The author received his B.E.E. from City College of New York in 1957. He joined Lambda in 1963 as Senior Engineer in the Advanced Development Group, where he was engaged in research on high-powered SCR switching systems, high-stability, low-power circuitry, and studies in FET applications. Later he designed low- and high-voltage series pass regulated power supplies and was in charge of supplying application information and quotations for non-standard requirements. He was formerly Manager of Instrument Products.

Power-Supply Principles and Parameters

By EDWARD S. BRENNER/Director of Engineering
Lambda Electronics Corp.

To make an intelligent selection from the large variety of available supplies, the user must know the operation and the most important specifications that are covered here.

POWER SUPPLIES and power regulators can be represented by a wide assortment of devices ranging from batteries and generators to dynamic electronic units using feedback. These include a large family of electronic converters: a.c. to a.c., d.c. to d.c., d.c. to a.c., and a.c. to d.c. Here we will be concerned with the a.c. to d.c. converter employing a series regulator.

Power-distribution systems usually use a.c. power because this power is easily generated and distributed. However, most system applications of power require d.c. power sources to energize the electronic circuitry. The specific function of the power supply is to provide substantially constant, ripple-free d.c. voltage and current from a primary source which is a.c.

Power conversion generally starts with rectification, a process which converts a.c. voltage to d.c. voltage. Because the output of a rectifier contains a relatively large a.c. ripple component in addition to its d.c. value, a filter must be used to attenuate the ripple component before this d.c. power is applied to the load. Figs. 1A and 1B illustrate two filtering configurations while Fig. 1C shows the effects of these networks.

The amount of ripple present after filtering the rectifier output is a function of the components used and the load current. No matter how efficiently ripple is reduced, the rectifier-filter d.c. output can change substantially with load current and/or power-line variations. Control of these variations is defined as power-supply regulation.

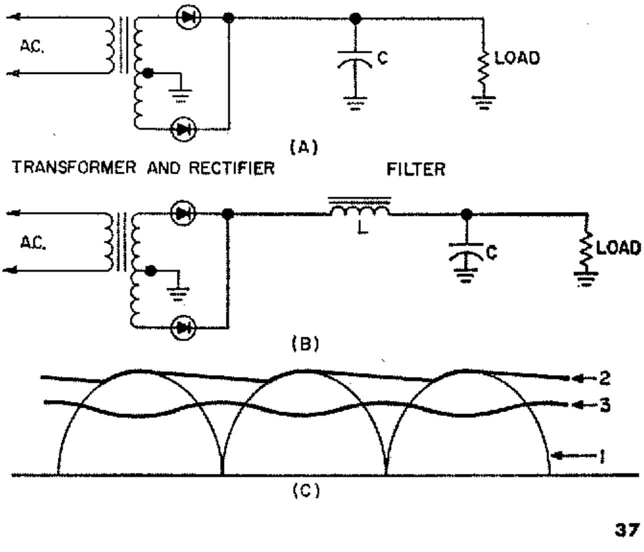
The demand for better regulation imposed by today's sophisticated circuits and complex systems can be met more effectively by the regulated or feedback-controlled power supply. Regulated power supplies are capable of maintaining a substantially constant output voltage at some selected value, even though changes occur in the a.c. supply voltage (within specified limits) and/or in the rated d.c. load current. In addition, these power sources can be made short-circuit-proof, preventing damage to the supply caused by the load, and can be made load-protecting by utilizing overvoltage protectors, which prevent load damage caused by internal supply failures.

The greatest demand for power supplies is in low-voltage (less than 100 volts) semiconductor applications, creating a market exceeding $100 million. The power supplies for this market are generally all-solid-state designs with more recent models using silicon semiconductors for high reliability and greater power-handling capacity per unit volume.

Power-supply packaging is dictated more by function than by appearance. Modular or system-type power supplies are available for various mounting configurations. Multiple-output power-supply systems can be assembled using modular power supplies and metered panels in rack adapters.

Some supplies can be used for either laboratory or system applications. When used in electronic systems, the rubber feet can be removed and a rack adapter provided for convenient mounting (as shown in photo on page 39). High-powered, full-rack regulators can be supplied with

Fig. 1. Rectifier and filter configurations showing (A) capacitor and (B) LC filters. (C) D.c. output voltage waveforms for single-phase, full-wave rectifier with (1) no filter, (2) capacitor filter, and (3) LC filter.



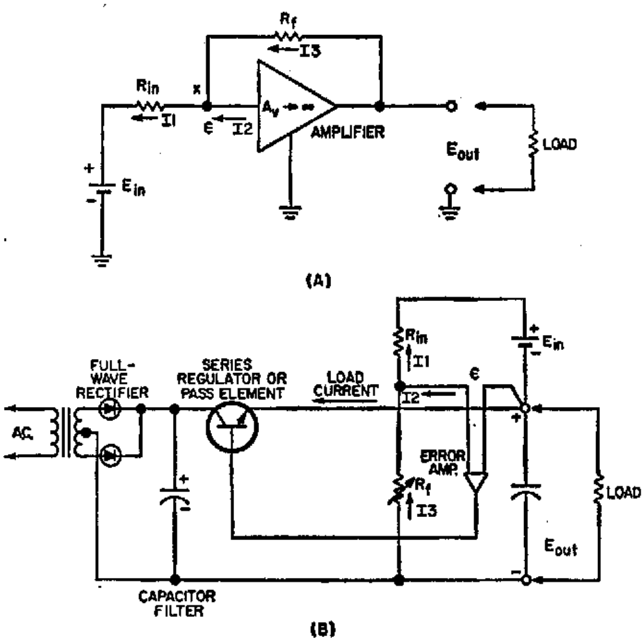


Fig. 2. (A) Operational amplifier. (B) Regulated supply.

rubber feet that are suited for laboratory and bench use.

In most cases, the user will find the power supply he requires from some manufacturer's "off-the-shelf" catalogue. To the user, this means that the device is readily available as a standard product with minimum delivery-time lapse. Standard product lines include supplies with ratings from the milliwatt range to units with ratings exceeding 10 kW. The price may be well under \$100 or well over \$5000, depending upon the power capacity and performance characteristics required.

Operating Principles

The series-regulated power supply belongs to a family of circuits referred to as d.c. operational amplifiers. These are extremely high-gain amplifiers that use feedback to control their output function and are capable of operating from d.c. to some finite limit in frequency. We will mainly concern ourselves with d.c. operation. See Fig. 2A.

The open-loop gain of the amplifier (A_v) is very large and assumed to be near infinity compared to the closed-loop gain or gain with feedback. Values of A_v on the order of 100,000 are not uncommon. In order to generate an output signal of magnitude E_{out}, an input or error voltage (ε) of E_{out}/A_v is required. Since A_v is many orders of magnitude larger than E_{out}, the error voltage can be considered to be zero. Using this approximation, we can then state that $I1 = E_{in}/R_{in}$ and $I3 = E_{out}/R_f$ because ε is at zero or virtual ground. Also, knowing that currents entering a node must equal currents leaving a node, we can sum the currents around node X and obtain $I1 = I2 + I3$. Generally, a system must be designed with $I2$ many times smaller than either $I1$ or $I3$, so that essentially $I1 = I3$. Consequently, $E_{out}/R_f \approx I1$, and $E_{out}/E_{in} = I1R_f/I1R_{in} = R_f/R_{in}$ = closed-loop gain. Hence, closed-loop gain is a function of external components R_f and R_{in}, as long as A_v is much larger than R_f/R_{in} and $I1$ is much larger than $I2$.

We now rearrange Fig. 2A to satisfy the circuit requirements of the series-regulated power supply, shown in Fig. 2B. Although this is basically a model of a power supply which can be operated over a wide voltage range starting from zero volts (zero supply), the theory is applicable to narrow-range (slot) supplies.

In the power supply, the error amplifier and pass element together are equivalent to the entire operational amplifier of Fig. 2A. A full-wave rectifier and a capacitor filter provide "B+" voltage for the pass element. The error amplifier is normally powered by an auxiliary bias supply. The input voltage, E_{in}, is created by a stable zener reference element using a compensated current source to supply it with constant excitation current. Similarly, the output of the power supply is: $E_{out} = E_{in}\, R_f/R_{in}$.

The output can be changed by varying either R_f or R_{in}. Varying R_{in} would then cause a variation in the current $I1$ supplied by E_{in}. A change in $I1$ causes a change in E_{in} because the stability of a zener diode is dependent upon specific constant operating conditions. Because varying R_f has no effect on $I1$, it is the preferred method for varying output voltage.

Most supplies can vary the feedback resistor, R_f, from a remote source either by providing a pair of terminals in series with R_f or by replacing it entirely. Both methods permit control of the output voltage from some point far removed from the regulator location. This is referred to as remote programming. Since $I1$ is a constant, the power-supply user can easily program the output voltage linearly by varying the feedback (or programming) resistor. As would be expected, a supply should only be programmed within its rated limits of operation.

Operating Parameters

Let us examine the important power-supply operating parameters, relate them to circuit performance, and investigate their limitations.

Load Regulation. Load regulation is defined as the amount the output voltage will vary for a specified change in load (output) current. It can be seen from Fig. 2B that load current is supplied by the pass transistor to the load. Because a transistor is a current-amplifying device, the current required at the base of the pass transistor is only a small fraction of the load current. The change in the error amplifier input current ($I2$) required to supply this base current is extremely small and normally less than a microampere. This change in input current causes a change in the error voltage (ε) which is the main factor affecting load regulation. For the circuit shown: $\Delta E_{out} = \Delta\varepsilon\ (1 + R_f/R_{in})$.

Load regulation depends upon two components, then; one a constant and the other a proportion of output voltage. The constant component is more important when a supply is operated at or near zero since, under these conditions, R_f/R_{in} would be essentially zero. When the power-supply operating point is such that R_f/R_{in} is much greater than unity, the variable component of regulation predominates. Because power-supply output requirements do vary, the user must recognize the need for specifying load regulation in two quantities. The series-regulated power supply will typically have a variable regulation band of from 0.01% to 0.1% of output voltage and a fixed component of from 1 to 5 mV for load current changes of from no load to full rated load. Values above and below this band normally are considered poor and good regulation, respectively.

Line Regulation. This parameter defines how much the output voltage will vary for a specified change in a.c. input voltage. This change causes a number of variations within the supply, *e.g.*, "B+" for the pass transistor changes, the error-amplifier bias supply voltage changes, and the reference zener diode (E_{in}) current source changes.

Because the pass transistor is within feedback loop, a change in its "B+" potential will not cause an appreciable change in E_{out}. Referring to Fig. 2B, the minimum capacitor-filter voltage must be equal to or greater than the maximum output voltage plus the pass transistor saturation voltage plus any internal voltage drops around the power loop, plus the peak ripple voltage across the capacitor-filter. Any capacitor-filter voltage less than the sum of these voltages will cause the pass transistor to become saturated, resulting in loss of control of the output and causing the excessive ripple of the capacitor-filter output to appear across the output terminals.

At the high end, the a.c. input is limited by the amount of power the pass transistor can dissipate. For a given load current, the power in the pass section will be a maximum when the difference between the capacitor-filter voltage and the output voltage is a maximum since this difference appears directly across the pass transistor. When developing the power rating for a unit, the power-supply manufacturer starts by selecting a reasonable a.c. line variation (usually 105-132 V r.m.s.), and then designs a transformer to deliver maximum output voltage at full load with low line input. Power dissipation capability required with maximum input line voltage and minimum d.c. output voltage determines package size because the power circuitry required for dissipating the excess power contributes largely to physical size. Its direct contribution to over-all gain and regulation is relatively small.

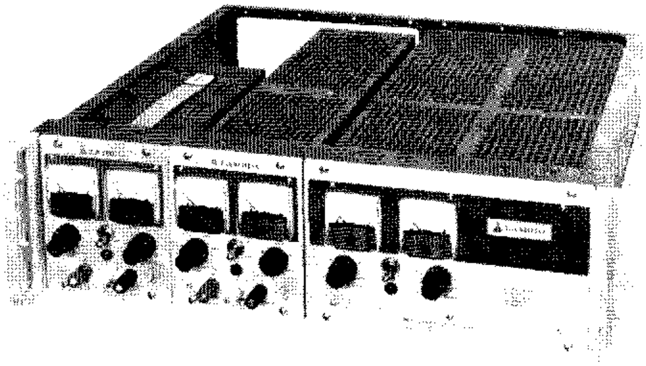
In addition to voltage variations, the a.c. input can also cause frequency variations. Normally a power supply is designed to operate over a wide input frequency range. The lower limit will be determined by either excessive transformer heating or increased ripple across the capacitor filter. The lower limit can usually be extended by reducing the maximum load current requirement. The upper limit is determined by a reduction of input voltage due to transformer leakage inductance or by increased output noise. Series-regulated power supplies are, in most cases, operable from 45 to 440 Hz. The effect of frequency variations on regulation is usually negligible.

Ripple and Noise. Fig. 3A illustrates a typical ripple and noise pattern at the output of a series-regulated power supply. Three distinct signal sources are detectable: (1) random noise generated by the reference zener and error amplifier as characterized by the thickness of the line; (2) ripple attributed to the line frequency, which has its origins in the reference zener bias circuit and pickup in the circuit wiring; and (3) low duty cycle spikes synchronized to the line frequency, which are generated by the input rectifiers and transmitted to the output. These spikes are normally reduced by using r.f. attenuation techniques.

To properly describe this over-all a.c. component at the d.c. output requires an r.m.s. as well as a peak-to-peak limit.

Temperature Coefficient (TC). The amount the output voltage of the supply changes in proportion to the ambient temperature (with all other operating conditions remaining constant) is expressed as the TC. The TC is mainly dependent upon the closed-loop parameters of the supply. Changes within the amplifier after the first stage caused by temperature variations can normally be neglected (assuming that the magnitude of these changes is within the dynamic range of the amplifier) since the effect reflected back to the input would be attenuated by the gain of the subsequent stages. Acceptable TC's are normally less than 0.05%/°C + 1 mV/°C.

Because load and line changes cause dissipation within the supply, internal ambient temperatures will vary independent of external ambient changes. Such variation could be from 10°C to 40°C at different locations within the package, depending on component layout and thermal properties. The effect would be the same as changing the external ambient temperature. This effect is not specified on a manufacturer's power-supply data sheet because its calculation depends on the user's techniques for ventilating and/or cooling, together with the magnitude of the user's line and load changes. However, it should be taken into account by system designers who use power supplies in large quantities in restrictive environments.



Three laboratory power supplies mounted in rack adapter.

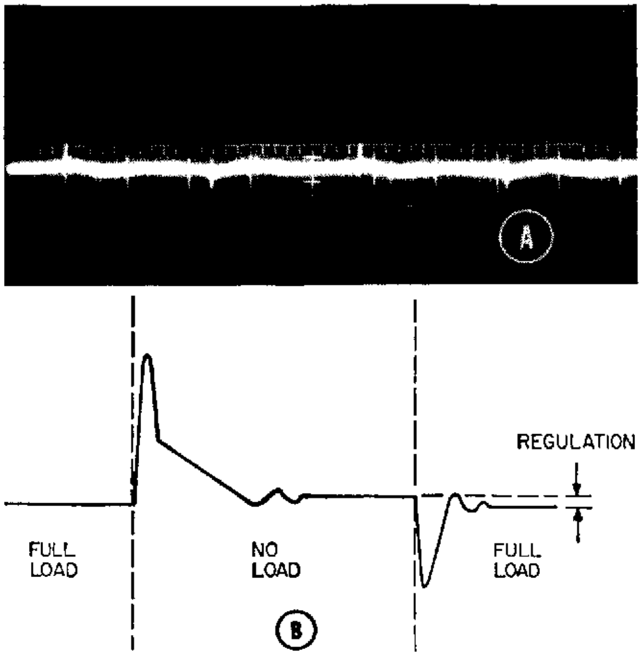


Fig. 3. (A) Waveform showing typical ripple and noise. (B) Transient response of series-regulated power supply.

Recovery Time (Transient Response). A power supply will usually be required to operate into a varying load, with extremely fast variations in relation to the response time capabilities of the power supply circuitry. Hence, power supply output terminals are shunted by a capacitor, which supplies reserve energy when operating into rapidly varying (transient) loads. Fig. 3B illustrates the transient response time of a series-regulated power supply. Changing from a full-load to a no-load condition results in an output voltage spike caused by the inherent inductance of the internal and external circuitry. Simultaneously, the power supply still supplies load current to the output capacitor until the amplifier regains control. This causes the output capacitor to be charged to a voltage higher than the desired output voltage. The power supply's internal circuits will then bleed off this excessive charge until the output voltage reaches the selected level. Going from no-load to full-load first causes the load current to be drawn from the output capacitor since the amplifier cannot respond immediately to the changed power requirement. When the amplifier again regains control, the capacitor is recharged and the desired output voltage is restored.

It is apparent that the nature of the load can have a significant effect on the transient response characteristic. A highly capacitive load will cause small peak excursions but relatively long settling times, while a highly inductive load will have just the opposite effect on these characteristics. Transient response is normally specified as the time required to return and stay within specified voltage limits surrounding the regulation band. For instance, a typical

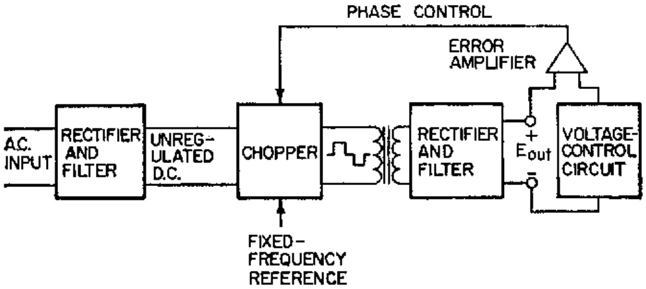


Fig. 4. Efficient phase-modulated switching power supply.

specification would be 100 μs to be within 100 mV of the regulation band. This specification refers to a resistive-type load, where error sensing is done at the power-supply output terminals.

Stability. Assuming that a power supply is operating from a constant input line and into a constant load while installed in any environment with fixed ambient temperature, small deviations, or drift, of its output voltage can be observed. This drift is referred to as the stability characteristics of the power supply. Even when operating under constant conditions, the power supply creates ambient differentials within isolated portions of its circuitry. Thermal currents thus created cause variation in temperature-sensitive components and mechanical stresses in critical potentiometers resulting in output variations. Easily available components used in today's circuitry will yield an output voltage stability of 0.1% or better for 8 hours after an initial warm-up period.

The power supply is a complex instrument, capable of many performance options and features. Consequently, a suggested model should be analyzed for intended application to insure the most economical and efficient handling of the customer's requirements. A convenient way of specifying performance is to select a regulation band which encompasses all the static operating conditions. This involves specifying upper and lower limits for each of the operating conditions.

There are many other specifications applicable to power-supply use: environmental specs describing vibration, shock, temperature cycling, and humidity limits, as well as specs for radio-frequency interference generation.

Whenever a standard model cannot meet a user's needs, a specification can be generated by the user, tabulating performance goals and physical requirements. This normally requires liaison with a power-supply manufacturer's applications engineer who will insure reasonable specifications and a clear understanding of the problems involved in creating a modified or custom power supply.

Other Types of Regulators

The series-regulated power supply is the most widely used type. Its major attributes are versatility and excellent performance; however, its greatest drawback is its low efficiency. When the input and/or output vary widely, the efficiency can be as low as 25% and not much better than 50%. For example, a 5-volt power supply with a ±5% output variation and a line voltage specification of 105 to 132 V r.m.s. will have a typical worst-case efficiency of 25% caused by the combination of high line input, low-voltage output with full-load operation. The efficiency can approach 50% for units with higher voltage ratings but will not rise much higher. The internal power dissipation can become excessive in uses requiring large amounts of power in a single system.

A partial solution to the problem is to utilize a method of power control employing switching techniques. This method, in turn, causes deterioration in such performance characteristics as response time, ripple, and noise, in addition to causing increased RFI. Recognizing these deficiencies, a user can obtain operating efficiencies exceeding 70%. In such circuits, a different and more efficient power control mechanism is substituted for the series regulating pass transistors.

One such technique is the use of line-voltage phase modulation with SCR's as discussed elsewhere in this Special Section. Another widely used high-efficiency system for power conversion is illustrated in Fig. 4. In this method, the a.c. input signal is first converted to unregulated d.c., then a chopping or switching circuit, controlled by a feedback loop, is used to produce a fixed-frequency output. The power is controlled by varying the duty cycle of this fixed-frequency output. A regulated d.c. output is obtained by rectifying and filtering this phase-controlled signal. The chopping frequency is normally many times higher than the input line frequency. This factor allows the use of a smaller isolation transformer which, in turn, makes possible the attainment of high voltages while using low-voltage control devices because the maximum output voltage then becomes a function of the transformer. Either SCR's or transistors can be used in the chopper section. SCR's handle large quantities of power but are limited to an operating frequency of about 10 kHz. Transistors are limited in power-handling capabilities but operate at faster chopping rates. This provides better response characteristics than SCR systems.

Making the Choice

When selecting a power supply, the user should evaluate three main factors:

Electrical Specifications. Consider the entire band of regulation desired instead of one or two attractive published specifications. For instance, a line or load specification of 0.005% is inconsistent with a temperature coefficient of 0.05%/°C. A power supply should be capable of operating with substantial input line variations. The load should be analyzed for severe demands such as those required by lamp filaments, motor windings, capacitor and pulsed loading. The performance of the power supply should then be evaluated accordingly. Special features and protective circuits for the load and for the supply should also be considered.

Mechanical Specifications. Intended usage should govern the physical appearance of the power supply. A laboratory supply should possess a full complement of meters and accessible controls whereas a system supply must be compact and adaptable to what may be a difficult mounting requirement. When necessary, system mounting can be provided together with accessible controls. The interior power-supply layout should allow convenient access for servicing or internal calibration and adjustment.

Thermal Environment. Power supplies, by the very nature of their use, generate heat. Control of temperature build-up can be accomplished either by convection or by forced-air cooling. Control becomes a critical factor when a power-supply rating is based upon the operating ambient temperature. When installed in large systems, the power supply presents a problem of great concern to designers. The units must be situated so that they do not heat up critical system components, yet they must still be capable of dissipating their generated heat into surrounding external ambient. For laboratory use, the power supply must possess no external heat sinks that can harm the user and cause damage to other equipment.

Before selecting a power supply, a careful check list should be made based on intended usage. Because a large capital expenditure can be involved in the supply and the circuitry dependent upon it, a selection must be carefully made based upon good judgment, intended use, and economics. Such an approach to selection is feasible only if all the characteristics associated with the product are understood and evaluated. ▲

The author is engaged in the development and marketing of d.c. regulated power supplies. He is the author of the "Kepco Power Supply Handbook" and various magazine articles on regulated power supplies. Prior to his association with Kepco, he served with the Army Ordnance Corps, attached to the Army Rocket & Guided Missile Agency (ARGMA), Research Branch, at Redstone Arsenal, Alabama. Preceding this service, he did circuit design in d.c.-d.c. power supplies with Universal Transistor Products Corp. of Long Island. He holds a BSEE from the Polytechnic Institute of Brooklyn.

Power-Supply Programming

By PAUL S. BIRMAN / Applications Engineer, Kepco, Inc.

The feedback circuit of the regulator section is well suited for use in adjusting the supply's output. Such adjustment, called programming, may be done either locally or at a remote location.

REGULATED power supplies are often used in circuits and systems where the ability to control, vary, or modulate the output is required. A remarkable property of the regulator section of the modern power supply is that its feedback mechanism is just as well suited to the problem of control as it is to the maintenance of a constant output voltage or current. The process of varying a power supply's output is called *programming*.

The output of many power supplies may be programmed by varying a resistance—or a conductance—or by applying a signal voltage or current. These, in turn, may be shaped or controlled by a variety of function generators, motor-driven devices, or may be output-related to the power supply itself to close a feedback loop.

In general, programming is limited to those power supplies whose design does not depend on mechanical aids to dissipation limiting. For example, units employing variable autotransformers as part of their control will normally be incapable of electronic *remote* programming (except by the use of motor-driven or similar mechanisms). Similarly, some power supplies that employ range switching—where that switching involves transformer taps—will usually be limited to external control within the span of any one range.

Error sensing is also provided with most precision power supplies to allow the equipment to feed back its corrective signals over a wire path separate from that used to deliver current to a load. This allows a power supply to include the drops in its load wiring as part of its own internal resistance, joining, among other items, the transformer resistance and rectifier drops. The process of compensating for an unwanted drop in the load circuit may be considered a form of *restricted programming* in which the supply *programs itself* by the needed amount. Even power supplies using mechanical control and otherwise not considered programmable, will have a 0.5 to 1-volt programming range for the sensing circuit. Simpler power supplies lacking feedback control mechanisms will, of course, not have even the degree of programming needed for remote error sensing.

Analysis of a power supply in terms of its signal flow rather than its power flow may be aided by a symbolic diagram (Fig. 1A) which reduces the supply to three basic elements:

1. A raw d.c. source, the output of a transformer, rectifier, and filter.
2. A regulator element, typically a tube or transistor, in series with the raw d.c. (An equivalent analysis could also be drawn for a shunt regulator.)
3. A high-gain d.c. comparison amplifier connected to drive the regulator in such a way as to maintain a null (zero volts) across its input terminals. *(If the amplifier has sufficiently high gain, its feedback voltage is practically the same as its output voltage so that its input voltage is vanishingly small, or essentially zero.—Editor)*

The amplifier input and the power supply's negative output form a feedback pair of terminals so that the output voltage will always be equal to the voltage across this pair (to maintain the input "null"). Several properties of the feedback pair are significant.

1. It passes negligible current into the amplifier and, therefore, possesses an apparent high impedance.
2. Any voltage achieved across the feedback pair will program the power supply's output one-for-one. Programming, then, becomes a matter of controlling the magnitude of the feedback-pair voltage.

Methods of Programming

The simplest method of programming involves placing a voltage source directly across the feedback terminals—perhaps a battery controlled by a potentiometer (Fig. 1B). Because of the high impedance, the potentiometer's wiper will not be loaded, yielding good linearity *vs* position. Programmed in this way, power supplies are sometimes used as impedance transformers. With "input" impedances in the megohm range and output impedances in the milliohm region, transformation ratios from 10^9 to 10^{12} ohms are common.

Becoming a bit more sophisticated, the feedback voltage might be controlled by placing a resistor across its terminals and contriving to pass a current through it. The *IR* product voltage will then program the output to an equal, but opposite, level. The current for the feedback resistance may be obtained from a separate source. If this current is constant, then the power supply's output voltage will simply be proportional to the resistance. For example, if the current is 1 milliampere, the output will be 1 volt for every 1000 ohms of feedback resistance. This is often called the *programming ratio;* 1 milliampere control current corresponds to 1000 ohms per volt, 2 milliamperes will give 500 ohms per volt, etc.

Output may also be controlled by varying the current; or the current and resistance may be varied simultaneously with the power supply's feedback circuit by simply multiplying the two, with the product being the power supply's output.

The current for the feedback circuit can be generated by connecting a current source *across* the feedback resistance (in which case the current generator must be capable of supporting the output voltage) or it may be connected across the amplifier's null terminals. Since the null terminals support little voltage (because of the gain), this pair appears to have a very low, almost zero, input impedance, and so is easily driven by a current source. Since the current does not flow into the amplifier itself, the path takes it through the feedback resistor where its passage generates the *IR* drop needed to program the power-supply's output (Fig. 1C).

A current source in this position is readily simulated. Because the amplifier's input impedance is nearly zero, any voltage in series with a suitable resistance can be used to generate the needed current. (*Since there is no voltage across the input terminals, the effective impedance across these terminals is close to zero. This nearly zero input impedance should not be confused with the very high "input" impedance of the feedback pair shown previously in Fig. 1B.—Editor.*) The current will be the input voltage divided by its series resistor. This current, and thus the current through R_f, is subject to control by varying either the source, E_r (the reference) or its series resistor, R_r. Control will be directly proportional to E_r and inversely proportional to R_r. (It is directly proportional to the conductance $G_r = 1/R_r$.)

Writing the complete equation: $E_o = E_f = E_r\ (R_f/R_r)$.

The resistance ratio R_f/R_r is sometimes called the *operational gain*, or *closed-loop gain*. When either R_f or R_r is varied to control output, the operation can be considered equivalent to varying the *gain* of an amplifier with a fixed input (E_r). If the gain ratio is allowed to remain constant, output may be varied in the selected proportion by controlling E_r.

E_r may, of course, be any voltage level as long as it is used in series with the appropriate resistor to produce the control current. The current needed will be dependent on the value selected for R_f, with larger values requiring the least amount of current.

In most modern power supplies, a shunt-regulated zener source is commonly used to produce the stable reference (E_r). The current from it is determined by a precision series resistor (R_r) and is customarily between 1 mA (1000 ohms per volt) and 10 mA (100 ohms per volt). The feedback resistor (R_f) is made variable and is mounted on the front panel and labeled "voltage control". To qualify as a remotely programmable power supply, these elements are connected to the circuit *via* appropriate terminals and links, so arranged that users have access to any or all elements for the substitution of external components (Table 1).

Programming mechanisms might include a remote feedback resistor which is variable, stepped, sequenced, or driven by a motor; or it might include an external source of voltage substituted for the reference. This, too, may be variable, derived in whole or in part from a function generator, sweeper, or sensor output for process control.

Next, let us consider some of the important design parameters that are involved.

ELEMENT (control by)	**OUTPUT**	**LIMITS**	**ADVANTAGES**
E_f (feedback voltage)	Directly proportional, 1:1	Needs voltage equal to output	Impedance transformer
R_f (feedback resistor)	Proportional to control current	R_f must support voltage E_f	Direct linear program
R_r (reference resistor)	Inversely proportional	Current from reference varies	R_r need only support E_r
E_r (reference voltage)	Proportional to $\frac{R_f}{R_r}$	E_r must provide control current	Low-level programming

Table 1. Programming is done by varying one of these elements.

The ability of a power supply to make its output follow a program accurately, linearly, and with good resolution is largely a function of the comparison amplifier's gain. The higher this is the more nearly perfect is the comparison. The gain is usually reflected in the power supply's load regulation rating with 0.1% to 0.01% supplies requiring 80-100 dB of amplifier gain. Actually, the significant gain is the open-loop gain (A) less the closed-loop gain (R_f/R_r). The balance is called the "loop gain" or *feedback return ratio*.

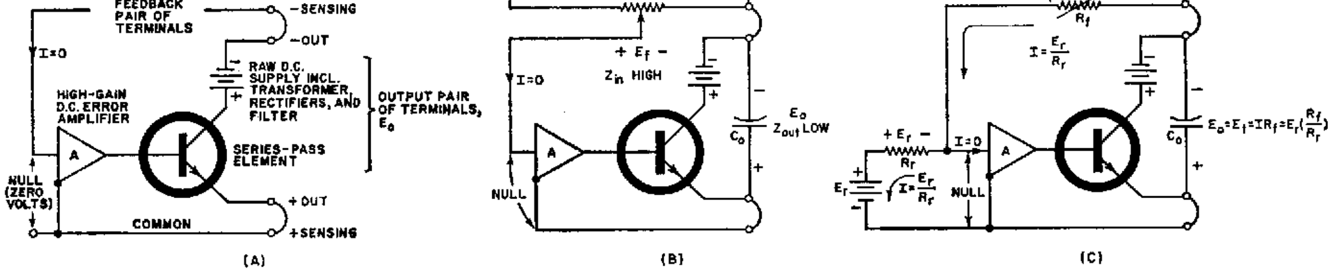
Also involved is an analysis of accuracy or linearity are the amplifier's offsets (residual input voltages and currents) whose presence must be accounted for in determining the precise output.

With modern emphasis placed on varying output (rather than the traditional power-supply role of maintaining constant output), the question of a power supply's dynamics (behavior while varying) becomes significant. Typically, power supplies have used large capacitors across the output terminals. These capacitors are characterized by high energy storage, low a.c. impedance, and resistance to voltage change, making them ideally suited to the demands of the classical *constant-voltage* power supply. These same characteristics, however, make the traditional output capacitor unsuited to the demands of a variable (modulated) power supply. In particular, the capacitor affects the *programming speed*—or *slewing rate*, the rate of voltage change following a step command, say from a switched feedback resistor. (Slewing rate is measured as the chord from the origin to the first time-constant on the exponential response to a step command, as in Fig. 2.) The relationship $I = C\ dv/dt$, where dv/dt is the voltage rate-of-change, limits the slewing rate to the current divided by the capacitance. Typically, for most output filtered supplies, this will be just a few hundred volts per second.

Fast-Programming Supplies

Some manufacturers now offer high-speed, or fast-pro-

Fig. 1. (A) Simple series dissipative regulator type of power supply showing signal voltage relationships. E_o equals E_f. (B) Voltage repeater 1:1 programming produces impedance transformation from very high-Z input to very low-Z output. (C) A voltage E_r in series with R_r produces a current through R_f equal to E_r/R_r. This current times R_f produces program $E_o = E_r\ (R_f/R_r)$. Current arrows show direction of electron flow.



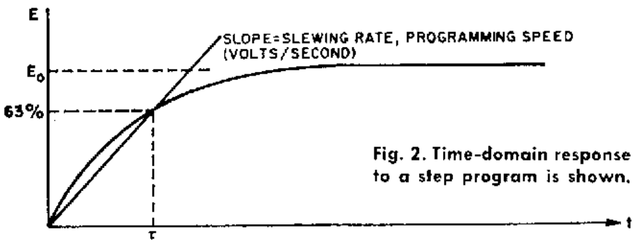


Fig. 2. Time-domain response to a step program is shown.

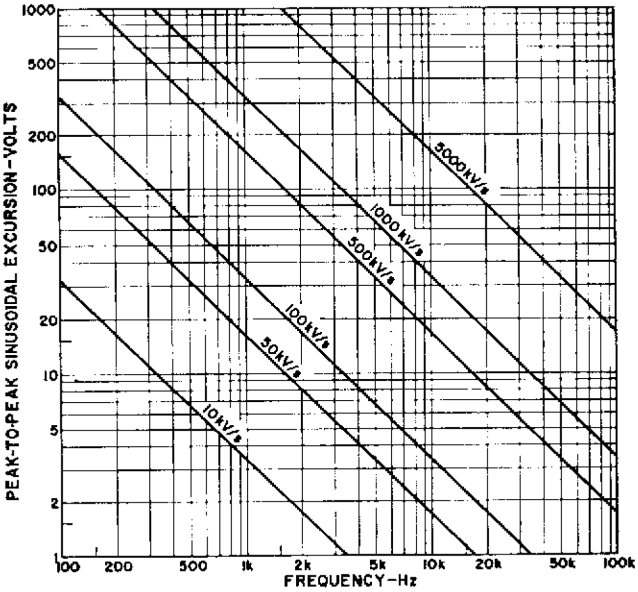
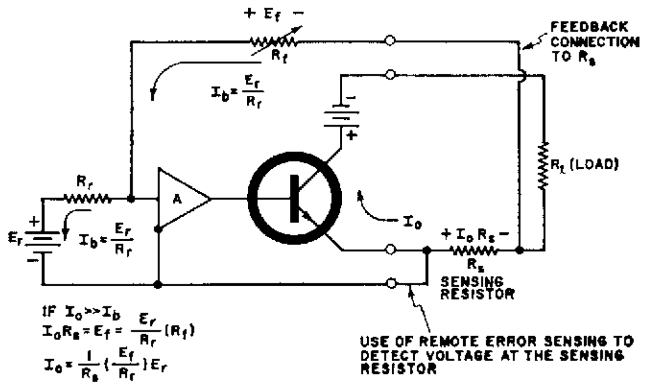


Fig. 3. Chart showing the maximum sinusoidal frequency vs the peak-to-peak voltage excursions for number of slewing rates.

Fig. 4. A sensing circuit for current regulation and control.



gramming power supplies. In these the output filter-capacitance is reduced or completely eliminated. This yields relatively high slewing rates, on the order of ½ to 2 volts per microsecond. Such power supplies are well suited to rapid programming of test circuits, or to digitally controlled step-value feedback-resistance programs. They may also be modulated with speech or other complex audio-frequency or sinusoidal waveforms, just as if the power supply were a wideband d.c. amplifier.

Sinusoidal bandwidth can be related to slewing rate by the chart in Fig. 3. This depicts the product $E_{p\text{-}p}\,\pi f = dv/dt$, which, for a given slew rate, dv/dt, and amplitude, $E_{p\text{-}p}$, plots the maximum sinusoidal frequency, f.

Power supplies used to regulate current are especially benefited by the capacitorless high-speed circuits. The transient response of a current regulator is a measure of its ability to restore the set current following a step load change. Since such a load resistance change calls for a corresponding change in the current regulator's output voltage, or compliance voltage, the speed of response is directly related to the voltage-rate-of-change, the programming speed. Essentially, the current regulator is a self-programmed power supply which automatically adjusts its output voltage to correspond to changes in load resistance, to maintain a constant voltage-resistance ratio.

Power supplies are made to control current, rather than voltage, simply by connecting their feedback resistor to a sensing resistor instead of the output load (Fig. 4). When this connection is made, the circuit regulates the voltage across the sensing resistor and makes it equal to the feedback voltage. Because the voltage across the sensing resistor is the product of output current and R_s, and since R_s is constant, then controlling the sensing voltage controls the output current.

The connection of the feedback resistor to either the load or sensing resistor—to the *point of regulation*—constitutes one of the power supply's *error-sensing* connections. The other is the connection between the reference voltage and the common terminal. By making these connections directly to the point of desired regulation, the voltage drops in the load-carrying wires are not included in the critical comparison of load voltage with feedback voltage, and the errors are compensated.

Modern regulators, subject to a variety of command controls, able to be modulated and capable of functioning as impedance transformers, summers, scalers, integrators, amplifiers, fulfill a growing role in the field of control engineering. By their ability to handle a small signal command, and respond to it with substantial power, such equipment can often simplify systems design, and reduce the burden on other equipment. ▲

OFTEN-USED POWER-SUPPLY TERMS

Ambient Operating Temperature: The range of environmental temperatures in which the supply is operated.
Bipolar: A system with two poles, polarities, or directions.
Compliance Voltage: Output voltage of a d.c. power supply in a constant-current mode.
Constant-Current Power Supply: A supply capable of maintaining a preset current through a variable load.
Constant-Voltage Power Supply: A supply capable of maintaining a preset voltage through a variable load.
Current Cut-off: An overload protective device designed to reduce load current as the load is reduced.
Current-Sensing Resistor: A resistor in series with the load that develops a voltage proportional to current.
Error Signal: The difference between the output voltage and a fixed reference voltage.
Filters: LC or RC devices arranged as low-pass devices. They determine output ripple value.
Frequency Response: A measure of a power supply's ability to respond to a sinusoidal program.
Isolation Voltage: The external voltage between the power-supply output and ground.
Lead, Lag Networks: Resistive-reactive components that control phase-gain roll-off versus frequency.
Load Regulation: The maximum change in output current or voltage with corresponding changes in load.
Overshoot: A transient rise beyond regulated output limits.
Programming: The control of a power-supply function by means of an external variable control.
Regulation: Maximum change in output caused by line voltage, load, temperature, or time changes.
Response Time: Time required for voltage or current reduction to 37% of its peak value after a step load or line change.
Ripple: The a.c. component in a d.c. output.
Series Regulator: A device in series with a power source that controls voltage or current output.
Short-Circuit Protection (Automatic): A current-limiting system that enables a power supply to operate into a short without damage.
Shunt Regulator: A device placed across the output which enables a supply to maintain constant output.
Stability (Long Term): Output voltage or current changes as a function of time.
Voltage Reference: A separate voltage source used as a standard.

The author is chairman of the Electronic Power Supply Committee of the National Electrical Manufacturers Association. A graduate of the Technical University of Warsaw, he worked several years in England before coming to the United States in 1951. He has worked in product engineering, application engineering, and has held management positions in marketing and manufacturing. He is a Senior Member of IEEE, a Registered Professional Engineer, and has a number of papers and articles to his credit.

How To Measure Power-Supply Performance

By B.C. BIEGA/Director of Engineering
Sola Electric Div., Sola Basic Industries

In order to compare specifications properly, measurements should be made according to certain standards. Here are the proper methods to use to avoid measurement errors.

A GLANCE at the ads in any magazine devoted to electronics and instrumentation technology will indicate the availability of many types of electronic power supplies. Their power outputs—ranging from milliwatts to kilowatts—are designed to provide fixed or variable voltage or current with almost any desired degree of precision and stability.

Growth of the power-supply industry, in a relatively short time, has been so rapid that it has been necessary to develop a whole new terminology to describe the performance characteristics of these power supplies. Further, as circuits and components have been improved, specifications for regulation, temperature coefficient, ripple, and drift have become tighter and tighter. But, for lack of common terminology and definitions, the user is often unable to make meaningful comparisons of the products of two different manufacturers.

Recognizing this problem, a number of major power-supply manufacturers are cooperating in the development of a Standard for Electronic Power Supplies through the Electronic Power Supply Committee of the National Electrical Manufacturers Association (NEMA). The Standard will include sections covering definitions, ratings, safety provisions, and measurement methods. This Standard is expected to be completed late this year. Its adoption by all power-supply manufacturers will eliminate most of the existing confusion as to the exact meaning of the various specifications.

Avoiding Errors in Measurement

The tighter the power-supply specifications, the more difficult it is to make measurements verifying spec conformance. This is so because measurement errors can become greater than the change in output being measured.

For example, if a power supply is rated at 24 volts output with 0.01-percent load regulation, this means the terminal voltage varies no more than $(0.01/100) \times 24 = 0.0024\ \text{V} = 2.4\ \text{mV}$ for a no-load to full-load change. If rated output current is 5 A, the internal impedance is $(2.4 \times 10^{-3}) / 5 = 0.48$ milliohm or 0.00048 ohm. The measurement of load regulation is, in effect, the measurement of this internal impedance—not an easy matter. Note that 1 inch of #20 A.W.G. copper wire has a resistance of 0.84 milliohm at a temperature of 20°C. The contact resistance of an alligator clip may be much higher. Consequently, it is essential to eliminate any series voltage drops between the power-supply terminals and the point where the measurement is made, and to keep the current

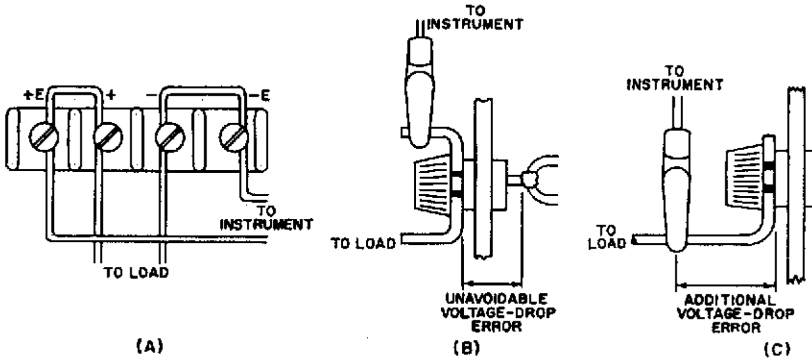


Fig. 1. (A) Proper lead connections to rear barrier strip. (B) Correct and (C) incorrect connections to the front-panel terminal of unit.

Minimum Equipment Needed	
Oscilloscope	Minimum bandwidth, 100 kHz; Vertical sensitivity 1 mV/cm
V.T.V.M.	
Millivoltmeter	With center zero
Variable autotransformer	
A.C. voltmeter	
D.C. ammeter	
Power supply	With voltage output of same magnitude as one being tested
Preferred Equipment	
Oscilloscope	Minimum bandwidth 20 MHz; Vertical sensitivity 100 μV/cm; Differential input
Digital voltmeter or differential voltmeter	

Table 1. Equipment needed to make power-supply measurements.

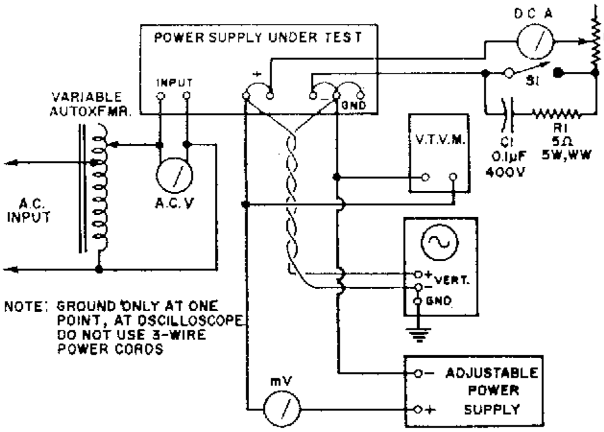


Fig. 2. Setup for measuring constant-voltage power supply.

flowing in the measuring circuit leads as low as possible.

Most precision power supplies have a rear panel containing two pairs of terminals: one for output or load leads, the other for remote error-sensing leads. Connect leads as shown in Fig. 1A to obtain the most accurate results.

In power supplies with only one pair of front-panel output terminals, connect the measurement leads as shown in Fig. 1B, rather than as in Fig. 1C. Even with the proper connection, an uncompensated source of error exists in the voltage drop on that part of the terminal post extending through the panel.

Separate pairs of measuring leads must be run from the same monitoring points to each instrument, avoiding mutual coupling effects. The pairs should be twisted to avoid pickup and, in some cases, shielded leads may be necessary.

Instrument resolution must be at least one order of magnitude better than the smallest quantity to be measured. For example, to measure down to 1 millivolt, the voltmeter must have a resolution of at least 100 microvolts.

Since the power supply being tested and the power supplies and amplifier in the measurement instruments all experience some drift or change during warm-up, it is essential that the equipment be energized, and the power supply connected to its load, for the specified warm-up time. If no specific warm-up time is indicated, allow a minimum of 30 minutes for the purpose.

Constant-Voltage Power Supplies

The most important measurements to be made are line and load regulation, PARD (Periodic and Random Deviations) which includes both ripple and noise, and transient recovery time. Table 1 lists the minimum and preferred equipment needed.

Fig. 2 shows the test set-up using the "minimum" equipment. The variable autotransformer is used to vary the monitored input voltage to the power supply. Make sure the rating of the autotransformer is 20 percent higher than the total output rating of the power supply, since it must handle the power-supply losses in addition to the load.

Load resistor R_L must have a resistance and wattage rating capable of handling the maximum current at the maximum output voltage of the power supply. The v.t.v.m. is used to measure the power-supply output voltages while a d.c. ammeter is used to measure the output current. Switch *S*1 is used for measuring load regulation. *C*1 and *R*1 are connected across the contacts of *S*1 to minimize switching noise. A double-pole relay should be used for *S*1 since the second set of contacts can then be used for triggering the oscilloscope sweep.

The adjustable power supply is used to buck out the output voltage of the power supply being tested so that the zero-center millivoltmeter measures only the change in output voltage. The adjustable power supply must have an output at least as high as that of the unit being tested, but its power requirement is very small. Ripple content should be lower than that of the supply being tested.

If a high-quality 6-digit digital voltmeter or differential voltmeter is available, it can replace the v.t.v.m. and the bucking-supply/millivoltmeter combination.

Measurement Procedure: Energize the set-up at rated a.c. voltage. Adjust the power supply for maximum rated output voltage and adjust R_L to draw maximum rated current. If the power supply has an adjustable current limit, set it well above maximum current rating. If it has automatic constant-voltage/constant-current crossover, adjust R_L so that the current is at 90 percent of the crossover point. Check set-up for pickup and ground-loop effects by switching the power supply "off" and observing the scope first with its leads connected together and then to each of the output terminals of the supply. If any signal is observed on the scope, change lead routing and ground connections until the problem is corrected.

After the specified warm-up time, readjust R_L to obtain correct output current. Finally, adjust the bucking supply so that the millivoltmeter is nulled.

Line Regulation: Vary the input voltage over the specified range (usually 10 percent above and below normal) and record the millivoltmeter reading. This will provide ΔV, the absolute value of the line regulation, in millivolts.

$$Percent\ regulation = (\Delta V/1000E) \times 100$$

where E is the total output voltage, in volts.

For variable power supplies, repeat at various levels of output voltage. Also repeat with no load on the power supply.

Load Regulation: Switch the load "on" and "off" and record the change in output voltage, allowing time for reestablishment of equilibrium after each load change. Repeat for lowest and highest specified line-voltage settings. The calculations for percent regulation are the same as for line regulation.

Recovery Time: During the load-regulation measurement, an output voltage transient may be observed on the oscilloscope. Typically, it may appear as shown in Fig. 3A. If the dashed lines represent upper and lower limits of the specified transient recovery band, recovery time will be specified in the NEMA Standard as "time elapsed from the initial excursion of output voltage beyond the limit until it returns and stays within this band". Fig. 3B shows the case of an overshoot along with an undershoot. Unless otherwise specified by the manufacturer, the transient recovery band is equal to the regulation band and is centered on the average of output levels before and after load change.

PARD (Ripple and Noise): The PARD of the power-supply output is a new and preferred method of specifying ripple and noise (periodic and random deviations) by indicating its maximum peak-to-peak value in millivolts. The value can be observed directly on an oscilloscope (Fig. 3C). The r.m.s. value of ripple, which is sometimes specified, may be two to four times lower in value, depending upon the waveform of the ripple component and the amount of noise present. The r.m.s. value may be measured by substituting a sensitive true r.m.s.-reading a.c. meter for the oscilloscope.

In order to detect high-frequency spikes on the output, a scope with at least a 20-MHz bandwidth is required. In fact, a differential oscilloscope with special coax cables and connectors must be used to accurately measure the amplitude of high-frequency spikes.

Note that a 60-Hz component in the ripple is usually indicative of undesirable stray pick-up. This should be eliminated to obtain a correct measurement of PARD.

Constant-Current Power Supplies

To measure constant-current power supplies, variations in output current (due to input line or load variations) are changed to variations in voltage drop across a series sensing resistor R_s. Then the procedures outlined for constant-voltage power supplies can be followed. The observed millivolt values are divided by the value of R_s to obtain milliampere current deviations.

However, difficulties in obtaining accurate results are even greater here than for constant-voltage supplies. For example, if the rated output of the power supply is 10 A and load regulation is stated as 0.01 percent, the specified current change is actually $10 \times 0.0001 = 1$ mA. If the sensing resistor R_s is 0.1 ohm, the voltage drop across it at rated current will be 1 V, while the change in voltage due to regulation will be 1 mV. This magnitude of change will also occur even in a precision resistor with a temperature coefficient of 20 ppm/°C if its temperature increases 50°C during this test.

Therefore, the sensing resistor must be selected with a power rating of at least 10 times (preferably more) the power dissipated in it at full rated current. Its resistance value should be chosen to provide an approximate 1-volt drop at rated current. A higher value would help in making measurements, but would reduce the available compliance voltage of the supply and tend to increase the circuit resistance when load resistor R_L is shorted out during the load regulation test.

A good quality ammeter shunt or a precision wirewound resistor should be used. To avoid sudden changes in its temperature, it should be shielded from drafts and preferably placed in an oil bath. The sensing leads must be connected between the resistor and its load terminals, as shown in Fig. 4. Keep all sensing leads as short as possible.

Load resistor R_L should be selected so that the supply's voltage output does not exceed its permissible compliance voltage rating. In the case of constant-voltage/constant-current supplies with automatic crossover, the supply's voltage output should not exceed 90 percent of its constant-voltage operating value. It is desirable to use a fixed resistor of ample power rating here. Small resistance changes at the brush contacts of a rheostat will show up as additional noise in making the PARD measurement. The power-supply voltage-limit control must be set at a level well above the maximum compliance voltage used in the tester.

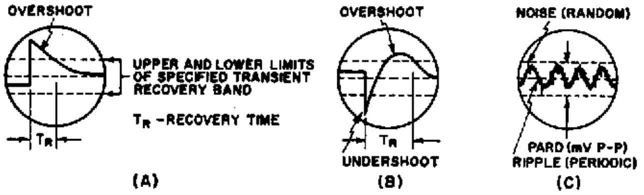


Fig. 3. (A), (B) Typical output voltage transients and recovery times. (C) PARD is specified in millivolts, peak-to-peak.

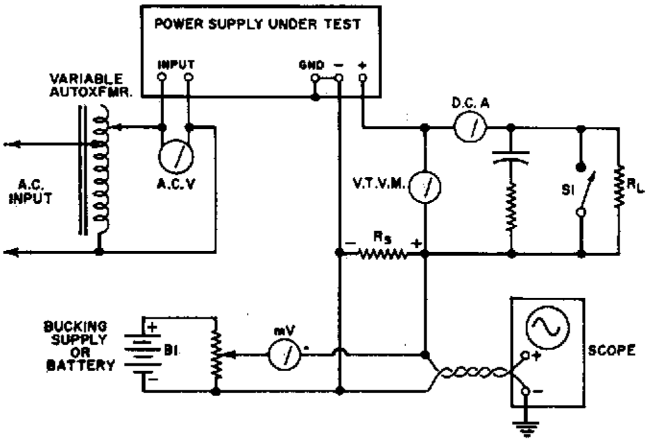


Fig. 4. Setup for measuring constant-current power supply.

Current flowing through the output voltmeter will show up as an additional load on the supply; therefore, a high-impedance v.t.v.m. should be used, connected as shown.

Note that switch *S1* shorts out the load resistor when closed. Therefore, the load regulation test is made by switching from rated load to short-circuit load.

Temperature Coefficient & Drift

Temperature coefficient tells us how the regulated output is varied as a result only of changes in ambient temperature, and is specified in absolute change ΔV or ΔI, or as a percentage change, per degree centigrade. This variation is not generally linear and should be specified as a maximum rate of change that occurs anywhere within the specified operating ambient temperature range of the supply. To measure this coefficient, an oven with precise temperature control is needed.

The power supply is placed in the oven and the temperature control is varied in 10°C steps over the entire specified range. After each temperature change, it is necessary to wait for the output to stabilize at its new level. This may take about 30 minutes for each step. It is important to maintain all other parameters (such as input line voltage and load resistance) constant. Stability of the measuring instrument is an important factor in making accurate measurements. It is also desirable to retrace all temperature points in the reverse direction to average out any errors that may occur.

Drift is the maximum change of output over a period of eight hours with all other parameters held constant. It is the most difficult characteristic to measure precisely, because unavoidable changes in the line voltage, load resistance, ambient temperature, and especially drift of the measuring instruments may have as great, or even greater effect on the measured supply output voltage or current than the inherent drift of the power supply itself. Tests should be conducted with both the power supply and all measuring equipment held in an ambient temperature which varies less than 1°C.

Measurement of drift should not begin until initial warm-up is completed. The output and all other parameters (such as ambient temperature and input voltage) must be checked every few minutes during the eight-hour period. Obviously, strip-chart recorders are ideal for this purpose. ▲

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IC Voltage Regulators For Power Supplies

By A.H. SEIDMAN/Contributing Editor

The integrated circuit has now invaded the power-supply industry. IC voltage regulators, some with current ratings of 2 amperes and load regulation up to 0.05 percent, offer new design opportunities.

THE integrated circuit, already well-established in digital-circuit applications and a growing factor in analog systems, has made its debut in power supplies. Typical of the industry, the five firms in Table 1 are marketing monolithic and hybrid IC voltage regulators in TO-5 and other small-size packages. Based on proven discrete designs, these units are capable of delivering up to 2 amperes at regulated voltages as high as 48 volts with 2 percent or better load regulation. Prices range from approximately $6 to $60 each in small quantities. With additional external components, the capabilities of some of these devices can be extended to current ratings as high as 25 amperes and voltage regulation on the order of 0.025 percent.

The advantages of integrated circuit regulators over conventional designs are numerous. These include small size, potentially greater reliability because of fewer connections, packaging flexibility in OEM designs, small inventories, and small design and lead times.

Two basic circuit configurations used for voltage regulators are the emitter-follower and series-regulator circuits of Figs. 1A and 1B, respectively. In both circuits a Darlington pair is used for the pass transistor where $Q1$ is a power device and $Q2$ a small-signal transistor. The small-signal transistor requires little base current thus permitting resistance R to be large. A large value of R simulates a constant-current source for the reference zener diode, thereby providing improved regulation.

The Darlington pair operates as an emitter-follower, reducing the output impedance of the unregulated source. Although it is simple and inexpensive, the voltage output of an emitter-follower regulator is limited to a value approximately equal to the zener diode voltage and load regulation is not much better than 2 percent.

In the series regulator, a portion of the output voltage that appears between the base of the control transistor ($Q3$) and common (pin 7) is compared with the zener reference voltage. The difference voltage is then amplified by the transistor. Assume, for example, the output voltage tends to increase because of a rising input voltage; the difference voltage increases and the collector current of $Q3$ rises. The collector-base voltage of $Q2$ increases and almost the entire change in voltage appears across $Q1$; the output therefore remains essentially constant. The series regulator is flexible and its regulation can be made to exceed 2 percent.

Integrated-circuit regulators share certain common features that must be considered by the applications engineer in his design. These features are:

1. The d.c. unregulated input voltage must be greater than the desired d.c. regulated voltage by approximately 2 to 15 volts, depending on the manufactured device used.
2. The operating temperature range is typically from −55° C to +125° C.
3. Most units can be used with external discrete or IC components to extend their current range or improve regulation. These components, however, can take up more space than the IC regulator.
4. For some applications, an external heat sink may be required. Specific details can be obtained from the manufacturer's data sheet.

To illustrate the flexibility of IC voltage regulators, the *Westinghouse* WM 110 monolithic regulator of Fig. 1B will be used as an example. Selling for $25 in small quantities, the circuit is housed in a low-profile TO-3 can and is rated at 0-2 amperes from 8 to 48 volts; load regulation at 1 ampere is 2 percent. Because the chip substrate and case are at ground potential, the device can be bolted di-

Table 1. A listing of some currently available IC voltage regulators and their important characteristics.

MANUFACTURER & NUMBER	TYPE	PACKAGE	MAX. AMPERES	REGULATED OUTPUT (V)	UNREGULATED INPUT (V)	PERCENT LOAD REGULATION	COST ($) (small quan.)
Beckman 803	Hybrid	Flat	0.5	21 to 32	27 to 38	0.05	30
Bendix BN-4100	Discrete	TO-3	1	5 to 25	9 to 40	2	6.60
Fairchild SH 3200	Hybrid	TO-5	50 mA*	8.5 to 30	10.5 to 35	0.05	50
National Semiconductor LM 100	Monolithic	Low-profile TO-5	20 mA*	2 to 30	8.5 to 40	0.5	60
Westinghohse WM 110	Monolithic	Low-profile TO-3	2*	8 to 48	10 to 51	2**	25

*Can be extended with external transistors, see text. **Can be improved with external components, see text.

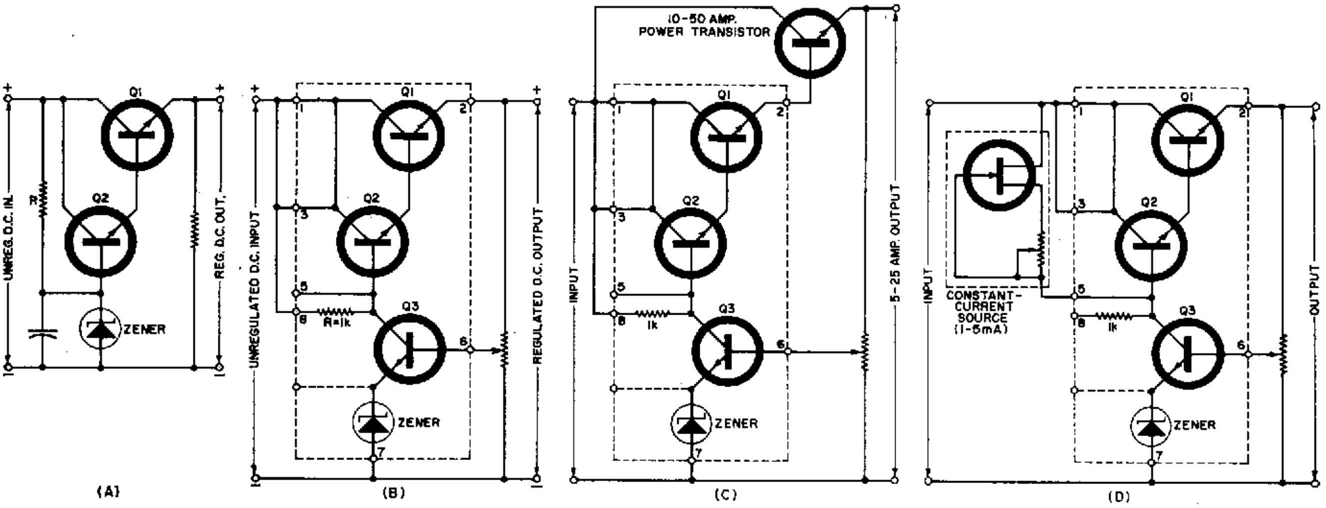

Fig. 1. (A) Emitter-follower as used in Bendix discrete regulator. (B) Series regulator used in Westinghouse monolithic unit. Methods of increasing the capabilities of an IC regulator. (C) Increasing current. (D) Improving regulation.

rectly to a chassis or to structure members for heat sinking.

For increased power handling, a discrete transistor may be added to form a triple Darlington, as shown in Fig. 1C. No additional biasing components are required and the 2-ampere output of $Q1$ is sufficient to drive 10- to 50-ampere power transistors to provide outputs from 10 to 25 amperes. Regulation may be improved by the use of an FET as a constant-current source for the zener diode (Fig. 1D). Regulation obtained with this modification is on the order of 0.1 to 0.2 percent for input voltage variations of ±20 percent and load variations of 1 ampere.

If precision voltage regulation is needed, the feedback signal to pin 6 may be boosted by another amplifier. With, for example, the *Westinghouse* WM 115 differential IC amplifier inserted into the circuit at pin 6, regulation will hold to 0.025 percent over a 2-ampere load range and a ±20 percent input voltage variation. Short-circuit protection can be provided by placing a small series resistance at pin 2 and having the voltage drop across this trip a small transistor whenever over-current conditions exist.

Beckman is offering its Series 803 thick-film hybrid voltage regulator with voltage output between 21 and 32 volts. Selling for $30 in small quantities and packaged in a small rectangular housing which is compatible with both flat-pack and dual in-line IC packages, the device handles a maximum of 0.5 ampere and provides 0.05 percent regulation for both line and load variations. Referring to Fig. 2, a triple Darlington is used to provide a gain greater than 10^6. A constant-current source comprising zener diode $D1$ and transistor $Q1$ operates between the unregulated input voltage source and the common line to provide an initial regulated constant current which is essentially independent of input voltage variations. The remaining circuitry is fairly similar to that used in the *Westinghouse* and other regulators.

Bendix has a series of discrete-circuit regulators housed in the standard TO-3 package. In the least expensive BN-4100 series, which sells for $6.60 in small quantities, an emitter-follower regulator (Fig. 1A) delivers 1 ampere. Output voltages of 5, 6, 12, 18, or 25 volts with load regulation in the range of 2 percent are available. Other units in the BN-4000 line provide 1 percent regulation and are higher in cost.

The monolithic (LM 100) voltage regulator made by *National Semiconductor* is packaged in a low-profile TO-5 can. Selling for $60 in small quantities, the output voltage is adjustable from 2 to 30 volts; load regulation is 0.5 percent maximum. Rated for a load current of 20 mA, the range can be extended to currents greater than 5 amperes by using external transistors.

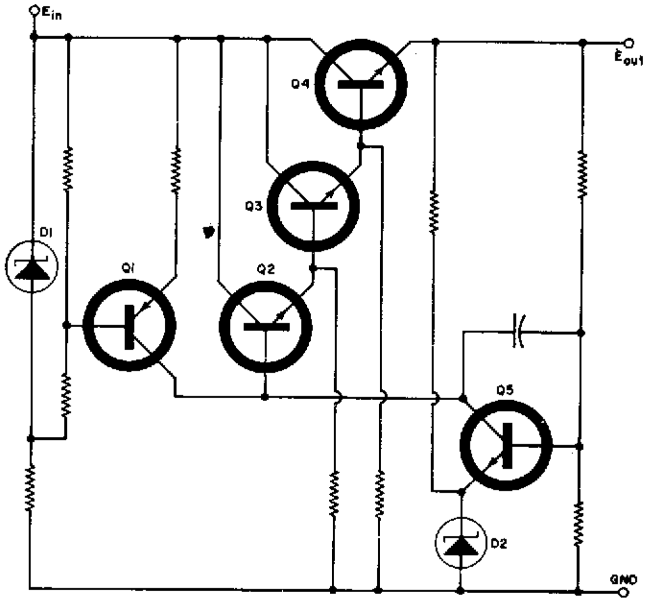

Fig. 2. Schematic of Beckman's hybrid voltage regulator.

Fairchild's SH 3200 adjustable hybrid voltage regulator is housed in a TO-5 can. A complementary version, the SH 3201, is also available for negative regulated voltages. Load regulation of 0.05 percent at 50 mA over an adjustable voltage range of 8.5 to 30 volts is obtained with the aid of the internal FET acting as a constant-current source for the zener diode. An external transistor extends the current range to 5 amperes. Cost of the SH 3000 is $50 in small quantities.

Other manufacturers producing comparable IC voltage regulators include *Amelco Semiconductor, Bourns, Continental Devices, General Instrument*, and *Raytheon*.

Where space and reliability are of considerable importance, the IC voltage regulators are superior to those using separately packaged, discrete components. IC regulators are especially attractive in systems where it is desirable to have many local regulators for noise isolation rather than one central power supply. Also, because of their small size, the designer has greater flexibility in layout, permitting him to come up with an optimum package size.

If cost is the important factor, the IC regulator may not always be able to compete with discrete designs—at least for the present. There is little doubt, however, that with improved technology and increased production, these units will drop in cost and become competitive with discrete regulators of comparable operating characteristics. ▲