to a constant current measurement setup are listed on the following pages.

PERFORMANCE MEASUREMENTS

Precautions

R_M 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 73.

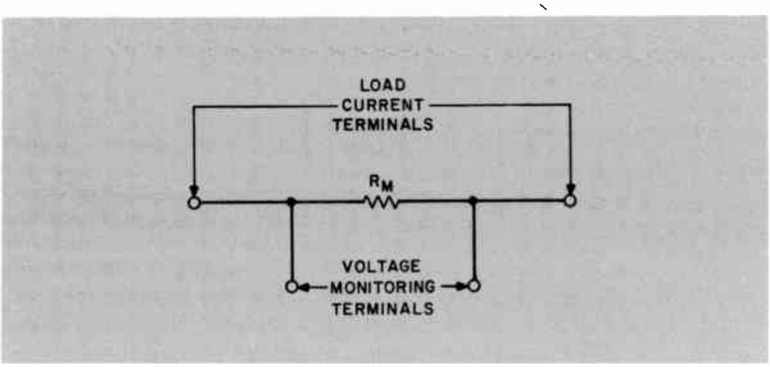


Figure 73. Four-Terminal Current Monitoring Resistor

Use Precision, Low T.C. Monitoring Resistor.

Resistor R_M 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 not subject to slow thermal fluctuations that cause similar changes in the resistance value.

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 20 ppm 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!

Keep Temperature of R_M Constant

Resistor R_M should be protected against stray air currents (open doors or windows, air conditioning vents), since these will change the resistance value, degrading the stability and temperature coefficient measurements.

Check Voltage Control Setting.

When measuring constant current performance specifications, the power supply's voltage control must be set above the maximum output voltage that 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.

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

Note that in Figure 72 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 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 74, this change in current through the incorrectly connected voltmeter will be accompanied by an equal magnitude change in current through the load and the current monitoring resistor, thus degrading the measured constant current performance.

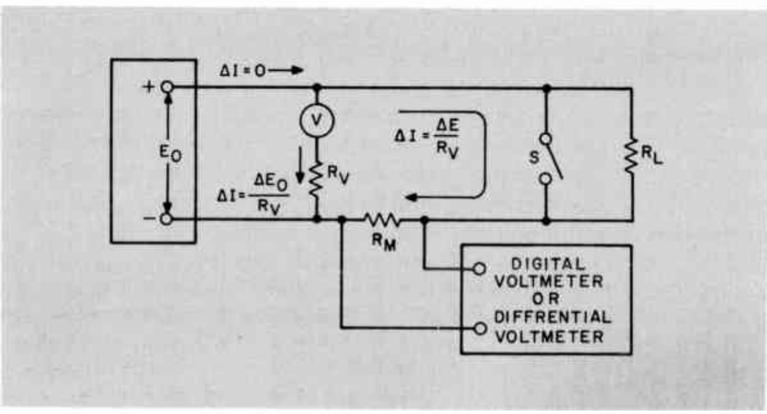


Figure 74. External Voltmeter Measurement Error on CC Power Supply

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 paragraphs as required.

CC Line Regulation

Definition: The change ΔI_{OUT} in the steady state value of dc output current due to a change in ac input voltage over the specified range from low line (e.g. 103.5 volts) to high line (e.g. 126.5 volts), or from high line to low line.

Measurement is accomplished by turning the variable autotransformer of Figure 72 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.

CC Load Regulation

Definition: The change ΔI_{OUT} in the steady state value of dc output current due to a change in load resistance from short circuit to a value which yields maximum rated output voltage.

Load regulation is measured by closing or opening the switch in Figure 72 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.

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_M is divided by R_M to obtain the peak-to-peak ripple current. For the rms value, a true rms voltmeter reading is taken across R_M after first utilizing the oscilloscope to insure that the input waveform to the rms voltmeter has a $2f_L$ (f_L = ac input line frequency) 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 75 illustrates the most important precautions to be observed when measuring the ripple and noise of a constant current supply. The presence of a $2f_L$ waveform on the oscilloscope is normally indicative of a correct measurement method. A waveshape having a fundamental component at f_L 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 on page 119, except that an appropriate load resistor R_L and current monitoring resistor R_M must be included, as illustrated in Figure 75C.

The peak-to-peak/rms conversion factors suggested by Figure 67 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 to constant current ripple and noise measurements.

CC Load Transient Recovery Time

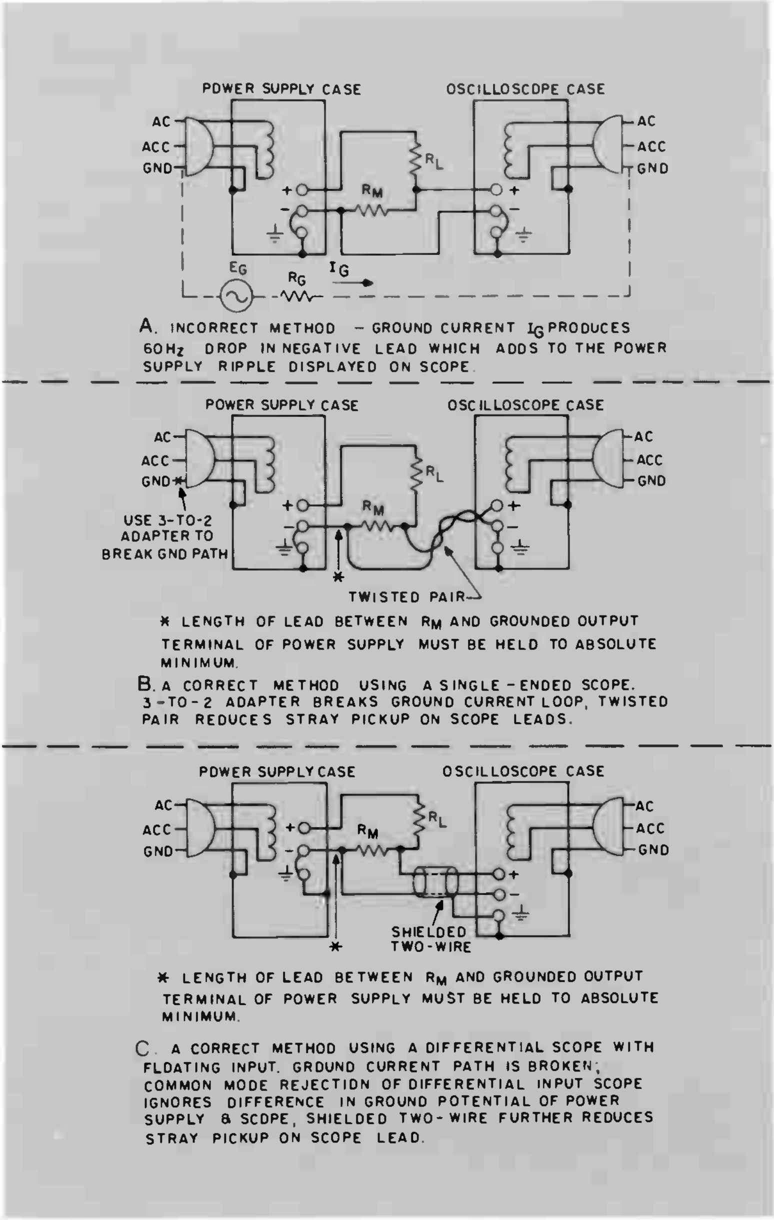
Definition: The time "X" for output current recovery to within "Y" milliamps of the nominal output current following a "Z" amp step change in load voltage—where:

"Y" is generally of the same order as the load regulation specification.

The nominal output current is defined as the dc level half way between the static output current before and after the imposed load change.

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

The test set-up used for measuring constant voltage transient recovery time should be used for measuring constant current transient recovery time except that the contacts of the mercury relay are connected in parallel rather than in series with the load resistance (refer to Figure 72). The waveforms obtained are similar to those indicated on Figure 67, but keep in mind that "Y" in millivolts must be converted to milliamps by dividing the value of "Y" by the ohmic value of the current monitoring resistor, R_M. All other comments and conditions mentioned previously under CV Transient Recovery Time apply equally to the constant current measurement.



A. INCORRECT METHOD – GROUND CURRENT I_G PRODUCES 60Hz DROP IN NEGATIVE LEAD WHICH ADDS TO THE POWER SUPPLY RIPPLE DISPLAYED ON SCOPE.

* LENGTH OF LEAD BETWEEN R_M 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_M 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 75. Measurement of Ripple and Noise Output of a CC Power Supply

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_M *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 measurement instruments is adequate.

CC Temperature Coefficient

Definition: The change in output current per degree Centigrade change in the ambient temperature following a 30 minute warm-up. During the measurement interval the ac line voltage, output current setting and load resistance are held constant.

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_M should not be placed in the oven, but must be held at a constant temperature while this measurement is made.

Other Constant Current Specifications

The measurement of 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 here can be obtained by contacting your nearest HP field sales office.

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