HEWLETT
PACKARD hp HARRISON
DIVISION

POWER SUPPLY/AMPLIFIER CONCEPTS AND MODES OF OPERATION

APPLICATION NOTE 82

SEPTEMBER, 1966

The Harrison Division of the Hewlett-Packard Company recently introduced a series of Power Supply/Amplifiers. These new and basic general-purpose instruments are capable of a variety of operating modes; in addition, they possess performance features previously unattained with either power supplies or amplifiers.

This Application Note describes the basic circuit configuration used in Power Supply/Amplifier Series instruments, lists the salient features, indicates some of the diverse applications for these versatile instruments, and shows in detail the rear terminal strapping pattern and associated circuit configuration for each of many possible operating modes.

Model 6824A

TABLE OF CONTENTS

100 Locust Avenue, Berkeley Heights, New Jersey 07922, U. S. A. Tel. (201) 464-12
Printed in U.S.A.
Europe: 54 Route Des Acacias, Geneva, Switzerland. Cable: "HEWPACKSA" Tel. (022) 42.81.

SECTION I
EVOLUTION OF THE PS/A CONCEPT

Figure 1 illustrates the basic circuit principle employed in the design of an hp well-regulated Constant Voltage DC power supply. AC input is rectified and filtered and fed through a series regulator to the output terminals. The series regulator in turn is controlled by a comparison amplifier which monitors the output voltage and compares a fraction of this output with an internal reference voltage E_R. Feedback action insures that the zero-volt difference is maintained between the "summing point" S and the negative output terminal shown in Figure 1. If any disturbance causes the output voltage to shift away from this equilibrium condition, the resulting voltage at S is amplified and changes the conduction of the series regulator by just the amount necessary to restore S to a zero volt condition. Thus the output voltage is continuously maintained at a value equal to the voltage drop across R_P.

Figure 1 thus portrays a CV (Constant Voltage) DC power supply in the fashion most familiar to power supply designers and users. Essentially, a diagram such as Figure 1 considers a power supply in terms of power flow — AC enters at the left of the diagram and DC leaves at the right.

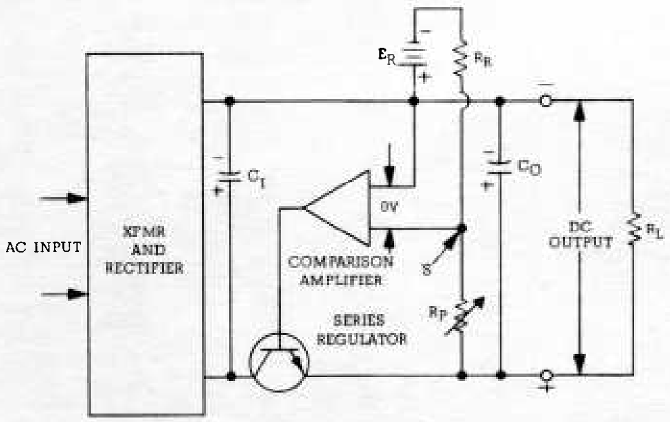


Figure 1. Design Principle — Well Regulated Constant Voltage DC Power Supply

There is, however, an alternative way of looking at the action of a power supply — in terms of signal flow. This concept, frequently more useful in applying power supplies to specific applications, treats the DC power supply as an operational amplifier (with considerable power output capability).

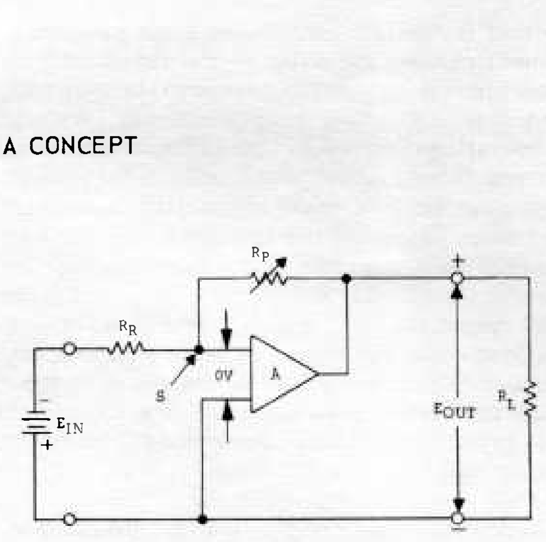


Figure 2. An Operational Amplifier With DC Input Signal

An operational amplifier* is a particular type of voltage feedback circuit having its feedback path connected as shown in Figure 2. With large values of voltage gain A, the "summing point" S is essentially at zero potential or "virtual ground", and the output signal $E_O = -(R_P/R_R)\,E_{IN}$.

The Block A includes an output stage which can be drawn separately along with its DC source. The result is shown in Figure 3.

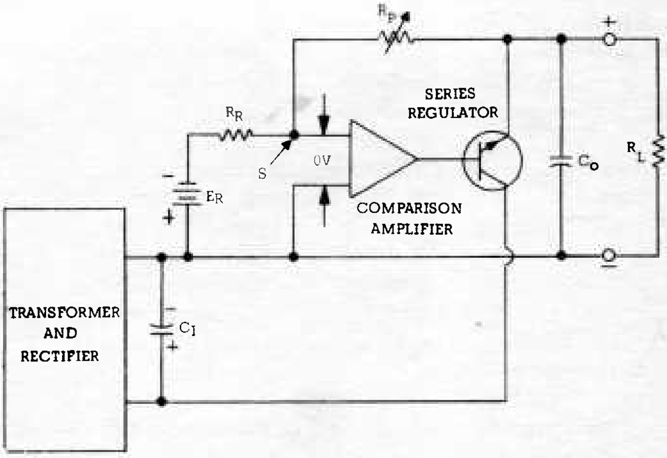


Figure 3. Operational Amplifier Representation Of An Adjustable CV Power Supply

---

*An introduction to the operational amplifier concept can be found in many texts on electronic circuitry, including Millman, J., and H. Taub: "Pulse and Digital Circuits," Chap. 1, McGraw-Hill Book Co., Inc., New York, 1956.

Notice that if Figure 3 and Figure 1 are compared, all connections are the same — the topography has not been altered. Thus Figure 3 reveals that an hp well regulated DC power supply is actually a high power operational amplifier! This immediately suggests many "non-routine" applications for power supplies, but some of these possibilities are eliminated when we recall the following restrictions for a normal well-regulated DC power supply:

1. The power supply normally has a large output capacitor C_O to insure feedback loop stability independent of the phase angle of the load impedance. This results in a significant bandwidth limitation if one attempts to use the power supply as an amplifier.

2. The power supply can conduct in one direction only, whereas an operational amplifier will, in most cases, be capable of an AC output symmetrical about zero.

In many hp power supplies it is possible to reduce the size of the output capacitor by a factor of 100 or more merely by removing rear terminal straps. Still, in order to design a DC power supply capable of changing its output voltage over its entire rated span in $100\ \mu s$ or less, it is necessary to eliminate the output capacitor (except for inevitable strays) and find an alternate way to insure feedback stability. Moreover, it is desirable to add elements capable of discharging the output capacitance (thereby reducing the output voltage) as rapidly as the normal series regulator is capable of charging the output capacitance. Still greater flexibility in applications can be obtained if the power supply is made to vary its output voltage symmetrically about zero — i.e., achieve an AC output without employing a coupling capacitor to the load.

These considerations lead to the circuit shown in Figure 4. Notice that this circuit differs from Figure Figure 1 in that:

1. A separate rectifier and series regulator transistor of opposite polarity have been added so that the output voltage can be pushed either positive or negative.

2. The output capacitor has been eliminated. Additional circuit modifications not shown in Figure 4 have been made to insure that the power supply will remain stable for any load, whether capacitive, resistive, or inductive, even though an output capacitor has not been included in the instrument.

3. A bi-polar reference circuit has been substituted for the uni-polar reference employed in the normal power supply of Figure 1. This permits the output voltage of the supply to be continuously varied with control R_Q from a positive to a negative value — a characteristic not previously provided in DC power supplies.

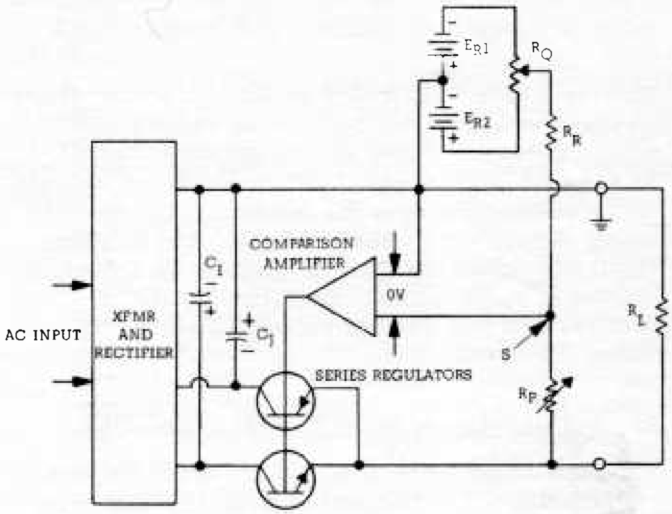


Figure 4. Power Supply/Amplifier Drawn As A Power Supply

Following the analogy between Figure 1 and Figure 3, the PS/A circuit of Figure 4 can be redrawn to show that it is essentially an operational amplifier with single-ended push-pull output. Notice that in this drawing (Figure 5) a signal generator has been substituted for the bi-polar reference circuit of Figure 4.

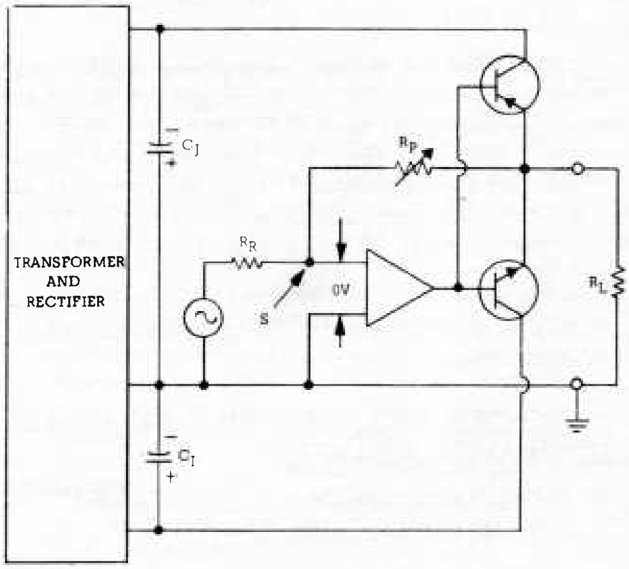


Figure 5. Power Supply/Amplifier Drawn As An Amplifier

Section II

FEATURES AND APPLICATIONS

Terminals have been added on the rear barrier strips so that connection can be made to various control points within the Power Supply/Amplifier circuit. In addition, a front panel switch has been included which readily converts the instrument between the power supply and amplifier modes. The resulting flexibility lends the PS/A to virtually an unlimited number of applications; the following list of features and related applications is suggestive rather than exhaustive:

A. REGULATED DC POWER SUPPLY FEATURES

1. Bipolar output — front panel control permits continuous adjustment of output voltage from full positive to full negative value (useful for curve plotting, X-Y displays, etc.).
2. High speed programming — less than 100 µs for output voltage change over entire rated span (useful for high speed components testing).
3. Can be resistance, voltage, or current programmed.
4. A small AC component can be added to DC output for incremental measurements.
5. Output can be Constant Voltage or Constant Current (with addition of external current monitoring resistor).
6. Normal hp high performance power supply specifications — regulation less than 0.02% + 5 MV; ripple and noise less than 2 MV RMS; fast transient recovery time; low temperature coefficient and stability specifications; no overshoot for turn-on, turn-off, or power removal; remote sensing; short circuit proof; output terminals front and rear.
7. Can be used as power "sink" (instead of source) with external power resistor.

B. DC POWER AMPLIFIER (HIGH POWER OPERATIONAL AMPLIFIER) FEATURES

1. Unusually low output distortion — less than 0.02% at 1 KHz and full output.
2. Frequency response ± 3 db from DC to 20 KHz (up to 100 KHz on special order).
3. High output signal/noise ratio.
4. Unusually low amplifier output impedance — less than 0.03 ohms from DC to 100 Hz.
5. Remote sensing capability permits low amplifier output impedance to be achieved at load terminals instead of at amplifier terminals.
6. Output can be Constant Voltage or Constant Current (with addition of external current monitoring resistor).
7. Output can be controlled by using either a voltage or current input.
8. Internal current limiting assures protection for both amplifier and load in the event of accidental output short circuit.
9. Front panel control permits gain to be varied from 0 to X10.

C. APPLICATIONS

1. A general purpose instrument useful in any laboratory engaged in research and development of electronic systems, circuitry, or components.
2. High speed programming DC power supply for automatic component testing.
3. Output amplifier for servo systems. DC coupled output useful for systems requiring position as well as velocity control, and permits the design of a servo system without complicating the low frequency stability problem by introducing a low frequency corner (such as results from the transformer of an AC Power Amplifier).
4. Magnetic deflection coil driver amplifier — Constant Current output readily achieved using external resistor, with control from input voltage or current.
5. Can be used with external oscillator to comprise power oscillator or variable frequency AC power source. Furthermore, if desired voltage/current ratio is not achieved directly at the PS/A output terminals, a step-up or step-down transformer can be added to change the voltage/current ratio delivered to the load.

6. Makes an excellent low frequency amplifier for testing the output impedance of other power supplies. The extremely low output impedance of well regulated CV supplies requires a high current AC source for accurate low frequency output measurements.

7. Can be used to maintain a constant magnetic field by connecting a field sensing coil to the sensing terminals.

Other features and possible applications will be suggested by the following sections, which show in detail some of the many possible modes of operation.

Section III

MODES OF OPERATION INVOLVING CONSTANT VOLTAGE OUTPUT

A. GENERAL COMMENTS

The following notes and precautions are applicable to all Constant Voltage modes of control.

1. The following diagrams show various operating modes in terms of the power supply concept of Figure 4, although each of them can easily be redrawn by the user in terms of the amplifier concept of Figure 5. This uniformity of presentation will better enable the user to devise his own connection patterns based on whatever combination appears most useful for a specific application.

2. Each of the following circuit diagrams has associated with it a barrier strip diagram which shows the necessary strapping pattern, as well as all components which must be added externally to the PS/A. These barrier strip diagrams are correct for all PS/A Series instruments, but when implementing these strapping patterns, check whether the terminal locations are the same as shown in the following diagrams, which are based specifically on the Model 6823A. In any case, the terminal designations are correct for all PS/A Series instruments and should be followed regardless of their location.

3. External resistors and potentiometers should be wire-wound and have a temperature coefficient of less than 20 ppm/°C; they should operate at less than 1/30th (preferably 1/100th) of their wattage rating in order to minimize short term "bobble" associated with elevated surface temperature.

4. Shielded leads should be used for all barrier strip connections, except that twisted leads may be used from the "Common" and "Output" terminals to the load. The outer sheath of the shielded wire should never be used as a conductor, but should be connected at the power supply end only to the terminal designated "Common".

5. Best high speed programming and wide band amplifier operation will be achieved when the load is connected at the rear terminals rather than at the front. Any capacitance in parallel with the load device should be minimized, since this capacitance will limit the high frequency bandwidth.

6. Unless the diagram indicates setting of the front panel "Mode" switch, the configurations shown have been selected so that operation is independent of whether the "Mode" switch is in the "Power Supply" or "Amplifier" position.

7. The front panel "Fine · Zero" control is operable for all modes. In front panel power supply operation it acts as a fine control on the DC output. In remote programming and amplifier modes, it provides a DC "offset" adjustment of approximately 1% of the maximum rated output voltage. Thus, this control permits the accurate setting of zero output voltage with zero ohms programming.

8. Particular care should be taken with external switching schemes to insure that no undesired rear terminal strapping condition exists, even on a momentary basis. See Sections III-C, III-D3, and III-D4 for switching precautions associated with remote sensing and remote programming.

9. Be sure screws on rear terminal strip are securely tightened before applying power.

10. If excessive 60 Hz component exists on output, check for ground loops. The system in which the PS/A is employed should have one ground point only. See Harrison Division power supply Application Manual, Sections D1a (6) and D1d for further discussion of typical ground loop problems.

B. NORMAL FRONT PANEL CONTROL

Figure 6 shows the circuit configuration and normal rear barrier strip strapping pattern for standard front panel power supply control with the front panel "Mode" switch in the "Power Supply" position. The DC output is continuously adjustable from its maximum rated positive value to an equal negative value — smoothly through zero with no polarity switch.

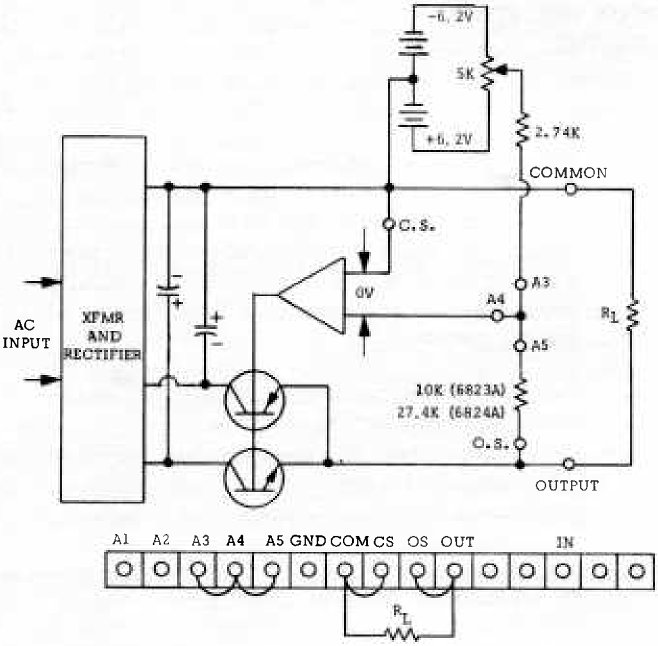


Figure 6. Standard CV Power Supply Operation, Front Panel Control, "Mode" Switch Set To "Power Supply"

Similarly, Figure 7 shows the circuit configuration, strapping pattern, and external oscillator connection points for standard front panel amplifier operation. The external oscillator must have a voltage output which is at least 1/10th of the peak output voltage desired; its current capability must be at least 600 μa for each volt input — in other words, the oscillator faces an input impedance of approximately 1.7K. The front panel gain control permits the amplifier gain to be set anywhere from zero to X10, although the gain setting will not be a linear function of control rotation. The front panel "Fine Zero" control permits the DC component of the output to be adjusted approximately 1% of the voltage rating of the instrument, thus enabling the average output value to be adjusted exactly to zero (assuming the input signal has either no DC component or only a small DC component). If desired, a coupling capacitor can be added to block any large input DC components, although in many applications this capacitor will be omitted so that the PS/A can amplify <u>all</u> input signal components, both DC and AC.

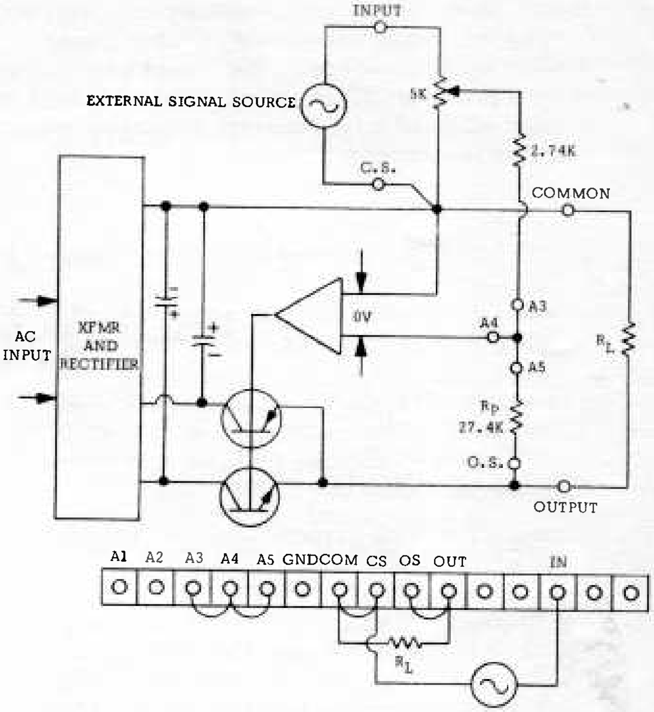


Figure 7. Standard CV Amplifier Operation, Front Panel Control, "Mode" Switch Set To "Amplifier"

C. REMOTE ERROR SENSING

In normal operation, a power supply develops an IR drop in the leads connecting it to the load. This reduces the output voltage actually present at the load terminals and also degrades the load regulation performance.

Extra terminals permit the feedback amplifier to sense at the load terminals instead of at the PS/A output terminals. This configuration is shown in Figure 8 and is applicable for all Constant Voltage modes of operation, both power supply and amplifier. Thus, although Figure 8 shows remote error sensing with front panel controlled power supply operation, the strapping pattern shown in Figure 8 can be combined with any of the Constant Voltage diagrams shown elsewhere in this Application Note in order to achieve optimum performance at the load terminals.

This does not mean that remote sensing can be used to compensate for an unlimited IR drop between the "Common" and "Output" terminals and the load. Any voltage lost in this way detracts directly from the output voltage available for the load. Furthermore, proper operation of the PS/A is insured only if the IR drop in the "Common" current-carrying lead is less than or equal to one volt.

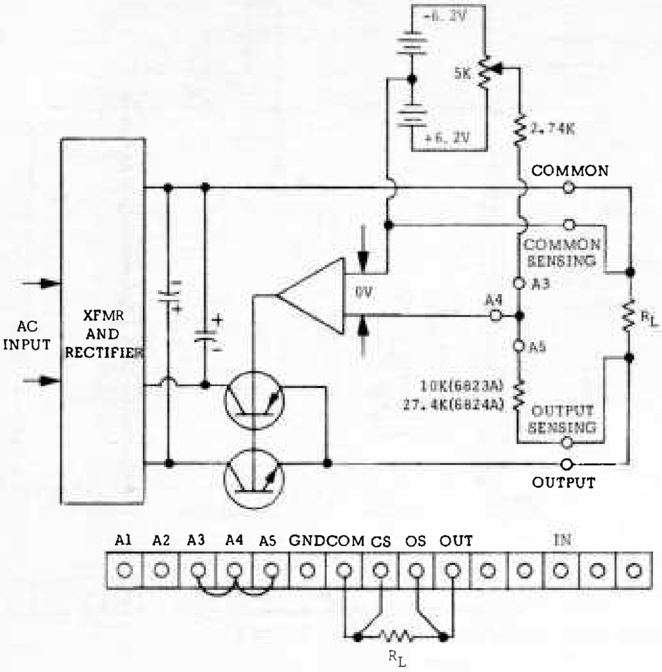


Figure 8. Remote Error Sensing

If external switching schemes are employed in conjunction with remote sensing, care should be taken that each sensing lead is not momentarily open circuited with respect to the corresponding output terminal; such open circuit conditions can result in the power supply delivering excessive voltage and/or current to the load, risking damage to both the PS/A and the load device. If it is impossible to insure that no open sensing lead condition will occur, it is recommended that a 100 ohm, ½ watt resistor be connected from "Common" to "Common Sensing", and a similar resistor from "Output" to "Output Sensing". This will minimize voltage and current transients if the sensing leads should accidentally become open circuited. Shielded leads should be used for all sensing leads, in accordance with the precautions given in Section IIIA.

D. REMOTE PROGRAMMED CONSTANT VOLTAGE POWER SUPPLY, $R_{IN} \rightarrow V_{OUT}$

1. UNIPOLAR REMOTE PROGRAMMING, POSITIVE OUTPUT, $R_{IN} \rightarrow +V_{OUT}$. Figure 9 shows the strapping pattern and associated circuit configuration for remote programming Power Supply / Amplifiers for positive Constant Voltage DC output at the rate of 500 ohms/volt. The programming control Rp should be wire-wound and selected in accordance with Section IIIA, "Comments". Its dissipation can be computed by remembering that the current through Rp is 2 MA.

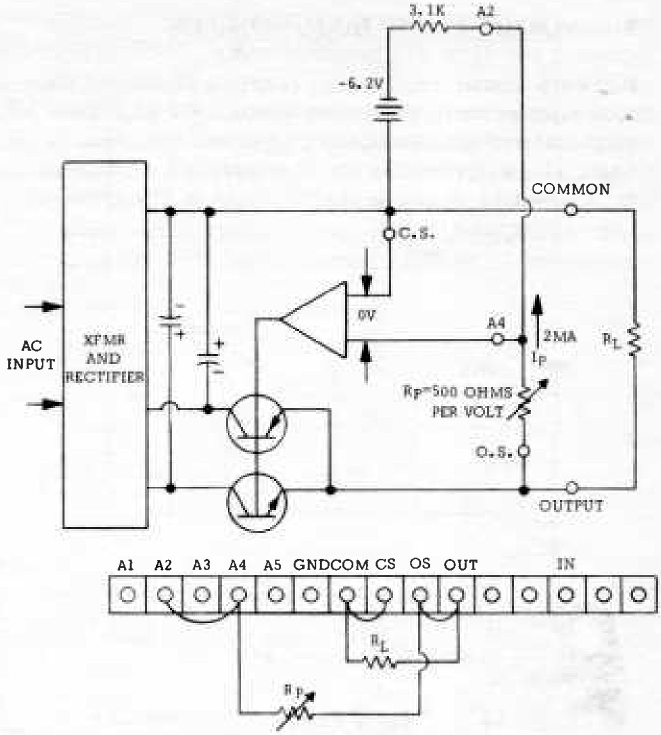


Figure 9. Resistance Programming, $R_{IN} \rightarrow V_{OUT}$

Figure 10 shows two resistance programming characteristics which are typical (although somewhat exaggerated) of the performance without programming alignment. The output voltage with zero programming always will differ from zero, being either positive (B) or negative (A), and the maximum output voltage will be achieved with a value of programming resistance not predicted by the programming coefficient.

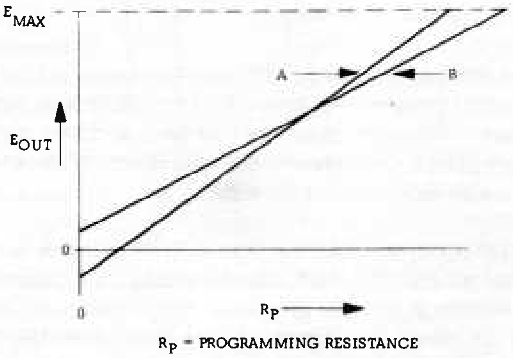
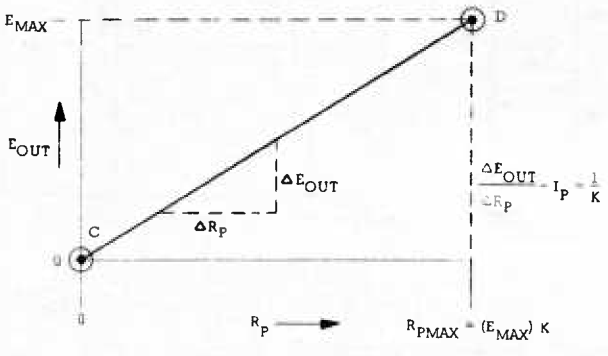


Figure 10. Typical Unaligned Resistance Programming Characteristics

Notice, however, that even with an unaligned instrument the typical characteristics of A and B are extremely linear — that is, there is no curvature. To convert either of the characteristics of Figure 10 to the desired programming characteristic of Figure 11, it is necessary to adjust both the zero crossing and the angle of the slope of the programming characteristic.



K = PROGRAMMING COEFFICIENT

Figure 11. Ideally Aligned Programming Transfer Function

In the PS/A Series the zero crossing is adjusted by means of the front panel "Fine · Zero" knob, while the slope of the programming function is adjusted by means of an internal control (R_{38} for positive output slope adjustment — not shown in Figure 9). First the zero crossing is adjusted; then a programming resistance, which according to the programming coefficient (500 ohms/volt) should yield the maximum rated output voltage for the instrument, is connected to the programming terminals, and R_{38} is adjusted until the output voltage is exactly equal to the maximum rated value. Since the two adjustments are mildly interdependent, it is necessary to repeat this procedure once.

2. UNIPOLAR REMOTE PROGRAMMING, NEGATIVE OUTPUT, $R_{IN} \rightarrow -V_{OUT}$. Figure 12 is the same as Figure 9 except that the linearly programmed output voltage is negative (here the internal programming slope adjustment is R39).

3. LINEAR BIPOLAR PROGRAMMING, $R_{IN} \rightarrow \pm V_{OUT}$. The circuits of Figures 9 and 12 can be combined to yield a power supply (Figure 13) which is programmable in either direction, depending upon the position of switch S1. One obtains a linearly programmed negative DC output when switch S1 is connected to A1; positive output when connected to A2. Switch S1 must be a break-before-make switch.

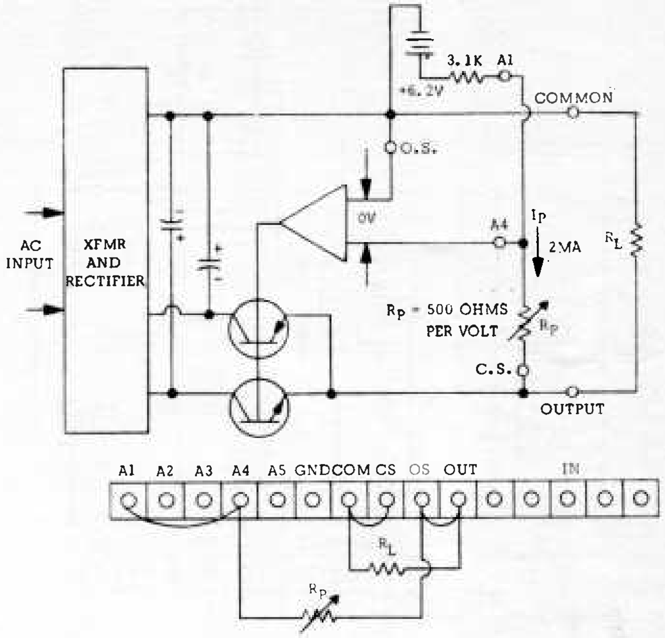


Figure 12. Resistance Programming, $R_{IN} \rightarrow -V_{OUT}$

The advantage of the configuration of Figure 13 is that the output is linearly programmed in both directions; the disadvantage is that a switch must be used in order to reverse the output polarity.

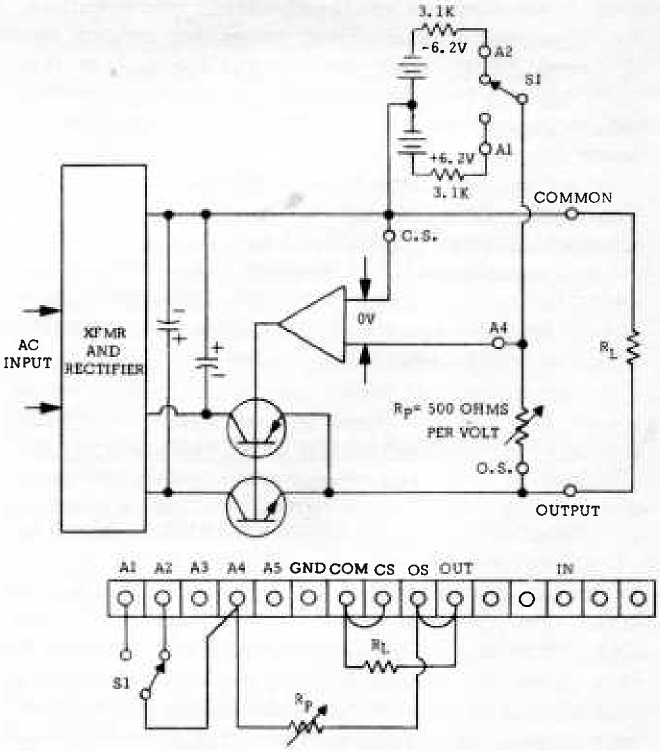


Figure 13. Linear Bipolar Programming, $R_{IN} \rightarrow \pm V_{OUT}$

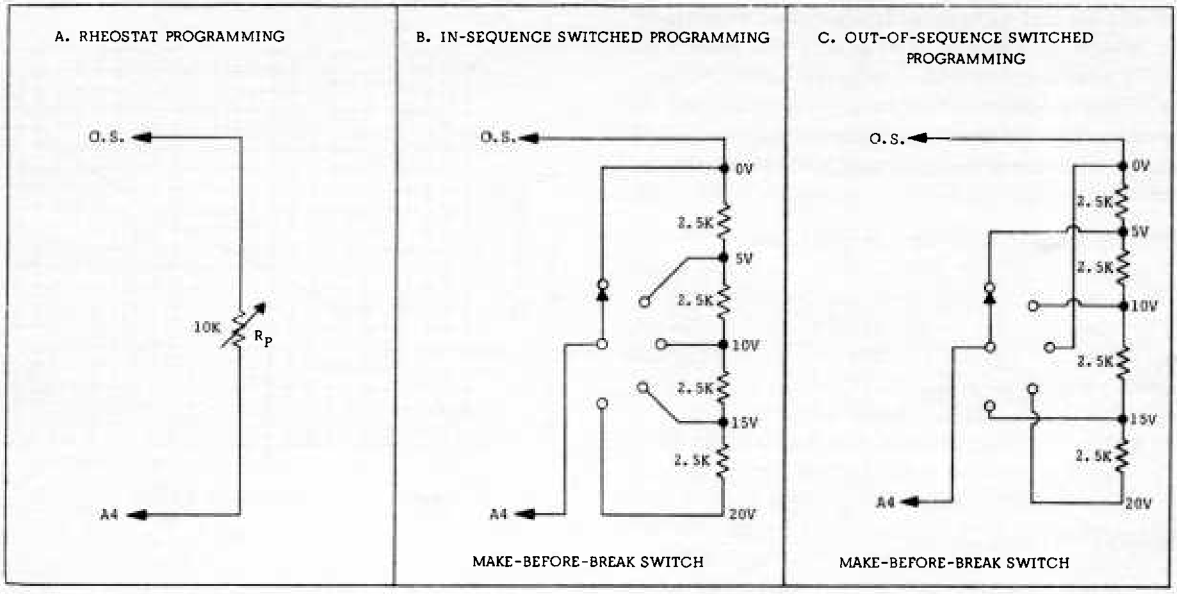


Figure 14. Switched Resistor Substitutes for Programming Rheostat R_P

If it is desired to achieve accurate programming reproducibility, or if it is necessary to repeatedly set the power supply output to specific voltage values, either of the substitute arrangements suggested by Figure 14B and 14C may be employed in place of the rheostat Rp normally connected to the power supply programming terminals (A4 and O.S.). Suppose, for example, it is decided to set the power supply over the span from 0-20V. If continuous adjustment is required, the best choice would be a 10K rheostat (since the programming coefficient is 500 ohms/volt). But if specific tests must be made at 0, 5, 10, 15, and 20V, the arrangement shown in Figure 14B should be employed, using a make-before-break switch. If the same voltage values are desired, but not in ascending or descending sequence, the terminals from the resistor string can be connected to the switch in any desired sequence, as suggested by Figure 14C.

These substitute configurations for R_P can be employed not only with Figures 9, 12, and 13, but any diagrams in this Application Note. In all such applications a make-before-break switch must be used so that output voltage transients will not occur during the switching interval; such transients can lead to damage to both the load and the power supply.

4. SWITCHLESS BIPOLAR PROGRAMMING, R_{IN} → V_{OUT}. Fig. 15 shows how to resistance program a PS/A for continuously variable output DC voltage, remotely controlled, without need for a polarity switch. Clockwise rotation of the 10K potentiometer will result in a positive output equal to the maximum voltage capability of the instrument.

The advantage of Figure 15 is that the output is continuously variable through zero with one control; the disadvantage is that the output is not a linear function of the rotation of potentiometer R_Q.

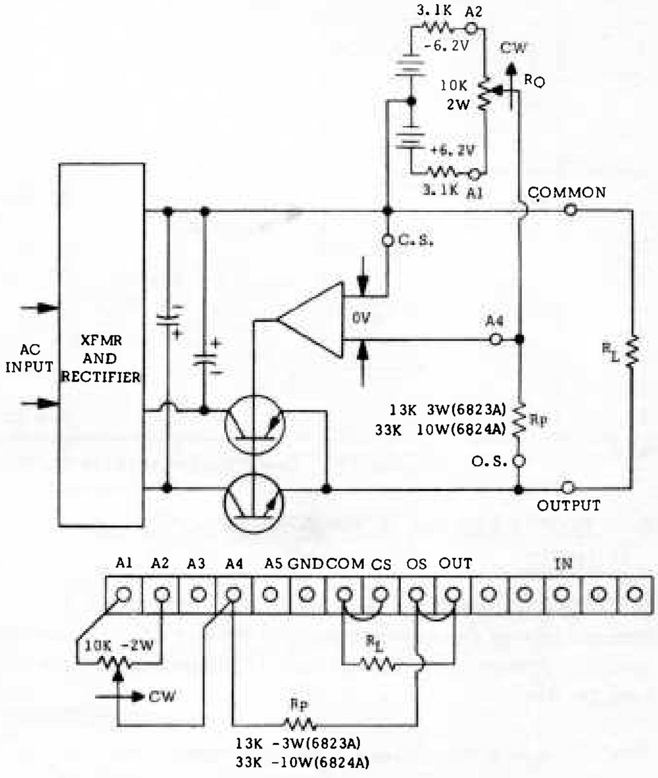


Figure 15. Switchless Bipolar Programming, R_{IN} → ± V_{OUT}

Figure 16 shows the nature and degree of this non-linearity, which is symmetrical about the zero volt setting. Of course this non-linearity could be reduced by using a lower resistance potentiometer for R_Q; however, the reference circuit within the PS/A is not designed to deliver any significantly greater output current.

If linearity is necessary, the circuits drawn in the previous sections can be used. But, in many applications it is not necessary that the programming function be linear, just reproducible. Substituting from Figure 17 into Figure 15, the power supply can be switched readily to positive or negative values, and later reset precisely at these same values. Note that the switched resistor configurations of Figures 17B and C can be substituted for R_Q in any drawings in this Application Note. The switch must be a break-before-make. When used as shown in 17B, the voltages are arranged on the switch in ascending or descending sequence; when out of sequence arrangements of the output voltage are required, the tap points from the resistor divider can be brought to the switch terminals in any desired sequence, as suggested by Figure 17C.

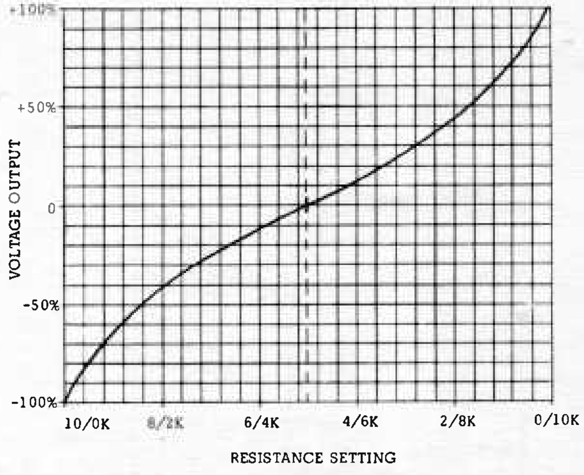


Figure 16. Nonlinear Behavior of Switchless Bipolar Programming

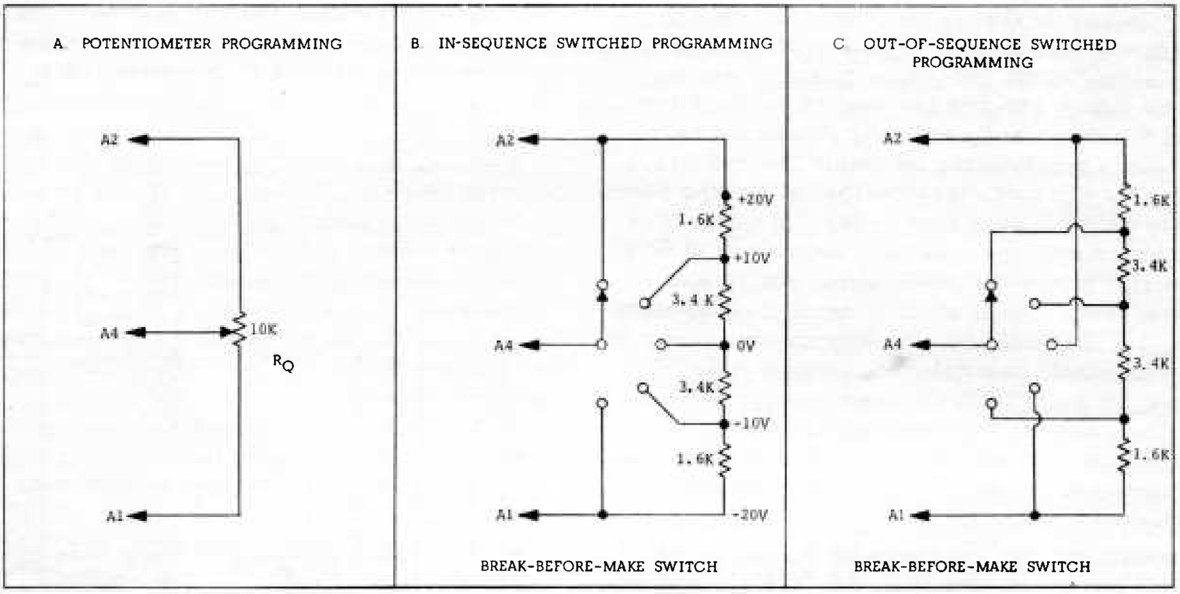


Figure 17. Switched Resistor Substitutes For Programming Potentiometer R_Q

E. POWER SUPPLY WITH SUPERIMPOSED AC OUTPUT

In some applications it is desirable to add an AC component to the adjustable DC output of a Constant Voltage power supply. Figure 18 shows how this can be done.

The PS/A is operated as a normal power supply from the front panel. The amplitude of the added AC component is controlled by adjusting R_Y, which, however, should not have a value less than the minimum load resistance which the external signal source is suited to drive, since the impedance looking into terminals C.S. and A4 is virtually zero ohms.

The AC Output component amplitude is given by $E_{AC} = E_X \cdot R_P/(R_X + R_Y)$, where R_X is the internal (Thevenin equivalent) source resistance. The capacitor C_Y is added in order to block the DC current path through the oscillator, and must be selected large enough to pass the lowest frequency of interest. The low frequency 3 db down point will be at

$$f = \frac{1}{2\pi(R_X + R_Y)\, C_Y}.$$

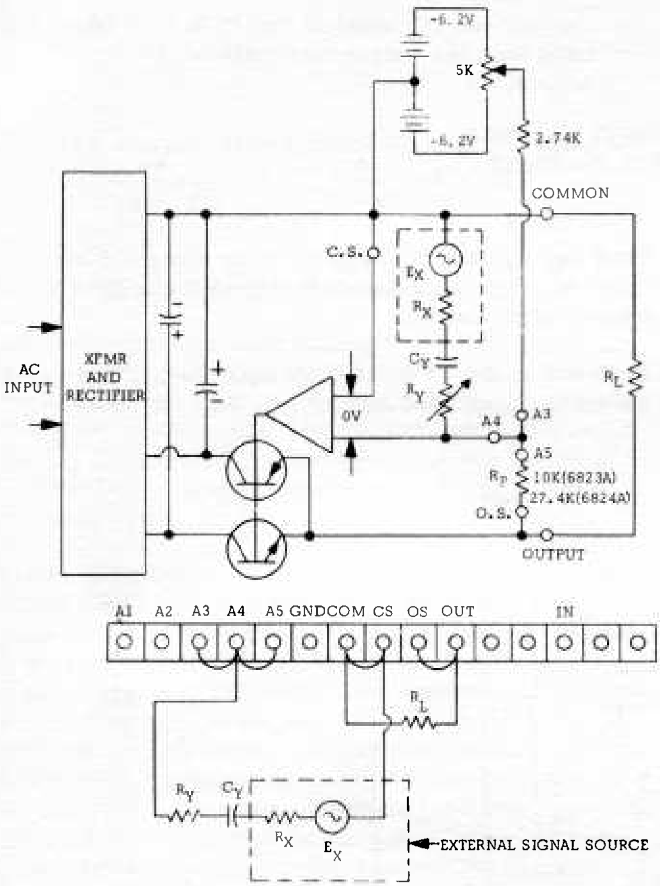


Figure 18. CV Power Supply With Superimposed AC Output, Mode Switch in "Power Supply" Position.

F. CONSTANT VOLTAGE AMPLIFIER WITH LINEAR REMOTE GAIN CONTROL

1. VOLTAGE INPUT, $V_{IN} \rightarrow V_{OUT}$. If it is desired to use the PS/A as a power amplifier with Constant Voltage output and linear remotely controlled gain, the circuit of Figure 19 should be employed. Thus Figure 19 differs from that of Figure 7 (standard Constant Voltage amplifier operation, front panel control) in that the gain is a linear function of control rotation, and the gain control is external to the PS/A. E_X and R_X are the equivalent (open circuit) voltage and output resistance looking back into the external signal source. R_Y must be selected to have a value at least as large as the minimum load resistance which the external signal source can feed without overloading or distorting. C_Y is inserted in order to block any small DC currents which otherwise might flow from the oscillator, producing a DC component on the output. C_Y must be selected large enough to pass the lowest frequency of interest; the 3 db down frequency is

$$f = \frac{1}{2\pi (R_X + R_Y) C_Y}.$$

If it is desired to amplify a DC signal, or one which has both a DC and AC component, then the capacitor C_Y should be eliminated from the circuit.

The output voltage is given by the equation

$$E_O = E_X \frac{R_P}{R_X + R_Y}.$$

Proper impedance levels will be maintained if approximately 2 MA is allowed to flow through R_Y and R_P. Thus wherever possible, R_Y should be selected so that

$$R_Y = \frac{E_X}{2\,(10^{-3})} - R_X$$

where the E_X for this equation is the maximum peak value which will be amplified. This equation, of course, assumes that the external signal source is capable of delivering 2 MA without overloading or distorting, and should be altered if less current is available.

2. CURRENT INPUT, $I_{IN} \rightarrow V_{OUT}$. Actually, the components E_X, R_X, and R_Y of Figure 19 comprise a current source feeding the summing point A4 and the gain control R_P. A current source can be substituted in place of these components, and the output voltage will be $V_{OUT} = I_X R_P$, where I_X is the current source connected between CS and A4. As shown in Figure 19, the capacitor C_Y should also be added in series if it is desired to suppress any DC component present in the input signal source.

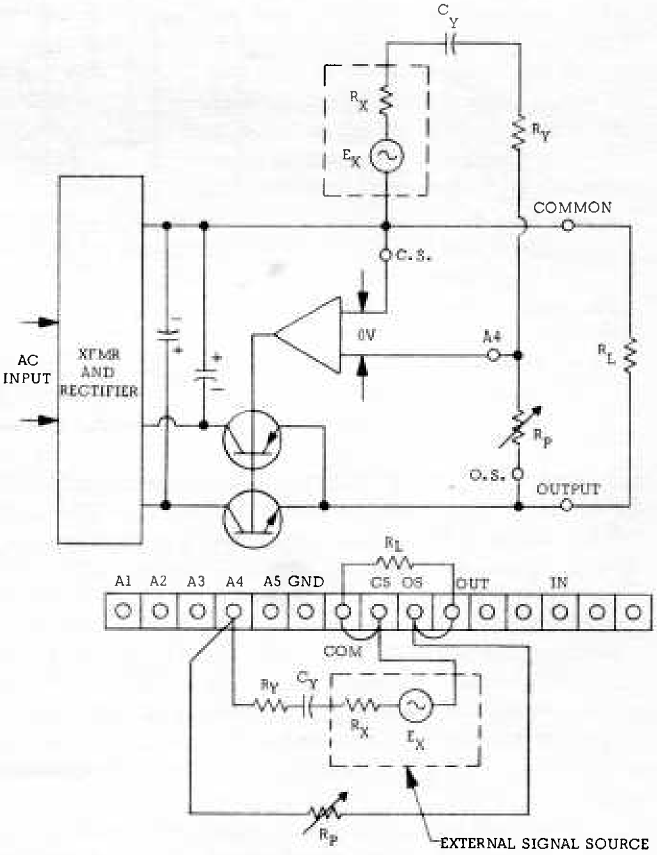


Figure 19. CV Amplifier With Linear Remote Gain Control

3. TWO OR MORE INPUTS. The concept of Fig. 19 is readily adapted using standard operational amplifier techniques to the simultaneous amplification of two or more signals. Figure 20 shows the manner in which two voltage inputs can be mixed and amplified; additional inputs can be added in parallel without limit, and current input signals can be substituted for voltage input signals, as discussed in the previous section. The capacitors C_Y and C'_Y are only included when it is desired to:

1. Prevent the DC input level of the signal from affecting the DC level of the output, or
2. Prevent the DC level of the PS/A from being fed back into the output terminals of the signal source.

The output for two (or more) inputs is given by:

$$E_O = E_X \frac{R_P}{R_X + R_Y} + E_X' \frac{R_P}{R_X' + R_Y'} + \dots$$

Thus R_Y, R_Y' can be made variable and used as relative level controls while R_P functions as a master gain control.

Notice that any of the signal inputs which are to be mixed and amplified may be AC, DC, or both.

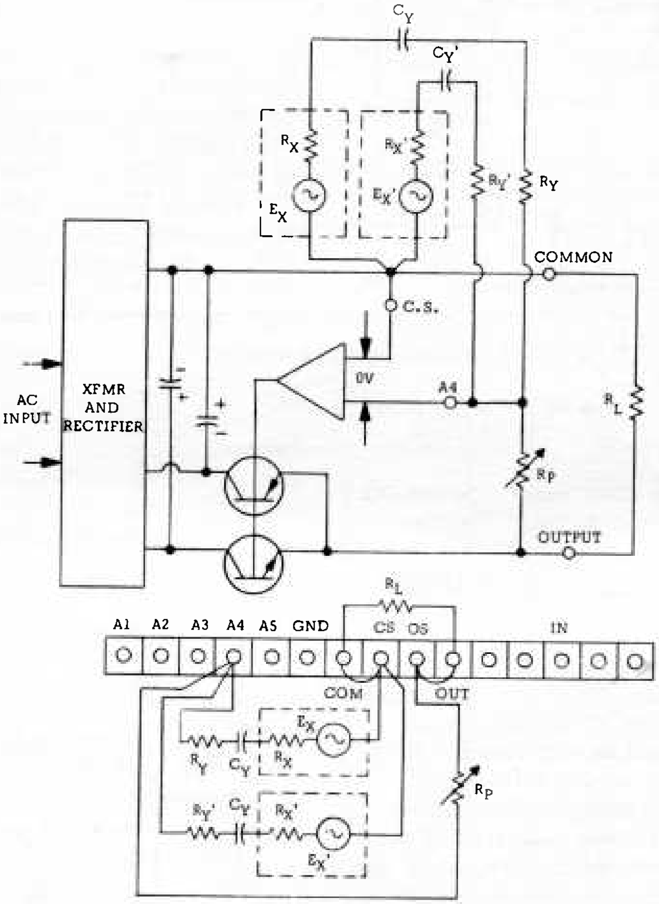


Figure 20. CV Amplifier With Two Inputs

Section IV

MODES OF OPERATION INVOLVING CONSTANT CURRENT OUTPUT

A. GENERAL COMMENTS

All of the notes and precautions listed in Section IIIA are equally applicable to Constant Current modes of operation. In addition, particular care must be paid to the manner in which the current monitoring resistor R_M is selected and employed, since Constant Current performance, on a percentage basis, can be no better than this resistor.

R_M is selected to yield a 1 volt drop at the maximum current rating of the instruments; its maximum dissipation is $\frac{1}{2}$ watt for the Model 6823A and 1 watt for the Model 6824A. It is therefore recommended that a minimum 30 watt wire-wound resistor be used for the former and 60 watt for the latter so that the surface temperature of this resistor will not be high compared to ambient, and therefore subject to long-term warm-up effects and short-term variations resulting in output "bobble". In any case, the temperature coefficient of the resistor should be 20 PPM/°C or less.

If it is intended to use the PS/A at less than maximum rated output current, proportionately higher values of R_M may be chosen. This will result in better performance at low currents. It should be remembered, however, that the resistor R_M cannot be increased in ohmic value indiscriminately for two reasons:

1. It soon becomes impractical to increase the wattage rating of R_M by the necessary amount.
2. The IR drop which occurs across R_M detracts directly from the power supply voltage rating available to the load device. Thus, a 20V PS/A will only have 15V available at the load if the drop across R_M is 5V.

Moreover, it is important to treat the resistor R_M in the same manner as an ammeter shunt. That is, the leads connecting Rp and Common Sensing to R_M should be connected as closely to the resistor as possible, so that these components are sensing the voltage across the resistor itself, without also being responsive to the voltage drop in neighboring current carrying wires. The proper method of employing R_M is shown in Figure 21 and all barrier strip drawings which follow, but for convenience and clarity, the remaining circuit diagrams do not show this correct connection pattern explicitly.

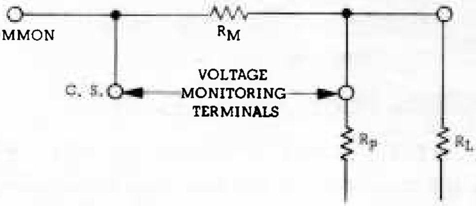


Figure 21. Four-Terminal Nature Of Current Monitoring Resistor.

All of the Constant Current configurations which follow are based on the principle of monitoring the output current with resistor R_M, thereby producing a voltage drop proportional to the output current, and then comparing this voltage drop with some fraction of the reference or input voltage. The only conceptual difference in any of the following Constant Current modes and the corresponding Constant Voltage modes of Section III is that the voltage which is being sensed by the feedback amplifier is the voltage across R_M rather than the voltage across the load. Thus for each of the following sections, the comments given for the corresponding Constant Voltage configuration in Section III are equally applicable, with the added precautions which are associated with the use of R_M.

The regulation, ripple, temperature coefficient, and stability of Constant Current Power Supply/Amplifier performance can be predicted by dividing the corresponding Constant Voltage specification by the ohmic value of R_M. For example, the use of a 2 ohm current monitoring resistor converts the 2 MV RMS Constant Voltage ripple and noise specification of the 6823A to 1 MA, etc. In the case of temperature coefficient and stability, it is also necessary to add in the percentage effect due to any change in ohmic value of the monitoring resistor R_M.

The output impedance of the Constant Current source at DC is given by the relationship $Z_O = (\Delta E_L/\Delta I_L)$, where ΔE_L is the change in load voltage associated with a load resistance change, and ΔI_L is the small resulting output current change. The fact that the PS/A has a high loop gain and no output capacitor means that the PS/A used in a Constant Current mode will have a high output impedance. In fact, it can be shown that the impedance at any frequency for a Constant Current source of this type will be approximately equal to R_M (AB), where AB is the loop gain of the feedback amplifier within the power supply at the frequency of interest. Since the PS/A has a bandwidth in excess of 20 KHz, this output impedance will remain quite high over a wide frequency band. Stated in terms of the time domain, the PS/A will respond quickly to changes in load resistance — the load current transient will be short.

B. NORMAL FRONT PANEL CONTROL

1. CONSTANT CURRENT POWER SUPPLY. Figure 22 shows the connection pattern and associated circuit configuration for operating the PS/A as a continuously variable, reversible DC Constant Current source. Thus, this is the Constant Current counterpart of the Constant Voltage mode of operation shown in Figure 6.

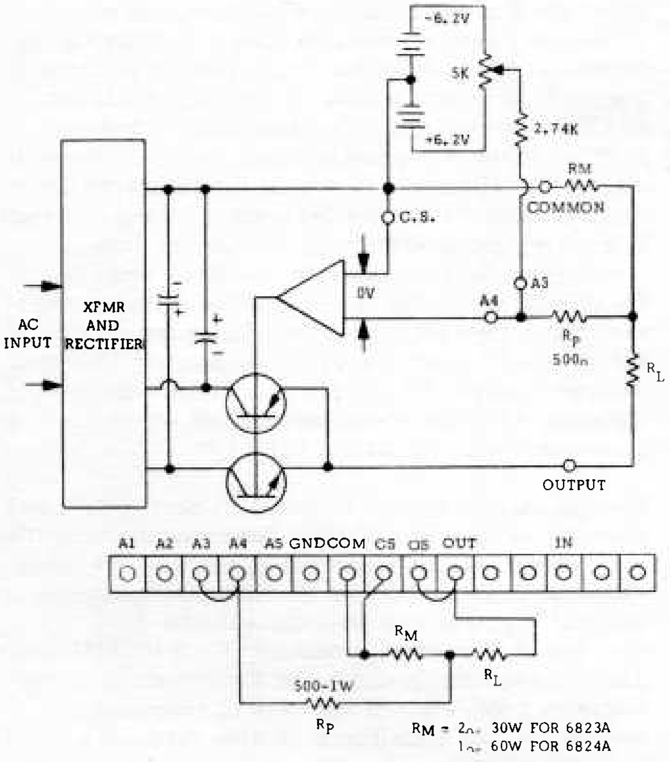


Figure 22. Standard CC Power Supply Operation, Front Panel Control Mode Switch In "Power Supply" Position

2. CONSTANT CURRENT POWER AMPLIFIER, $V_{IN} \rightarrow I_{OUT}$. Figure 23 shows the simplest way of operating the PS/A as a Constant Current output amplifier with continuously variable gain. The front panel "Fine · Zero" control should be adjusted for zero DC output current (assuming the input source has no DC input component or that a blocking capacitor is used in conjunction with the input source). With the values given in Figure 23, the external oscillator must have a voltage output of 1.5 volts peak in order to drive the power amplifier to its full output current capability. The impedance seen by this external voltage source will be approximately 1.7K.

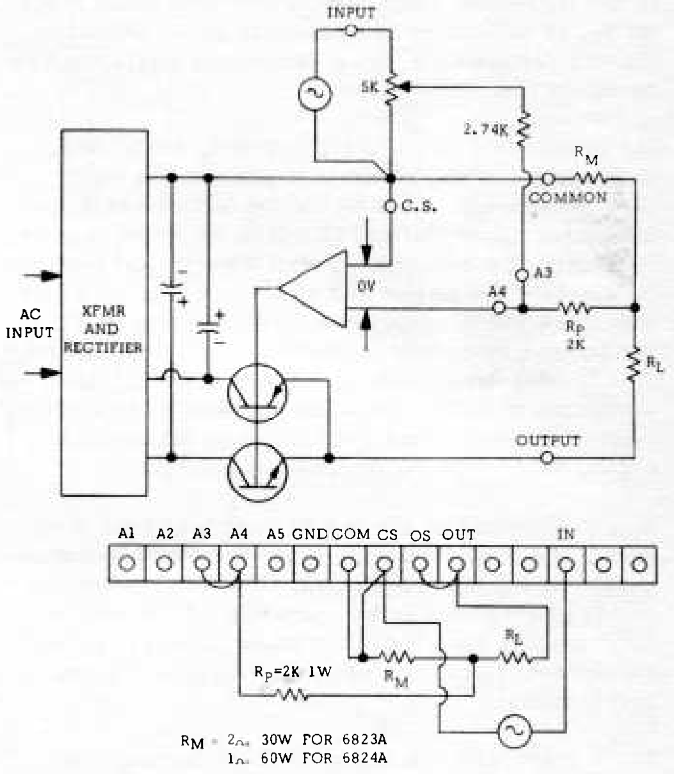
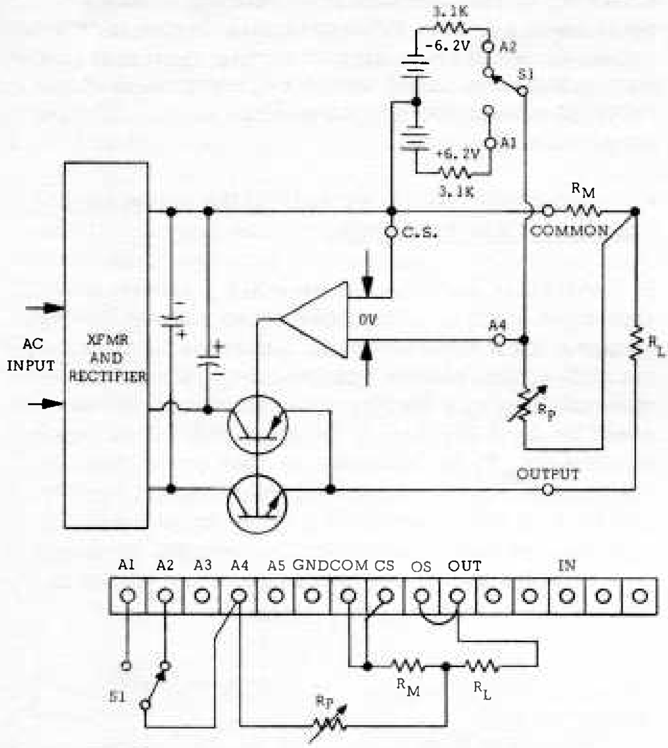


Figure 23. Standard CC Amplifier Operation, Front Panel Control Mode Switch In "Amplifier" Position

C. REMOTE PROGRAMMED CONSTANT CURRENT POWER SUPPLY, $R_{IN} \rightarrow I_{OUT}$

1. LINEAR PROGRAMMING. Figure 24 shows one method of controlling the output of the PS/A as a remote programmed Constant Current power supply. Switch S1 causes the output current to be either positive or negative. If it is desired to achieve only a positive or only a negative output current (unipolar output), then S1 can be eliminated and terminal A4 strapped directly to A2 for positive output and directly to A1 for negative output.



R_M=2Ω, 30W for 6823A
R_M=1Ω, 60W for 6824A

R_P=1 OHM/MA for 6823A
R_P=0.5 OHM/MA for 6824A

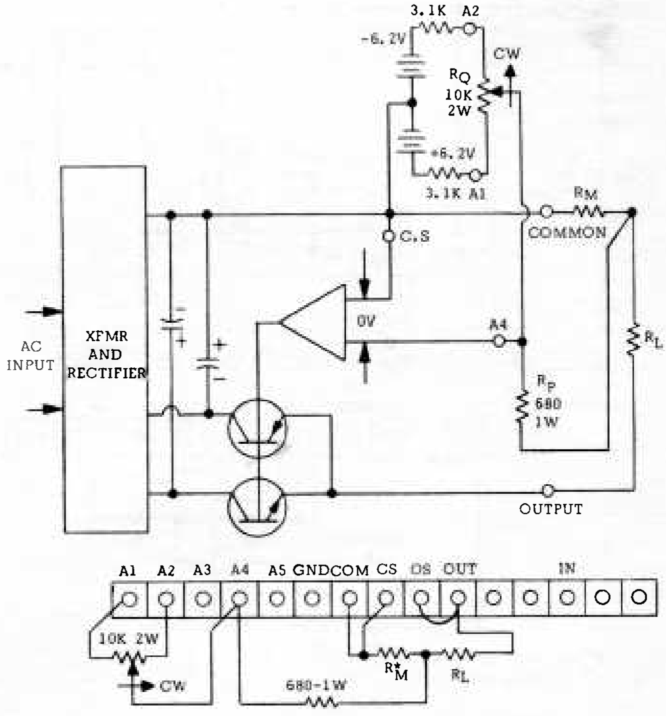
Figure 24. Linear Bipolar Programming, $R_{IN} \rightarrow \pm I_{OUT}$

R_P is selected according to the programming coefficient shown in Figure 24; the current through R_P is 2 MA.

The front panel "Fine · Zero" control permits the output current to be adjusted to zero when R_P is set to zero, while the slope of the programming coefficient is adjusted by means of R_{38} (positive output) and R_{39} (negative output). Either of the make-before-break switched resistance programming methods of Figure 14 may be substituted for a variable R_P in this and any other Constant Current diagrams which follow. The comments of Section IIID related to the programming alignment and programming alternatives are equally applicable to Constant Current configurations. The advantage of the circuit of Figure 24 is that the output current is a linear function of the programming resistance; the disadvantage is that a switch must be used in order to accomplish polarity reversing.

2. SWITCHLESS BIPOLAR PROGRAMMING. Figure 25 shows the method of connecting the PS/A for Constant Current bipolar programming without the necessity for polarity switching. The 680 ohm resistor should be wire-wound with a temperature coefficient of less than 20 PPM/°C. Either of the break-before-make switched resistance schemes of Figure 17 may be substituted for the programming rheostat R_Q in Figure 25.

The advantage of the circuit of Figure 25 is the elimination of polarity switching. The disadvantage lies in the non-linear (but accurately reproducible) programming characteristic. Figure 16 indicates the nature of this non-linearity as a function of potentiometer rotation — it is only necessary to change the vertical axis from voltage to current.



R_M=2Ω, 30W for 6823A
R_M= 1Ω, 60W for 6824A

Figure 25. Switchless Bipolar Programming, $R_{IN} \rightarrow \pm I_{OUT}$

D. CONSTANT CURRENT POWER SUPPLY WITH SUPERIMPOSED AC OUTPUT

Figure 26 shows the method of adding an AC component on top of the adjustable DC output of the PS/A operated as a Constant Current source; this adjustable DC level is controlled in the normal fashion from the front panel. The amplitude of the added AC component is determined by the value of R_Y, which, however, should not have a value less than the minimum load resistance which the external signal source is capable of driving without overloading or distorting.

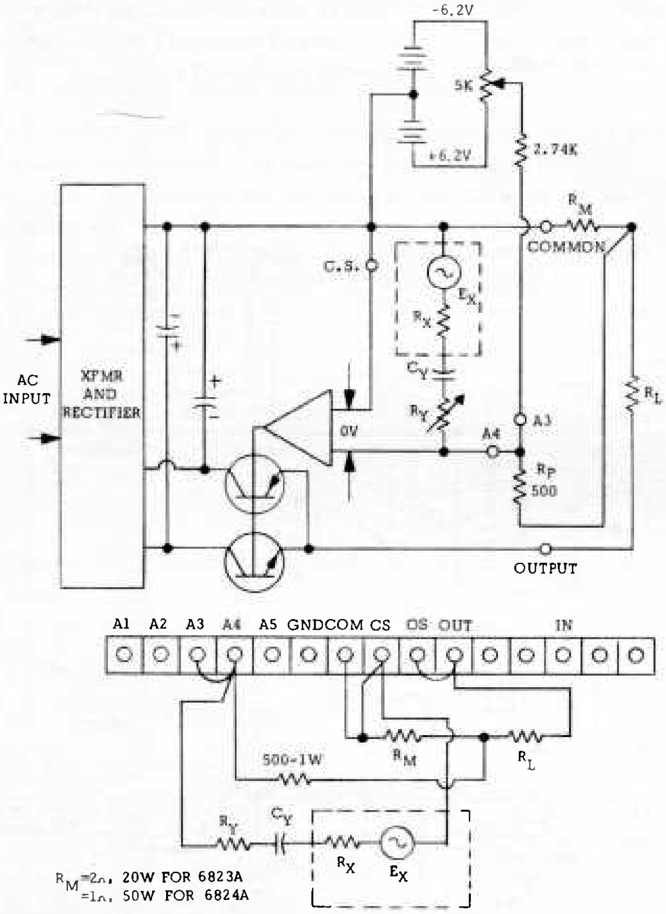


Figure 26. CC Power Supply With Superimposed AC Output Mode Switch Set To "Power Supply"

The peak voltage E_X which is necessary to achieve a peak output current equal to the maximum rating of the instrument, equals $(R_X + R_Y) / R_P$. The capacitor C_Y is added to block the DC current path through the oscillator. C_Y must be selected large enough to pass the lowest frequency of interest; the low frequency 3 db down point will be at

$$f = \frac{1}{2\pi (R_X + R_Y) C_Y}$$

where R_X is the internal (Thevenin equivalent) source resistance. Of course, the capacitor C_Y is not employed if it is desired for the Constant Current output to respond to the DC component of the external signal source, as well as to the DC front panel control setting.

E. CONSTANT CURRENT AMPLIFIER WITH LINEAR REMOTE GAIN CONTROL

1. VOLTAGE INPUT, $V_{IN} \rightarrow I_{OUT}$. Figure 27 shows the method of connecting an external voltage source with a PS/A to obtain Constant Current output with linear remote gain control. Using the recommended values for R_M, the output current is given by $I_O = (E_X/R_M) \cdot R_P/(R_X + R_Y)$. It is recommended that R_Y be selected so that at the peak input voltage E_X the current flowing through R_X, R_Y, and R_P is 2 MA; that is, $E_X/(R_X + R_Y) = 2$ MA. With this choice, $R_P = 500$ ohms results in an output current equal to the maximum rating of the instrument.

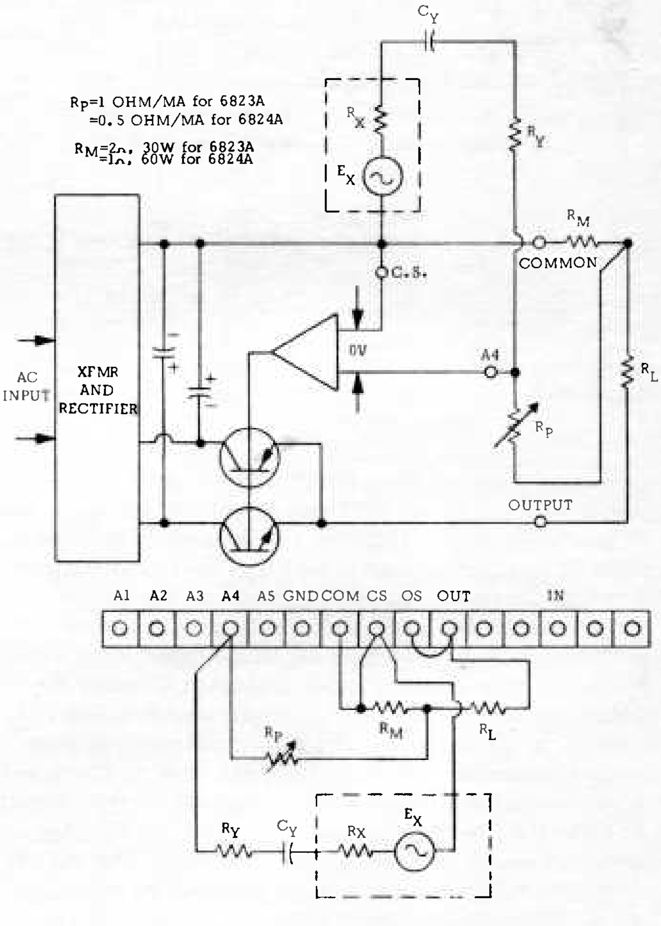


Figure 27. CC Amplifier With Linear Remote Gain Control

C_Y is chosen large enough to pass the lowest frequency of interest and is omitted if it is desired to have the output current responsive to the DC (as well as AC) component of the input voltage E_X. The low frequency corner introduced by C_Y occurs at $f = 1/\,2\pi\,(R_X + R_Y)\,C_Y$.

Care should be taken that R_Y is not chosen less than the minimum load resistance which the external signal source can feed without overload or distortion. However, R_Y should not be chosen too large, or the current flowing through R_P will be influenced by the current into the comparison amplifier. Thus it is undesirable to select R_Y so that the current flowing through it with full input signal is less than 1 MA.

2. CURRENT INPUT, $I_{IN} \rightarrow I_{OUT}$ The combination of components E_X, R_X, and R_Y can always be replaced by a Constant Current source. If this is done, the current gain of the configuration of Figure 27 is:

$$\frac{I_{OUT}}{I_{IN}} = \frac{R_P}{R_M}.$$

3. TWO OR MORE INPUTS. If desired, the circuit of Figure 28 can be used to add the effect of two or more signals. All the equations given in this section hold true for each of the multiple inputs, with no interaction.

$$I_O = \frac{E_X}{R_M}\ \frac{R_P}{R_X + R_Y} + \frac{E_X'}{R_M}\ \frac{R_P}{R_X' + R_Y'} + \cdots$$

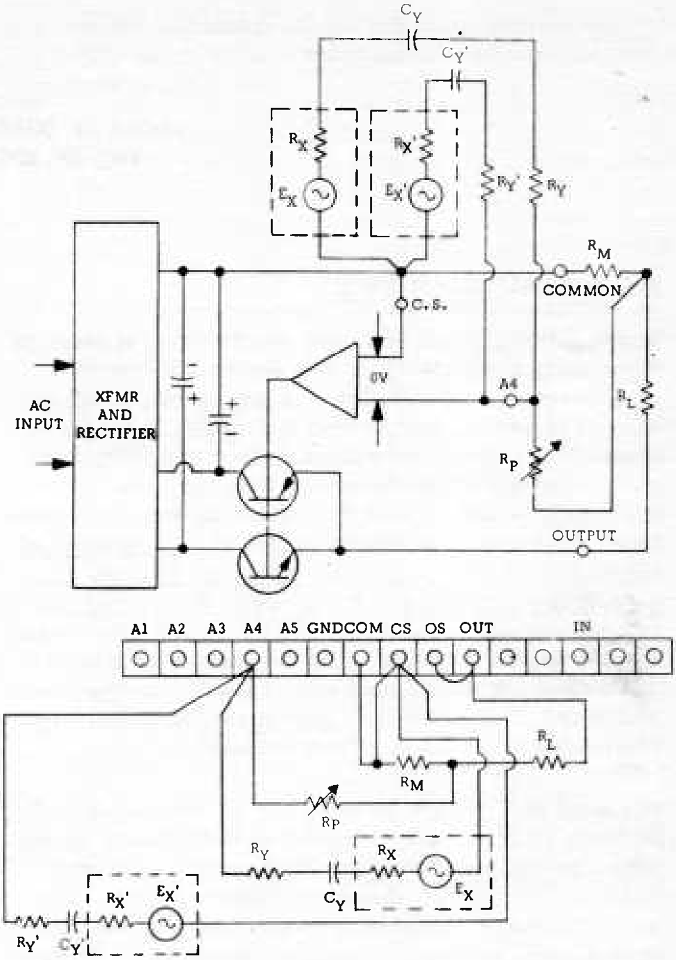


Figure 28. CC Amplifier With Two Inputs

Section V
MODES OF OPERATION INVOLVING TWO OR MORE PS/A UNITS

A. GENERAL COMMENTS

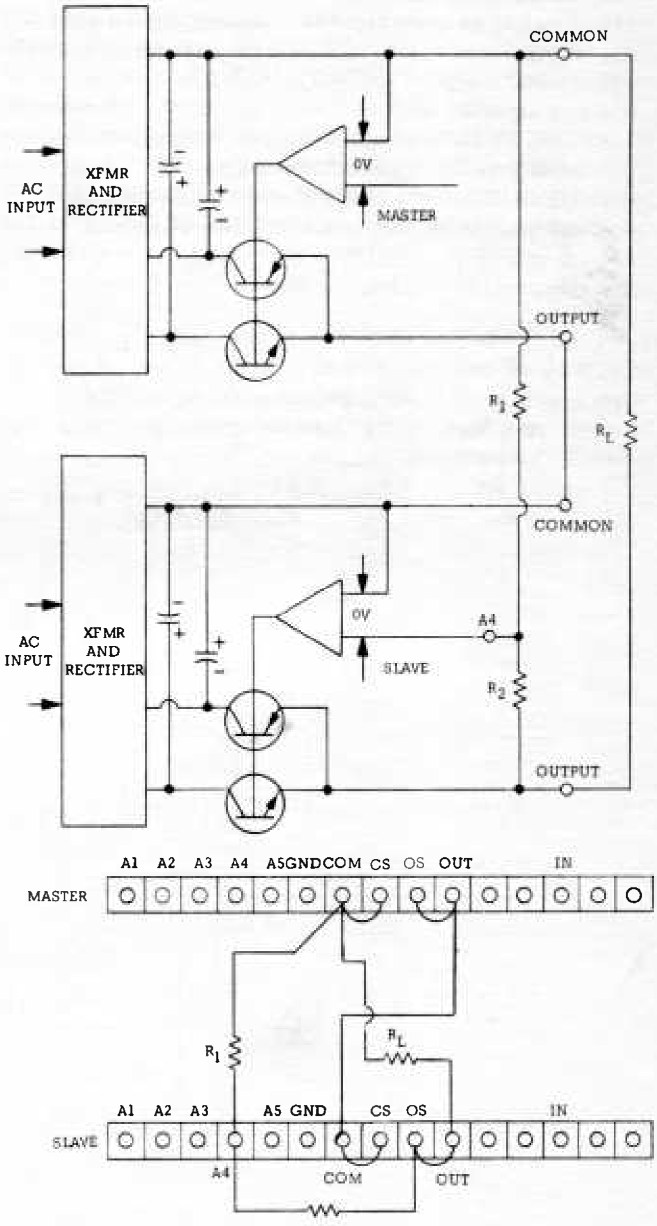
In the following sections are shown several ways of combining separate PS/A's in series and parallel combinations. These methods are employed whenever it is required to extend the voltage or current capability beyond that available from one instrument alone. In all of the following diagrams the strapping pattern and circuit configuration for slave units have been shown in complete detail. In several of the diagrams, however, the strapping pattern and circuit configuration have not been completed for the Master unit, since the configuration chosen for the Master is determined by the manner in which it is desired for the ensemble of supplies to operate, and may be selected from any of the diagrams already given in this Application Note.

For example, Figure 29 shows a method of connecting two units in series for increased voltage output. Whether this series combination acts as a power supply or amplifier, Constant Voltage or Constant Current source, locally or remotely controlled by resistance, voltage, or current, depends entirely on the connection mode selected for the Master Unit. If Constant Current output is desired, the resistor R1 should be connected to the common output terminal (as shown in Figure 29), not to the junction of the added current monitoring resistor R_M and the load resistor R_L; this is necessary in order to avoid degrading the Constant Current load regulation because of the shunt current through R_1 and R_2.

Any PS/A instrument may be Master or Slave depending only on the strapping pattern chosen. Units may be connected in series, as shown in Section B, up to 300V off ground, and need not be the same model number, but should all be PS/A Series instruments. Similarly, units may be connected in parallel, as shown in Section C, without any limit, except that all instruments must be PS/A Series and employ an external monitoring resistor which develops a 1 volt drop.

B. COORDINATED SERIES OPERATION

1. AUTO SERIES, TWO UNITS, SINGLE ENDED OUTPUT. Figure 29 shows the correct method of connecting two units in Auto-Series. The front panel switch position of the slave is not significant, but the front panel position and barrier strip wiring of the master unit depends upon the operating mode desired for the system of two power supplies, and should be selected from one of the previous sections.



BALANCE OF STRAPPING PATTERN FOR MASTER DEPENDS ON DESIRED OPERATING MODE.

FOR EQUAL SHARING
$R_1 = R_2 = 10K$, 1/2 W FOR 6823A
25K, 1W FOR 6824A

Figure 29. Auto Series Operation, Two Units, Single Ended Output

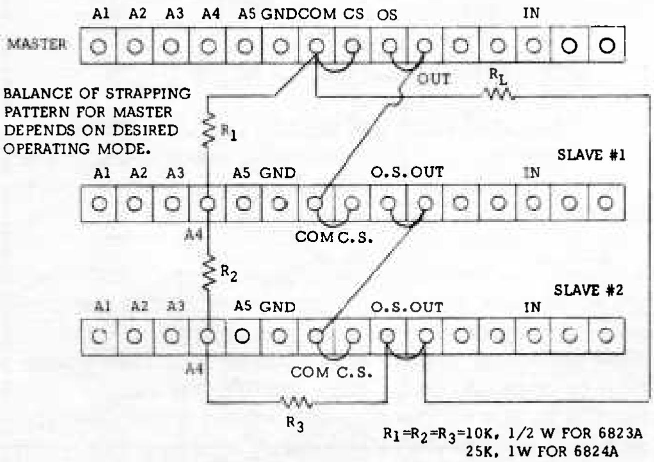
For instantaneous equal voltage sharing, R_1 and R_2 must be equal. However, if it is desired for the slave to have a voltage, which although always proportional to the output of the master supply, is greater than or less than the output of the master supply, then R_2 should be selected according to the relation $E_S = E_M (R_2/R_1)$ where E_S and E_M are the output voltage of the Slave and Master instruments respectively.

As a general rule, the current through R_1 and R_2 should be approximately 2 MA at full output. The correct value for any desired ratio of master and slave can then be calculated by remembering that the voltage across R_1 always equals the output voltage of the Master, while the voltage across R_2 always equals the output voltage of the Slave.

2. AUTO-SERIES, THREE OR MORE UNITS, SINGLE ENDED OUTPUT. The concept of the previous section is easily extended to three supplies, as shown in Figure 30. If unequal voltage contributions are desired, the output of Slave #1 is given by $E_{S1} = E_M (R_2/R_1)$; for Slave #2, $E_{S2} = E_M (R_3/R_1)$.

The concept of Figure 30 is easily extended to series combinations involving more than three units merely by iterating that portion of the circuit configuration which is bounded by the two horizontal dotted lines.

All of the comments of the previous section are equally applicable to configurations involving three or more units.



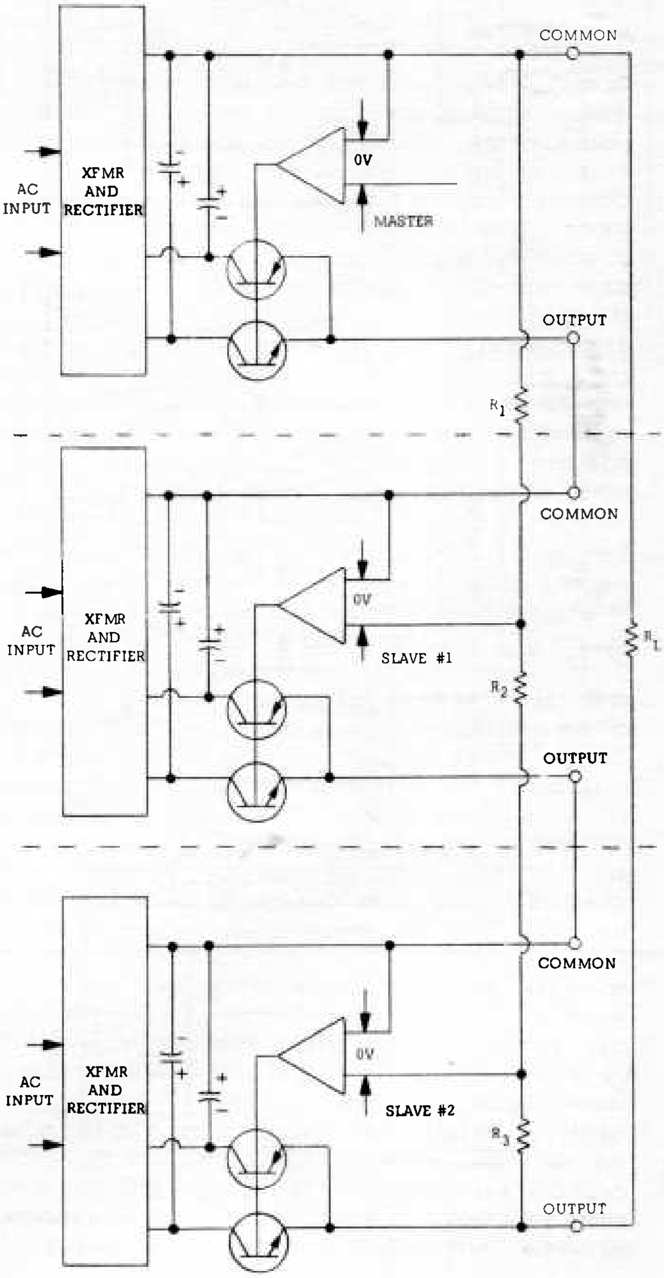


Figure 30. Auto Series Operation, Three Units, Single Ended Output

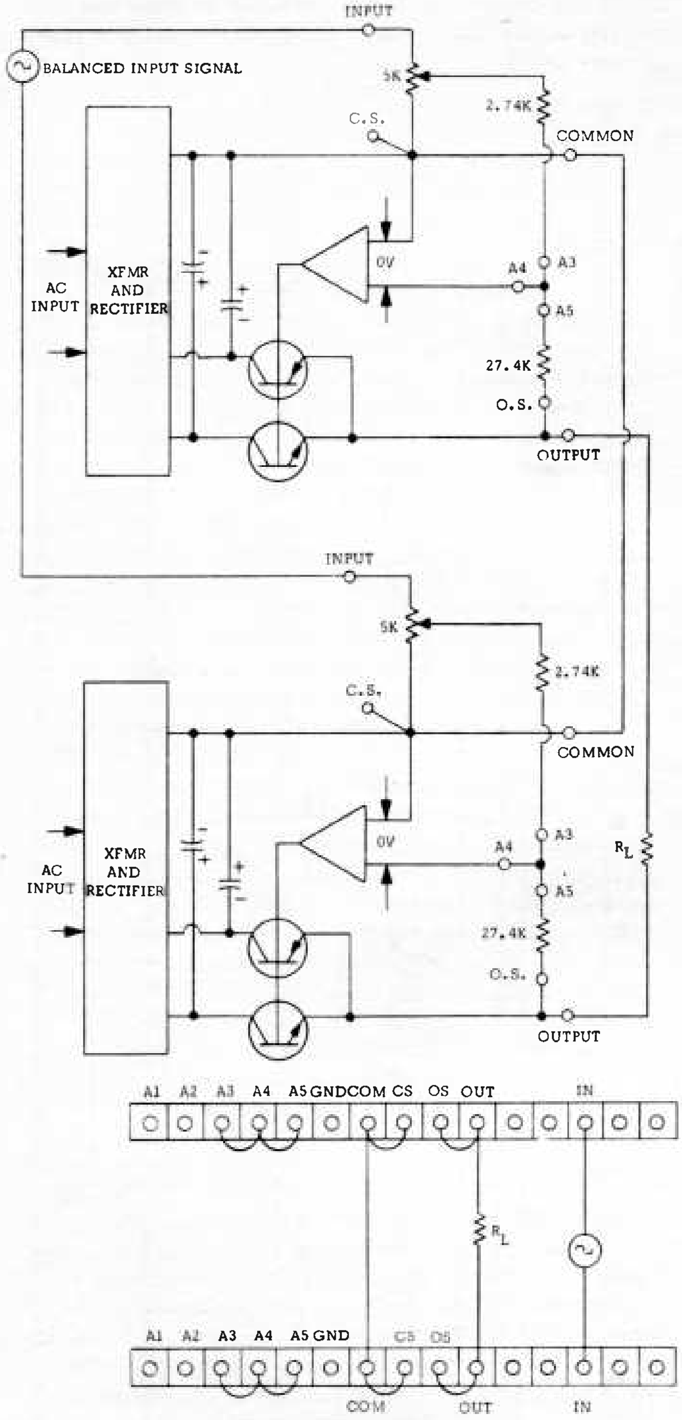


Figure 31. Balanced Input/Output Series Operation, Two Units, Output Mode Switches Set to "Amplifier"

3. BALANCED INPUT/OUTPUT SERIES OPERATION, TWO UNITS. The previous Auto-Series configurations are accomplished with single-ended input and single ended output having a common terminal. In some applications, however, it is necessary to employ an amplifier with input and output signals balanced about ground. Figure 31 shows the circuit configuration and strapping pattern for this mode of operation.

Since this mode is more likely to be employed as an amplifier rather than as a power supply, the circuit diagram and strapping pattern of Figure 31 are shown with an oscillator input (and no straps omitted). The voltage input to this circuit must be at least 1/10th the desired voltage output; the input impedance seen by the oscillator is approximately 3.4K.

The balanced input concept of the previous section can be extended to even higher voltages if voltage Slaves are added to each side. Figure 32 shows this configuration, which has an output voltage capability four times that of one unit alone, as well as a balanced input and a balanced output. The input oscillator must have a voltage capability of at least 1/20th of the output voltage desired, and faces an input impedance of 3.4K.

Notice that with an oscillator and this amplifier ensemble (or with four units connected in Auto-Series, as suggested by Figure 30), four 6824A's achieve an output of ±200V, with peak currents up to 1A, thus simulating 115VAC line voltage with variable frequency and amplitude.

C. AUTO-PARALLEL, TWO OR MORE UNITS

1. CONSTANT VOLTAGE OUTPUT. Figure 33 shows the correct method of connecting two PS/A's in parallel for increased output current in Constant Voltage operation.

Although the terminal configuration has been completed for the Slave unit, the remainder of the connections to the Master unit are dependent upon whether power supply operation or amplifier operation is desired, etc. Thus the Master can be connected in any of the patterns shown in Section III, and the Auto-Parallel system will behave accordingly.

For equal current sharing, the leads from common to R_M and R_M to R_L should be short and have equal resistance for the two supplies.

Still greater current capability can be obtained by connecting more Slaves to the Master unit; that is, the slave configuration of Figure 33 can be iterated to include as many instruments as desired.

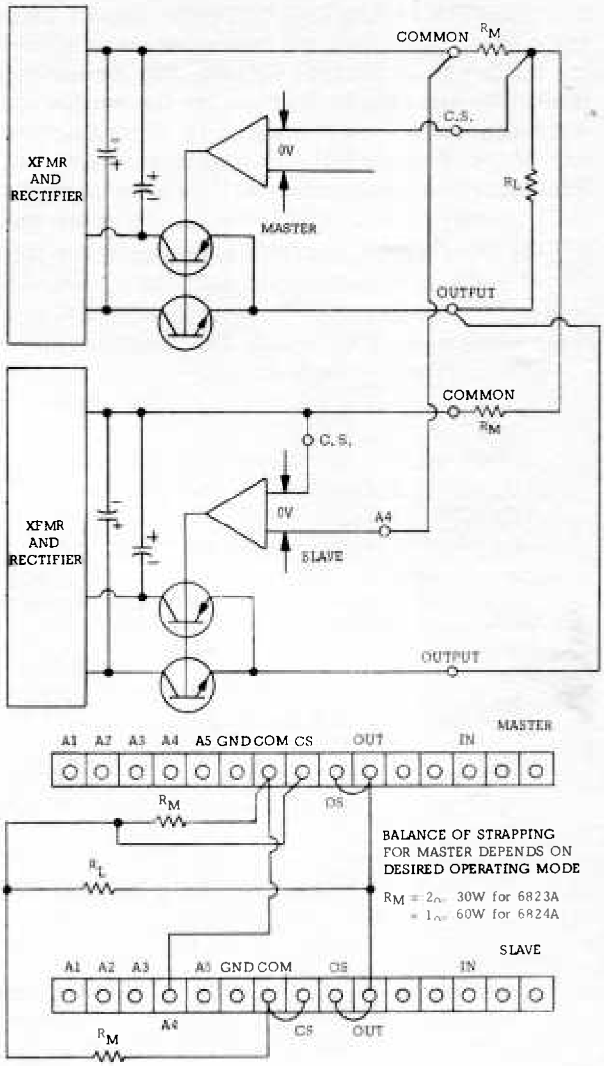
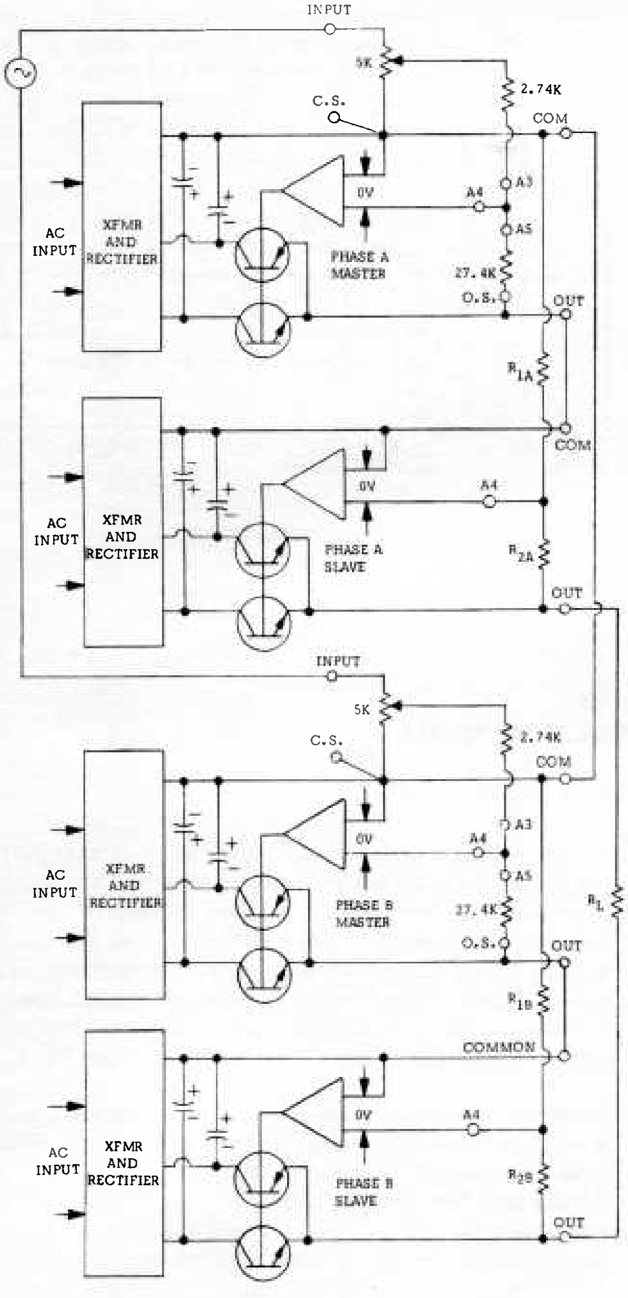


Figure 33. Auto Parallel Operation, Two Units Constant Voltage Output



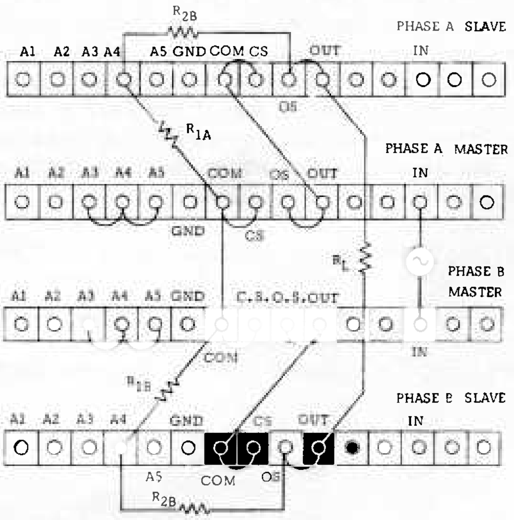
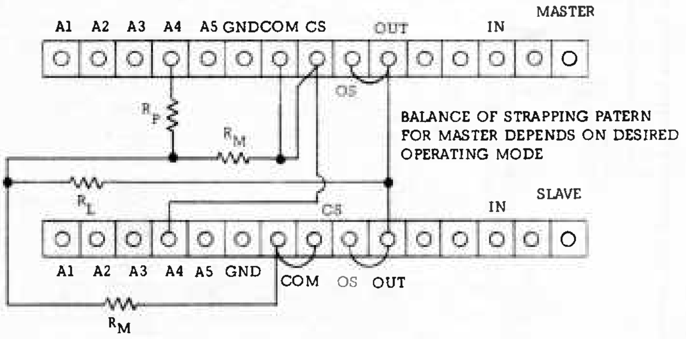
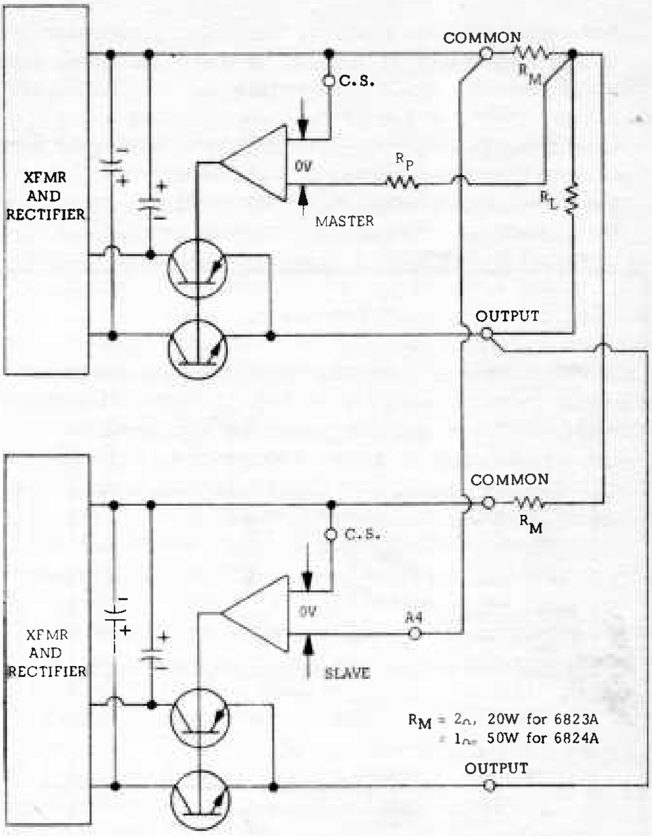


Figure 32. Balanced Input/Output Series Operation, Four Units

2. CONSTANT CURRENT OUTPUT. Figure 34 shows the method of connecting two supplies in Auto-Parallel for Constant Current output. The strapping configuration and circuit diagram for the master unit are not complete but can be wired in accordance with any of the diagrams given in Section IV, and the Auto-Parallel combination will behave accordingly. Still greater current output can be accomplished by adding any desired number of slaves to the master in the same way.



BALANCE OF STRAPPING PATERN FOR MASTER DEPENDS ON DESIRED OPERATING MODE



R_M = 2Ω, 20W for 6823A
= 1Ω, 50W for 6824A

Figure 34. Auto Parallel Operation, Two Units, Constant Current Output

Section VI
PS/A USED AS SINK INSTEAD OF SOURCE

In any of the configurations discussed, it has been tacitly assumed that the PS/A will act as a source, i.e., its instantaneous positive output terminal will have current flowing outward, and current will flow into the instantaneously negative output terminal. If this is not the case, and if the PS/A is expected to act as a sink (absorb energy rather than deliver it), then an added precaution must be taken to avoid possible damage to the instrument.

As an example, let us suppose that a PS/A will be called upon to deliver 400 MA as a Constant Voltage source during most of its cycle and will be required to absorb 100 MA during the remainder of the load duty cycle. In order to avoid excessive dissipation in the output transistors, it will be necessary to attach a 100 MA load resistor (computed at the value of voltage present when the load is forcing 100 MA into the instrument). This will result in the power supply being called upon to deliver anywhere between 0 and 500 MA — in effect, the added load resistor absorbs the 100 MA from the load and properly biases the output load current of the PS/A.

In general, a load resistor should be added which will draw a current equal to the peak current which otherwise would be forced back into the PS/A. This means that the current rating of the PS/A instrument used must be equal to or greater than the sums of the absolute values of the "source" and "sink" currents.

Section VII

CONCLUSION

The configurations shown in the preceding sections by no means exhaust the various modes in which the PS/A can be used. The reader is encouraged to consider this instrument in terms of operational amplifier techniques; this viewpoint will suggest and facilitate many other areas of application. Many such possibilities are suggested by handbooks on operational amplifiers (e.g., "Handbook of Operational Amplifier Applications" — Burr-Brown Research Corporation, Copyright 1963).

Such handbooks suggest how operational amplifiers can be used as integraters, differentiaters, ramp function generators, etc.; with the PS/A, these techniques are extended to previously unattained power levels.

An alternate viewpoint is to consider the PS/A as a general-purpose DC-coupled precision power transducer capable of accepting either resistance, voltage, or current input (AC and/or DC) and delivering a power output, Constant Voltage or Constant Current, AC and/or DC.

Questions and comments concerning variations of any of the configurations given in this Application Note, or any other modes, are always welcome. Feel free to contact your nearest hp Field Sales Office, or the Harrison Division in Berkeley Heights, New Jersey.

HEWLETT
PACKARD
HARRISON
DIVISION