OBJECTIVE
Design a power supply including a series-pass voltage regulator, using discrete components, to provide an adjustable regulated output voltage between 7 and 22 VDC, with short-circuit current-limiting activated between 14 and 15 milliampere. Inexpensive commercial integrated circuit voltage regulators, preassembled and tested, generally would be very much preferable to a completely discrete design. However assembling a power supply simply to meet specifications is not the underlying purpose here; it is only a vehicle with which to obtain added experience in the art of design. The restriction to a discrete component design also adds emphasis to understanding principles and details of operation of the series regulator rather than simply on overall functional operation. The regulator is a 'system' coordinating a number of interacting modules to perform an overall function. It is the design coordination of that interaction that is the underlying objective.

The basic circuit for the raw power supply to be used for this experiment is illustrated in Fig. 30.1. It is a capacitor-filtered bridge rectifier, with a series 'internal' resistor R deliberately added to assure a relatively poor regulation. Note particularly the use of the variac and isolation transformer AC source to avoid 'ground loops' between the different laboratory stations, and to limit casual exposure to line voltages. Insofar as this experiment is concerned the terminals of the power supply are those labeled ⊗.

Note: A 'step-down' transformer may be substituted for the variac and isolation transformer.
Design Notes

Note 1
An elementary voltage regulator circuit is illustrated in the figure; the basic circuit is that of an emitter-stabilized transistor. The battery serves as a reference voltage which is compared to the regulated output voltage to identify changes in the output voltage from a base value. The emitter junction voltage is the difference between the two voltages, and changes in this voltage difference indicate variations in the output voltage. The transistor serves also as the control element with which corrections are made, i.e., if the output voltage decreases (for example) the emitter junction voltage difference increases, this increases the load current, and the output voltage is increased to offset the original decrease. The collector-emitter voltage changes to accommodate variations in the unregulated voltage.

Consider the generalized functional block diagram of a regulator circuit drawn to the left. The Reference block is a generalization of the function served by the battery, i.e., it is the criterion against which changes of the output voltage from the desired value are measured. An electronic reference, better representative of practice than a battery, is illustrated in Fig. 30.4. A Zener diode, properly biased, provides the basic reference voltage. The Zener supply generally is taken from the unregulated supply voltage to avoid passing the Zener current through the control device. The RC voltage divider provides a low-pass filter to remove voltage variations due for example to rectifier ripple voltage. As an incidental matter the divider provides a reference voltage lower than the Zener voltage itself; as will become apparent the reference voltage used for the comparison operation will be the lowest voltage which can be regulated.

In the simple regulator circuit the reference (battery) voltage is compared directly to the output voltage, implying that the reference voltage and the output voltage have to be (nearly) equal. On the other hand the regulator could be used to regulate a sample (i.e., fraction) of the actual output voltage rather than the actual output voltage itself. If the sampling fraction is constant regulation of the sample voltage effectively regulates the larger voltage as well, allowing a given regulator circuit to be used for different load voltage requirements. In fact if the Sampler function is adjustable then the output voltage of the regulated supply also is adjustable. A illustrative sampling circuit is drawn to the right. Note again that the sample voltage is what will be compared to the reference, and it is actual the sample value the regulator will attempt to hold constant. Since the sample voltage has to be nearly equal to the reference to which it is compared, and since the largest sampling fraction of the potentiometer is 1, it follows that the smallest voltage which can be regulated is the reference voltage.

Applying this same reasoning further it follows that the smallest sampling fraction corresponds to largest output voltage which can be regulated. For one reason or another this maximum voltage is limited, e.g., as will be seen it must be less than the supply voltage in order for the regulator to function. This is the purpose for inserting the fixed resistor in series with the potentiometer in the sampling; it fixes the smallest
The COMPARITOR function in the simple regulator illustrated earlier is performed by the emitter junction of the transistor. A more flexible arrangement is illustrated to the right. This is a CC-CE differential-input configuration which buffers (presents a high input resistance to) the reference voltage, and amplifies the difference between the reference and sample voltages. The amplified 'error difference' voltage is used (as described below) to adjust the output voltage. Note that the error voltage is the change from the quiescent bias voltage.

The same transistor that is used for the comparison function in the simple regulator also provides the correction. Separating these functions better enables an optimization of the circuitry for each function rather than a compromise choice. A 'series pass' transistor (see drawing below), so-called because it is placed in series with the current path, is a commonly used control arrangement. The transistor functions as an emitter follower, with the load resistor completing the circuit. The circuit diagram drawn below puts all the pieces together in a representative discrete device series regulator configuration.
Note that the collector-base resistor of the control device actually is the collector resistor of the 'error' transistor in the comparator; the series-pass transistor base current will be small compared to the collector current. The base current of the series-pass transistor is the 'load' for the 'error' transistor. Adjusting the sampling potentiometer changes the quiescent setting of the pass transistor base voltage; thereafter fluctuations in the output voltage produces amplified corrective changes in the base voltage.

Adjust the variac to produce a nominal no-load DC output voltage from the bridge rectifier between 35 and 35.5 VDC; thereafter leave the variac setting unchanged. Carefully measure the load regulation and the p-p ripple for this supply for later comparison to the regulated supply characteristics. Remember that R is the internal resistance of the supply as far as this experiment is concerned.

The relationship between the simple emitter follower as applied to voltage regulation and the expanded circuitry of the preceding figure may be seen in the functional circuit diagram to the right. The difference between the voltage reference and a sample of the output voltage is applied to the emitter follower base through an amplifier; the phase of the amplified signal is such that it mitigates changes in the output voltage. This is a basic feedback control circuit for which the overall amplifier 'gain' is estimated as shown. Note that to the extent the 'loop gain' fA >> 1 the output voltage is a fixed multiple of the reference voltage.

**Note 2** Accidents happen. With power supplies, for example, it is not uncommon for the supply to be accidentally short-circuited because of a load failure of some sort. An output short-circuit defeats the regulating circuitry because the pass transistor attempts to increase the short-circuit voltage by increasing the output current, generally beyond allowable circuit limits. To avoid this extreme behavior current-limiting circuitry can be added which (ideally) is inactive in normal operation but becomes active when the current exceeds a preset set-point value.

One type of current-limiting circuit is illustrated by the circuit drawn to the left. The current from the pass transistor emitter is passed through a small sensing resistor placed in series with the load, and the voltage drop across this resistor is monitored by the emitter junction of a transistor. When the voltage drop is large enough this transistor is turned on and diverts current from the pass transistor base, limiting the emitter current. The more current the error signal attempts to provide the more strongly the current-limiting transistor turns on and the more strongly base current to the pass-transistor base is diverted. Note that the current-limiting transistor does not have to handle high output currents; it 'works' at the considerably lower level of the base current of the pass transistor.

A principal constraint on the maximum current permitted is the allowable dissipation in the pass transistor. The largest power dissipation for the pass transistor occurs with maximum rated load current and the minimum rated output voltage (the voltage across the pass transistor is the difference between the supply voltage and the output voltage, and so is a maximum for the condition stated). Be careful to insure that
your design operates within the transistor ratings under all circumstances. With a supply voltage of 35 volts, an output voltage of 7 volts, and a load current of 15 ma the pass transistor dissipation is roughly 400 milliwatts.

**Note 3** Miscellaneous Reminders

a) The lowest voltage which can be regulated is equal to the reference voltage since the sampling fraction cannot be greater than 1.

b) The largest regulated voltage has to be sufficiently smaller than the unregulated voltage (at full load) to avoid having the pass transistor saturate; if the pass transistor is saturated the output voltage simply tracks the collector (supply) voltage rather than being controlled by the amplified error signal.

c) The sampling potentiometer should not draw too much current. This current flows through the pass transistor and so detracts from the available load current. On the other hand the current should be high enough for the lowest regulated voltage to provide enough base current to drive the comparator amplifier.

d) The comparator amplifier has to be designed to operate in the forward active mode with the collector voltage varying over the specified regulated voltage range. The collector current has to be large enough to supply the base current requirements of the pass transistor. On the other hand this current is drawn from the unregulated supply and contributes to the lowering of the poorly regulated supply voltage; it should not be too large.

**Note 4**

Test Specifications: After designing your regulator assemble the power supply and measure the regulation of the unregulated supply; this will serve as a basis for evaluating the effectiveness of your regulator. On the same axis for which the reference regulation is plotted also plot regulation curves for 20, 12, and 7 volts for the regulated supply. Compare these curves meaningfully.

Quantitatively compare the ripple voltage observed before and after the regulator circuitry; do this both with and without the filter capacitor on the bridge rectifier. If the regulator is functioning properly it should correct (at least in part) for attempts to change the output voltage because of supply voltage variations; the ripple is such an attempt. Similarly, reduce the DC no-load supply voltage a few volts to simulate the effect of extreme line voltage fluctuations, and observe the effect on the output voltage.

For the preceding measurements the most convenient load in general is a potentiometer. (A small resistor (measure resistance) in series with the potentiometer having a small known resistance is a convenient way to monitor current.) However when these measurements have been completed replace the load resistance by the transistor 'active' load as illustrated in Fig. 30.11. By varying the base voltage using the triangular waveform from the function generator an electronic swept-current load is available; the regulation curves can be displayed dynamically with connections as indicated in the figure. Make sure the current-limiting circuitry is functioning properly before doing this.
In place of a 'triangular' swept load current apply a step current change, simulating a sudden unexpected load change; use the square-wave output of the function generator with a period sufficiently long to isolate the rising- and falling-edge transients. Observe the settling period, i.e., the time for the load voltage to settle within (say) 1% of final value. How effective is the current-limiting for a sudden short-circuit. Add a 50 µf, 50 VDC capacitor across the load and observe the effect on the step recovery time.

**Note 5** Your report shall include a well-written, clear description of your design procedure as well as the circuit diagrams, test results, and explanations and evaluations. Results of a computer simulation of all the tests should be included in the report and test results compared to these.