mailto: allabout@gernsback.com

WILLIAM SHEETS, K2MQJ, and RUDOLF F. GRAF, KA2CWL

Basic Regulator Circuits

This article will discuss a very basic subject—simple power-supply regulators. Most experimenters will use off-the-shelf power-supply regulators available as IC functional block devices. Actually, for most experimenters, the regulator can usually just be a 7800- or 7900-series IC. You will seldom build regulator circuits, unless your project is a large, high-energy power supply or a very high-powered audio amplifier. Even then, power supplies and high-power amplifiers are often better and more cost effective if purchased ready-made. Many companies provide such items at a reasonable cost, often less than the cost of the large transformers, filter capacitors, and heatsinks. You will also need to obtain PC boards, small parts, meters, and a case. Power supplies are basic, off-the-shelf items.

How "The Wheel" Works

So why discuss regulator circuits? Why reinvent the wheel when someone has already done it, cheaper and better than you can probably do? For openers, it is always important to know how and why "the wheel" works. Eventually today's wheelmakers and wheel engineers will stop designing, improving, and making wheels. If no other wheelmakers and designers replace them, eventually there will be no more wheels. Technology can be lost and forgotten. That is why it is important to know how wheels work or anything else for that matter.

If you do not understand it or have never done it, "old" technology is new to you and something worth exploring. In addition, you just might have fun and learn something new by reading articles like this. Also, you won't become just another technical whiz who cannot solder, use an oscilloscope, and whose electronics knowledge is limited to trendy pseudo-science, the latest in stereos, and what's hot at the computer store or software emporium.

This point made, let's discuss simple, plain-jane power-supply regulator circuits. You will also better understand the black-box ICs you will use in your projects and their various applications. The subject of power-supply circuits is complex and cannot really be adequately covered in a short article. However, by understanding a few basic circuits, you can figure out how some of the more sophisticated supplies operate. Packaged IC regulators such as the 7800/7900 series and the LM723 use these basic circuit ideas in their internal circuitry, in various forms and guises.

More Power To You

A power supply uses a regulator to maintain output voltage or current at specified limits. An ideal power supply would have zero internal resistance (ideal voltage source) or infinite internal resistance (ideal current source) so that the output voltage or current is independent of load. These sources would have to be capable of supplying infinite amounts of power and, of course, exist only in theory. They are used in engineering for analytical purposes.

A real-world supply will have finite internal impedance. This impedance may vary with the load on the supply. The maximum current a voltage source can deliver into a short circuit or the maximum voltage a current source can deliver across a load can sometimes be quite high. For example, a common 12-volt automobile battery can deliver as much as 1000 amps or more into a dead short (and possibly explode in the process).

Constant-current sources are less common. One common application was the use of a constant-current transformer to drive a series street-lighting circuit (used in the past for arc and incandescent lighting applications). These circuits could deliver several kilovolts or more if the circuit were to be opened. The lamps had devices in the circuit such that the normal 120 or 240 volts across the lamp would not have any effect, but the opening of a filament would cause the high voltage to appear across that lamp. The device would effectively short-circuit the lamp, maintaining circuit continuity.

This principle is used in today's Christmas decorations, where 25–50 series-connected low-voltage bulbs have built-in shunts that will conduct when full-line voltage appears across the open bulb, maintaining continuity of the circuit. Both constant-voltage and constant-current supplies can be approximated electronically with a regulator circuit to almost any degree desired, within the current and voltage restrictions imposed at their inputs. Often, both forms of regulation are provided. For example, in a current-limited power supply, the supply provides a specified maximum load current with the output voltage dropping off at heavier loading. The output voltage can exceed the input voltage in the case of switching-type regulators and electromechanical regulators (transformers with motor driven tap switching, etc.), but the linear regulators to be discussed produce an output voltage that is lower than the input voltage.

Therefore, some power will be dissipated as heat. Switching regulators make use of energy-storage components (L and C) and generally have better efficiency than linear regulators, often 65–90 percent or better. In addition, the elimination of heavy, expensive, large 60-Hz transformers will reduce cost size and weight. Eliminating the transformer results in greater circuit complexity and greater circuit noise due to switching transients. This factor often limits the use of switching regulators in applications where noise may cause problems (i.e. low-

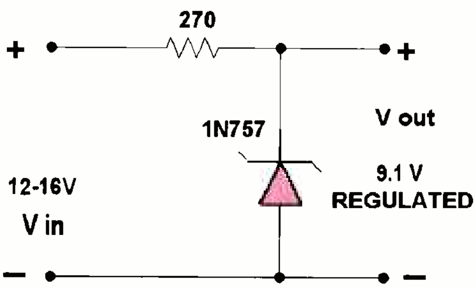


Fig. 1. This schematic is a basic shunt-regulator circuit. A zener diode is placed in parallel with a resistor in order to regulate the 12–16 volt input to a 9.1-volt output.

level audio and RF circuits operating at frequencies in the noise spectrum of the power supply).

Keep The Noise Down!

Remember that 60-Hz rectifiers operating into large-capacitor input filters can produce large AC-line current spikes and RF noise, especially if fast rectifier diodes are used. This 60-Hz noise can be as bad as a poorly designed switching supply might produce, making 60 Hz noise well up into the HF radio spectrum. So 60-Hz supplies are not necessarily always as noise-free as you may think. Linear regulators will usually yield lower noise, ripple, and better regulation when a really pure DC supply is needed. Regulator-circuit complexity is reduced greatly by the many available regulator IC devices, and a relatively complex regulator of high performance is easily placed in an IC chip. IC regulators supplying fixed voltages of 3–24 volts at currents from 100 mA up to several amps are readily available and cheap, and they can easily be interfaced to higher-power bipolar or FET devices for high-current supplies.

These regulators are commonly three-terminal devices (input, common ground, and output) and often only require a few external peripheral components (the common 7800- and 7900-series regulators only need two capacitors of 0.01 to 1 mF, and only under certain conditions.) These regulators will easily provide well under 1-percent regulation and offer some current-limiting and built-in fault protection. Switching regulators and voltage converter ICs that use a few peripheral capacitors and little else are also available. These low-cost regulators and converters make it practical and easy to supply individual circuits with special voltages not supplied by a systems main-power source, such as higher or opposite polarity voltages. This setup may often circumvent power supply limitations, allowing more design freedom.

The simplest regulator makes use of a two-terminal device that has the property of maintaining a constant voltage across it (zener diode, gas-discharge tube) or a constant current through it (field effect transistor, temperature-limited vacuum diode). The basic circuit is shown in Fig. 1. A zener diode is generally used, although gas-discharge devices (common in vacuum-tube circuitry, but relatively rare nowadays) are sometimes used for higher voltages. For still higher voltages, these devices can be connected in series in any combination. A current-limiting (ballast) resistor must be used; as these devices will attempt to maintain constant terminal voltage, drawing whatever current is needed from the supply to do so.

Efficiency Is Key

The impedance of the regulating device can be very low, and it can easily draw destructive amounts of current without a limiting resistor. This circuit (Fig. 1) is a shunt-type regulator, as the regulating device is shunted across the load. Often, for low-power applications where only a few milliamperes of current are required and regulation (percentage change of voltage or current under differing loads) of a few percent is adequate, this approach will work very well. The efficiency is generally poor, especially at light loads, since the total current through the ballast resistor is the sum of the load current and the regulator current needed to maintain the voltage. When the load is removed or varies, the excess current must flow

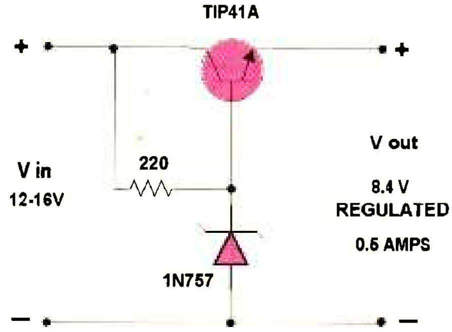


FIG 2a
SIMPLE REGULATOR

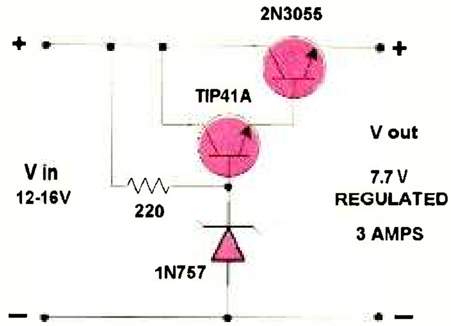


FIG 2b
SIMPLE REGULATOR
FOR HIGHER CURRENT

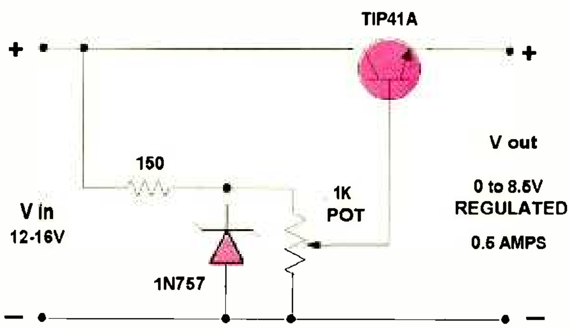


FIG 2c
SIMPLE ADJUSTABLE REGULATOR

Fig. 2. Here are three regulator circuits that incorporate transistors. All of the circuits can handle an input of 12–16 volts. Each successive circuit grows slightly more complex.

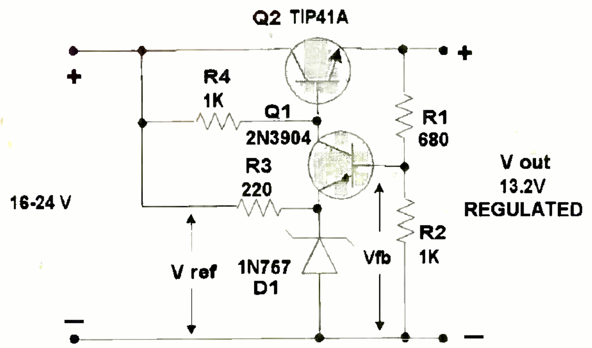


Fig. 3. This is an example of a simple feedback regulator that uses a single transistor-error amplifier. Resistors R1 and R2 perform as a voltage divider that is used to sample the output voltage.

through the regulator. While not a problem in a circuit such as a receiver-local oscillator drawing only a few milliamperes, it would be a problem in a circuit such as a small digital system drawing 1 amp at 5 volts.

In certain cases (LED displays, on-off controls), the system may draw less than 50 milliamps in standby and 1 amp while active. A zener-diode regulator would be very inefficient, since around 1 amp would have to flow through the zener when the system was inactive and not drawing its operating current. If the input voltage was 12 volts, the efficiency of the 12V to 5V regulator would be very poor with over 1 amp constant load on the 12-volt supply, even when the 5-volt load was light. This would be 12 watts or more of useless heat generation, a very inefficient situation. A solution is to use an active regulator that does not require so much current to operate.

However, note that there will always be some voltage drop across the regulator. The regulator circuit is an amplifier and will therefore need some voltage to operate. The base-emitter voltage of the pass transistor has a value of 0.6 to 0.7 volts, and there will be some voltage drop in the bias resistors. The input voltage must always have a minimum value, generally 2 to 5 volts, above the maximum expected output voltage; and it must never fall below this voltage or regulation will be lost. This minimum voltage must be maintained at maximum load, under minimum-input line-voltage conditions. Instantaneous variations due to input-supply ripple, load transients, etc. below this level will cause loss of regulation ("drop-out").

In Fig. 2A, a transistor connected as an emitter follower is used to reduce the current drawn by the regulator device. The zener diode has 10 or 20 mA flowing into it. This voltage is fed to the base of the transistor, called the "pass" transistor, as it is used to pass the load current. It can be a large power transistor capable of handling several amps of current. The load current consists of the collector current, which is the lion's share of the current, plus the base current. The base current is equal to the collector current divided by the DC gain (or β, typically = 50) of the transistor. With a β of 50 and a load current of 1 amp, the collector current would be $\beta/(\beta+1)$ of 1 amp or 50/51 amps and the base current would be $1/(\beta+1)$ or 1/51 of an amp. This is a little less than 20 mA. The current flow is shown in Fig 2A.

Figure 2B shows how an intermediate transistor can act as an intermediate stage in case the pass transistor is a very high-current unit. Note that with no load, the only current drawn by the circuit is that of the zener diode. Also note that by placing a pot across the zener diode and connecting the wiper to the base of the transistor, a variable output voltage may be obtained (see Fig. 2c).

The problem with this circuit is that it is not any better (actually, slightly worse) a regulator than the zener diode. There is no mechanism to guarantee the output voltage to the load. In addition, a small drop in output voltage occurs due to the base-emitter drop in the pass transistor (0.6 to 0.7 volts per transistor typically). There is additional resistance drop in the potentiometer if used for varying the output voltage. This resistance causes some loss in regulation. The regulator cannot "know" if there is a drop in the output voltage. What is

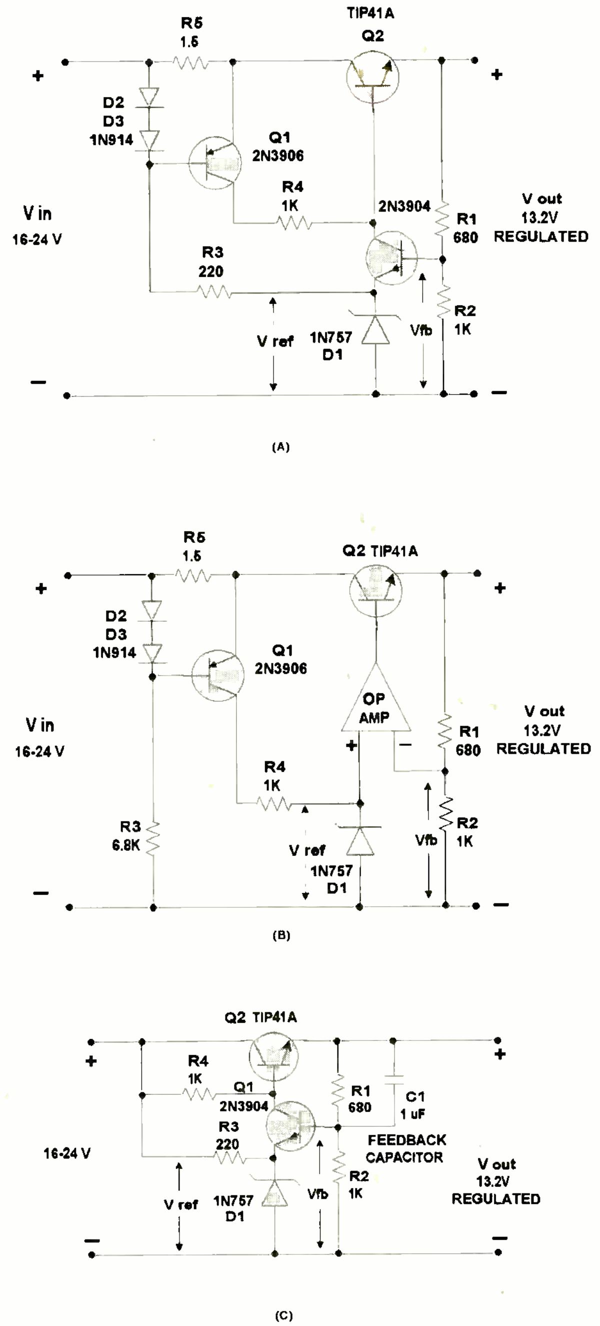
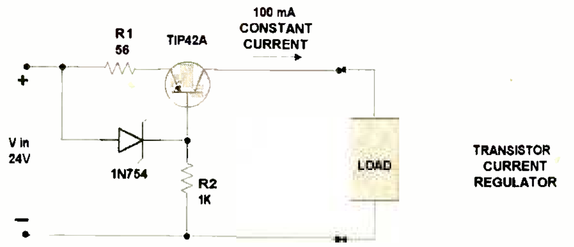
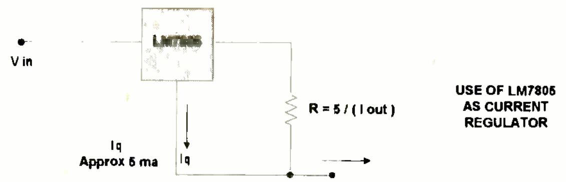


Fig. 4. These are three regulator circuits that each employ a unique method of tweaking the output—current-limiting transistor networks, improved regulation through the use of an op-amp, and improved transient regulation using a capacitor.





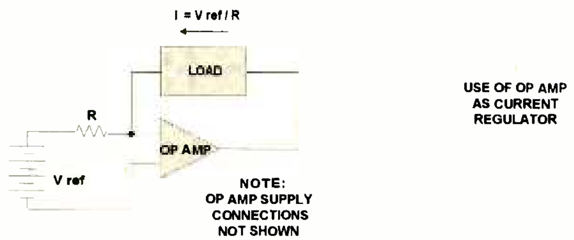


Fig. 5. The circuits above are examples of constant-current regulators. One circuit uses an LM7805 to regulate the output power, while the other circuit uses an op-amp for the same purpose.

really needed is some way of sensing the output voltage, comparing it with a fixed reference, and automatically adjusting the output voltage to the desired value. This requirement implies a feedback or servo system that will act to control the output voltage. We will show you a very basic way to do this with a few additional parts.

A very basic feedback regulator in which the output voltage has some say in its exact level is shown in Fig. 3. A voltage divider, R1 and R2, samples the output voltage and feeds it to the base of transistor Q1. The emitter of Q1 is held at a fixed and regulated (we hope) voltage produced by the drop across zener diode D1. This drop is produced by bias current from R3 and the emitter current of Q1. Should the output voltage drop, Q1 will be turned off, drawing less current through bias resistor R4. The collector voltage will rise, increasing the voltage at the base of pass transistor Q2 and, therefore, the emitter of Q2, which happens to be the output terminal for the power supply regulator. This rise in voltage will be passed to the base of Q1, compensating for the initial drop. The overall effect will be the stabilization of the output voltage.

No Such Thing As Perfect

However, this compensation is not perfect. The regulator circuit is a feedback amplifier with finite gain. Since the voltage gain comes mainly from Q1, the circuit may have a net open-loop voltage gain of 20–100 or so—depending on the gain of Q1, the power-supply load, the impedance of the zener diode, and other factors. Loop gain would be defined as the product of the total gain multiplied by the feedback factor. The feedback factor in this case is the ratio R2/(R1+R2). The higher the loop gain, the better the regulation, all else being equal. In practice, this circuit will produce an improvement in regulation of around 10X or better over that of the previous circuits. There are limitations with this circuit, some of which are:

- Output voltage cannot be less than the zener voltage plus the base-emitter drop in Q1
- No means of current limiting or short-circuit protection exist
- Maximum regulated output voltage is limited, as there will always be a voltage drop across R4
- Regulation is progressively poorer as output voltage increases, since feedback factor R2/(R1+R2) decreases
- Since some of the bias currents (through R3 and R4) come from the unregulated side, output will be influenced by input voltage variations, degrading regulation

These problems can be solved with circuit changes and additional components. A solution to the first one is to use a low zener voltage, although the most stable zeners are around 5 to 8 volts. It is possible to use a separate floating power-supply circuit to provide voltages below (negative) the ground level and return R2 to a negative voltage instead of ground. Place a resistance in series with the input; and the voltage drop across this, a function of load current, can control the regulator output. Additional transistors or an op-amp can be used to get more open-loop gain

Some Solutions

Figure 4A shows one method by which current limiting can be added. Resistor R4 is in series with a PNP transistor, Q3, acting as a current source. This resistor is necessary to limit the current supplied to D1. Diodes D2 and D3 produce a fairly constant voltage that is 1.4 volts below the regulator input voltage, at the base of Q3. As long as the voltage drop produced across sampling resistor R5 by the pass-transistor collector current is less than about 0.7 volts, Q3 conducts. As the load current increases, the drop across R5 will increase to the point where it starts cutting off Q3. Now, R4 can pull down the base of pass transistor Q2, causing the regulator output voltage to drop off. Since this current also biases reference zener diode D1, the reference voltage also drops—reducing the output voltage. In this way, the current drawn from the regulator can be limited. About 0.7 volts drop across R5 will start current limiting, so R5 should have the value of 0.7/(Current Limit), about 0.7 ohms for 1 amp, 0.35 ohm for 2 amps, etc.

Looking at Figure 4B, we see how an op-amp can be added to improve regulation. Note that the gain will now be very high. However, frequency compensation will probably prove necessary in some cases, as loop phaseshift may be such as to cause oscillation at some or all load conditions. The bias for the op-amp may be obtained from the regulator itself, although generally a separate auxiliary low-power supply is preferable. The op-amp may need a negative source, especially if the regulator is expected to be variable or to go down to

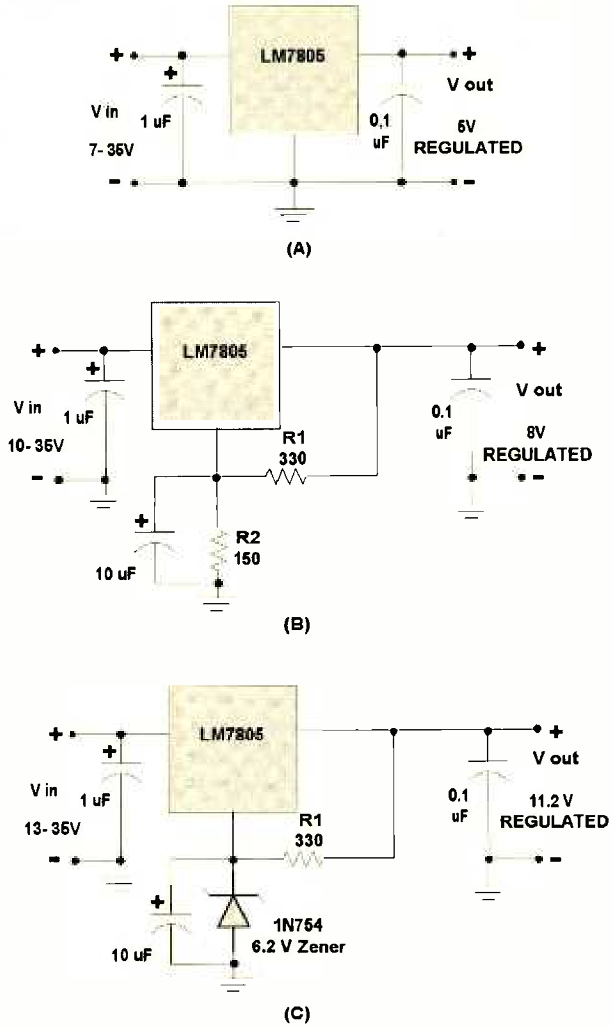


Fig. 6. All three of the circuits above contain the LM7805 voltage regulator. The LM7805 is widely used, affordable, and practical. As you can see, a variety of voltages can be used with the popular regulator series.

zero volts output, as in a laboratory power supply.

A way to improve transient regulation of the regulator in Fig. 4 is shown in Fig. 4C. The capacitor provides increased feedback for AC signals. Note that this may cause problems with loop stability in some applications using op-amps.

Capacitors can and often are placed across the regulator output terminals to reduce residual ripple and to ensure low output impedance, but be aware that capacitive loads may cause problems with loop stability. Also, if the input voltage falls below the output voltage due to a short or component failure or sudden removal of the input voltage, this capacitor can discharge back into the regulator, possibly damaging the pass transistor emitter-base junction due to reverse over-voltage. A protection diode is often added across the pass transistor to guard against this type of fault.

Referring to Fig. 5, we see a few simple constant-current regulators. The collector current of a transistor can be held constant by the use of a zener diode and emitter resistor, as shown in Fig. 5A. The emitter current equals the zener voltage less the base emitter drop (about 0.6 to 0.7 volts) divided by the emitter resistor. The current will remain constant within a percent or two as long as the load voltage stays below the input voltage minus the zener (or other reference) voltage plus the saturation voltage of the transistor. The maximum output voltage under specified current conditions is sometimes called the compliance. This principle is widely used inside ICs where a high impedance current source is needed.

Figure 5B shows the use of a 5-volt regulator IC to produce a constant-current source. The three-terminal regulator maintains 5 volts across the current-sensing resistor. A small current flows out of the common lead, but this is typically only 5 mA and is fairly constant. A power transistor can be used to handle higher currents, if needed. With the 7805 regulators and adequate heatsinking, a constant current source up to about 1 amp can be obtained.

Using an op-amp, you can produce a constant current (see Fig. 5C). Since the sum of currents at the summing junction of an ideal op-amp must be zero, the op-amp will deliver to the load whatever voltage is needed to force a current through the load equal to the reference current. The reference current is equal to V_{in}/R1.

One application of this principle uses a high-voltage capability op-amp to check breakdown voltages of semiconductor junctions. The desired current is fed to the op-amp input, and a voltmeter connected to the op-amp will read the voltage needed to force this same current through the semiconductor junction. Since this current can be constant, it makes safe, nondestructive testing possible.

Since ICs can have many transistors and resistors built in, additional regulator features are easily added. Numerous manufacturers publish data sheets for their IC devices that show some or all of the internal circuitry. It is often necessary to provide this information for applications and interfacing not shown in their data sheets or discussed in their application notes. You might want to get some of these data sheets and examine the internal circuitry of a few of these chips. You will be better able to use them in original designs and not be limited to "cookbook" published circuits that are not exactly what you want. Yes, you really do have to know what is going on in the black box if you ever are expecting to do anything original. Working blind may get you into problems and hours of futile effort that can often be avoided if you know what is happening.

Ample And Affordable Supplies

A lot can be done with inexpensive three-terminal regulators. Figures 6A, 6B, and 6C contain a few circuits that use the

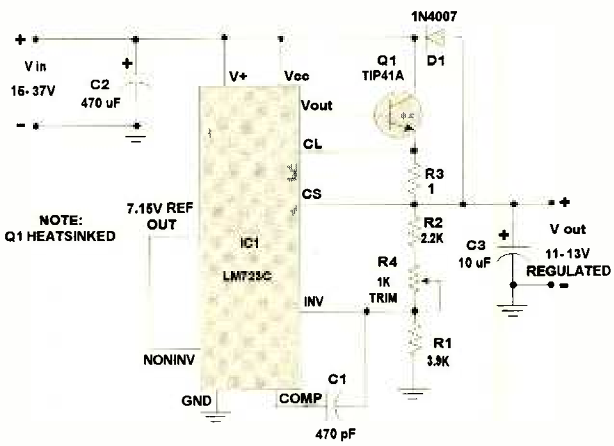


Fig. 7. The LM723 IC is another favorite for building power supplies. Using resistors, the output voltage can be programmed to fit your needs. The chip has an internal reference of 7.15 volts, nominally.

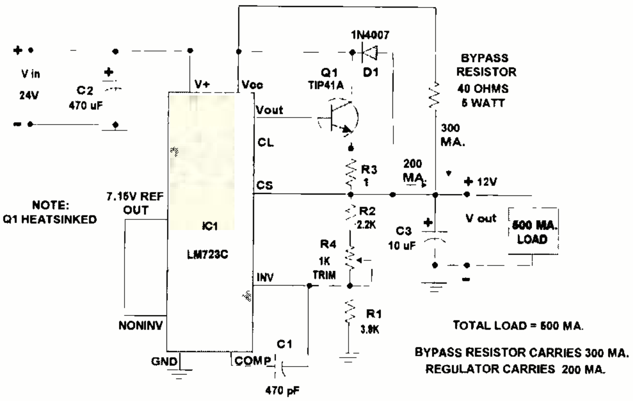


Fig. 8. A resistor is placed across the regulator in the circuit above in order to lessen the dissipation and heat load that the linear regulator experiences during performance.

7805. These widely-used regulator IC chips are probably the easiest for the experimenter to obtain. They come in versions from 100-mA TO-92 and surface-mount types to large TO-3 types good for several amps. While all these are made in various output voltages from 3 to 24 volts, it is possible to get output voltages higher than their rated output without much sacrifice in performance. For example, you need 8 volts from a 5-volt regulator. While an 8-volt regulator is available (LM7808), your local electronics supplier may not stock them, your other suppliers have a minimum order, or you may have plenty of 5-volt units and not want to buy 8-volt units for just one application. You can fool the LM7805 into delivering 8 volts, using the circuit in Fig 6A. The three-terminal regulators are referenced to ground, and they draw some operating current (around 5 mA).

By placing a resistor(s) in the common ground lead, you can lift the common terminal above ground a few volts. We recommended using two resistors as shown and running about 15–20 mA through the voltage divider. By making R2 a pot, you can get an adjustable output voltage. Note that a zener diode can also be used here, and the regulated output will be 5 volts plus the zener diode voltage. However, remember that the regulator is designed to keep the voltage between its common terminal and output terminal dead constant, not the voltage between output and ground. You will get some small loss of regulation using this circuit, but for most applications it is not serious and saves money. Also, there will be no need to stock 8-volt units. You can get up to about 10 volts with excellent performance, although higher voltages are possible if some fall-off in regulation is allowable. For higher voltages (ouputs in the 12- to 24-volt range), use the LM7812—very common, cheap, and widely available. Again, it is a good idea to use a protection diode between input and output to guard against accidental reverse voltage, if this is a possibility.

Voltage In, Voltage Out

The LM723 has been around a long time and is one of the most widely used ICs for building power-supply regulators. By itself, the LM723 will handle up to 150 mA, with outputs from 2 to 37 volts. However, dissipation in the regulator is limited to 660 to 900 milliwatts, depending on the package. Figure 7 shows a typical application of this device as a 12-volt regulator for a small-bench power supply. The LM723 has an internal reference of nominally 7.15 ± 0.20 volts (± 0.35 V for LM723C version). By selecting a few resistors, you can program the output voltage to suit.

A power transistor is used to handle most of the output current, and a resistor in the emitter is used as a current-sensing device for current-limiting purposes. An internal transistor in the IC is turned on if this voltage drop exceeds about 0.6 volts, providing current-limiting action via internal circuitry. Capacitor C1 is a compensating capacitor that maintains loop stability. It is in the feedback network in the internal error amplifier, between output and the inverting input. Since the reference voltage is 7.15 nominal and is applied to the non-inverting input of the error amplifier, at equilibrium, the input to the inverting amplifier must also be very close to 7.15 volts (assuming high error amp gain).

Therefore, for 12-volt output, the voltage divider made up of R1 and R2 must provide 7.15 volts at the junction of R1 and R2. Resistor R2 is not critical, and almost any reasonable value can be used. For practical reasons, between 1 and 10K is usually used. Choosing 3.9K for R2 will require R1 to be 2.65K, and 2.7K is a close standard value. This divider will yield 12.1 volts, subject to reference voltage tolerance (about 5%). Resistor tolerances will add to this, so, in practice, using a 2.2K resistor in series with a 1K resistor for R1 will allow trimming of output voltage between 11.2 and 13 volts. Resistor R3 must provide 0.6 volts drop at 500 mA current-limiting, so a 1.2-ohm resistor is needed. In practice, a 1-ohm resistor will allow 600 mA maximum, giving a little extra margin. Component Q1 must be adequately heatsinked, since at 12 volts output and 20 volts input as much as 4.8 watts will be dissipated in Q1 (8 volts drop at a possible 600 mA).

Under full-load conditions (12V at 500 mA), with 20 volts DC in, 4 watts will be dissipated in Q1. A short-circuit on the output could produce 12-watts dissipation if the regulator input were 20 volts. This possibility must be considered if short-circuits are likely. Also, D1 is used to provide a way for energy stored in the load (capacitors, inductive spikes, accidental application of higher voltage due to component failures in load) to dump into the large input filter capacitor instead of the regulator. This situation can occur also when the DC input supply is shut down. Load regulation with the LM723C in this circuit should be 20 mV or better, no load to full load (500 mA), with about 2–3 mV change during a 5-volt change in input voltage (15 to 20 volts). As can be seen, a pretty good performance can be obtained with few components and a sim-

NORTH COUNTRY RADIO:
A HAVEN FOR WIRELESS BUFFS

Graf and Sheets are no strangers to the pages of Gernsback. Their educational projects, such as the *RF-Field Strength Meter* and the *MPX2000* FM Transmitter, can be found at **North Country Radio**. Established in 1986, this company offers projects related to amateur TV transmitters/receivers, AM and FM transmitters/receivers, video cameras, and numerous other subjects. Visit the Web site at **www.northcountryradio.com** for more information.

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Engineering and Technical Support
PO Box 200, Hartford, NY 12838
Voice/Fax: 518-854-9280
e-mail: support@northcountryradio.com

ple circuit. We highly recommended consulting the manufacturer's application notes and data sheets (you can usually download these on their Web sites), as there are many other configurations and applications of these devices.

By using auxiliary power transistors and adequate heatsinking, you can construct power supplies delivering commonly used supply voltages (12, 24, or 32 volts) at up to 50 amps or more. However, remember that at these high power levels there may be considerable power dissipation in the regulator system, so the regulator should be operated at as low a voltage drop as possible consistent with minimum expected input voltages at maximum load. In variable voltage output regulators, the worst case is full load current at minimum output voltage, since this case produces the largest voltage drop and power dissipation in the pass transistors. One should always consider the possible use of switching supplies, which are more efficient and less bulky, at high (>25 watt) power levels. The tradeoff point is generally somewhere in the 10- to 100-watt range, but this is subject to various other considerations. The elimination of 50- or 60-Hz magnetics, large heat sinks, and cooling fans can greatly reduce cost and weight.

Also, a switching type pre-regulator before the main regulator can take some of the dissipation and heat load off the linear regulator. Another method, if the load is fairly constant, is to use a resistor across the regulator as shown in Fig. 8. Some of the load current passes through this resistor, reducing dissipation in the pass transistors. The total heat generated still remains the same, of course, but power resistors are less delicate than power transistors. The load must never be smaller than the current passing through the shunt resistor, or else the regulator will be cut off and the load voltage will rise above the desired voltage.

There is much more to power supplies than discussed here, but this information should prove a useful start for most hobbyist and experimenter power-supply requirements. These circuits can be built and experimented with, as there is no substitute for hands-on experience. The ability to design and build exactly what you need can be very useful and can save some money. P