The Versatile LM723

This may well be the world's greatest power-supply IC— if you can understand what it can do

By J. Daniel Gifford

One of the oldest and most repetitious problems in electronics is that of regulating power supplies. Whether for bench or project use, regulated supplies have become more and more necessary, due to the ever more finicky requirements of ICs and discrete circuits. While small-size, high-conversion-efficiency switch-mode power supplies have become popular for commercial use (especially in computers), the traditional linear power supply will probably remain the choice of hobbyists and experimenters in the forseeable future, basically due to its relative ease of design and construction.

A linear power supply is best designed from scratch, using individual op amps, precision voltage references, and hand-selected transistors. Since this is obviously an overkill approach for all but the most demanding circuits, a better alternative for the experimenter is to use an "all-in-one" IC to do the job.

Of the many all-in-one ICs available, three types are the most common and least expensive. The first actually represent a group of devices in the LM78xx and LM79xx, along with the nearly identical LM340/320 fixed-voltage three-terminal types. These easy-to-use devices are often found in simple ±5- and 12-volt supplies so popular in experimenter projects and commercial products. For variable and adjustable supplies, there is also the popular three-terminal LM317.

The third all-in-one IC is the LM723, a "precision voltage regulator" that is one of the oldest and least expensive ICs around and is also one of the most versatile! It is so versatile, in fact, that it can replace *all* other linear power-supply chips and do a better job for less money. (Many mail-order houses sell prime 723s for about 50¢, even Radio Shack's price is only 99¢.)

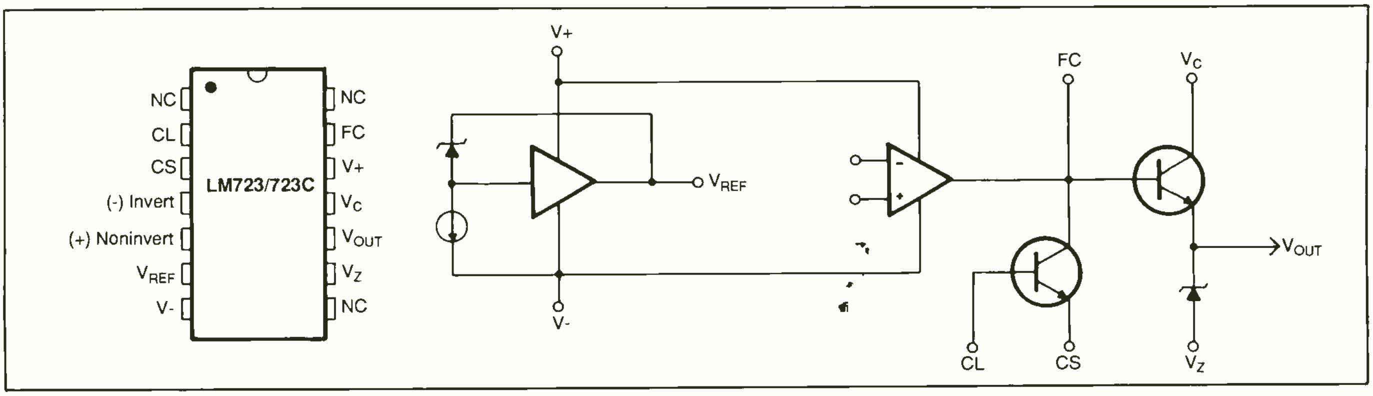
If you're like most hobbyists, you've probably skipped over the 723 in favor of the LM317. The LM317 is very easy to use because it requires only two resistors and an optional capacitor to provide a regulated 1.2-to-37-volt output. The 723 is also easy to use, though not as easy as the 317. It would be a lot easier to use if it didn't suffer from poor documentation by the manufacturers of the device. Current data and application notes are so confusing that many potential users of the 723 shy away from it for lack of information they can understand.

In this article, we will cut through the confusion about the 723 and take a detailed look at this versatile IC chip. Once you understand how flexible and talented this device is, you'll probably never use any of the other ICs for your fixed and variable low-voltage power supplies again.

Regulated Power Supplies

A regulated power supply requires four things: a source of clean, ripple-free dc power, a precision voltage reference, a means of sampling the output voltage, and a means of comparing the reference and output volt-

Fig. 1. Pinout and internal details the LM723/LM723C.



ages and correcting the latter as the load and supply voltage fluctuate. The three-terminal fixed-voltage regulators have all but the first of these built into them, with the output sampling fixed for a particular output voltage (usually 5, 12, 15, 18 or 24 volts). Though the LM317 is similar in design, its output sampling is controlled with two external resistors.

The major drawback of all three-terminal regulators is that current limiting is internally fixed and is, thus, not adjustable. Hence, the only way to lower the level of current limiting in these devices is with external circuitry. The external circuitry can be a simple "brute-force" limiting resistor or, for variable-voltage supplies, a relatively complex circuit using op amps and a negative-voltage supply. Neither type of circuit is particularly satisfactory because a great deal of heat must usually be dissipated by the resistor, while the external operational-amplifier circuit is unnecessarily complicated.

Enter the LM723. Not only does this device have a precision voltage reference, an output comparator (error amplifier) and all of the circuitry needed for adjustable current limiting on-board, this circuitry is only partially interconnected. Most of the circuit connections are made externally, which lets you tailor your power supply to suit particular requirements. Obviously, this results in a more complex circuit layout than is needed for three-terminal regulators. But the enormous flexibility gained by using the LM723 more than makes up for the added complexity.

Inside The LM723

Two versions of the 723 are available, as with nearly all ICs: the military-grade LM723 in a ceramic case and featuring an extended temperature range, and the more common LM723C in a plastic case with a 0-to-70-degree C temperature range. The pinout of the device is shown in Fig. 1, along with a diagram of the internal circuitry. At the left of the diagram is the voltage reference circuit, the heart of which is a nominal 7.15-volt zener diode. (The specified range for the LM723C is 6.80 to 7.50 volts.) The zener is connected to a buffer amplifier and is biased by a constant-current source to keep the reference level stable under varying supply conditions. For the most part, this portion of the circuit can be ignored, because the only external portion of the reference circuit is the V_{ref} output at pin 6, which is a stable 7.15 volts for external reference use.

In the center of the diagram is a regular op amp with both its inverting (−) and noninverting (+) inputs externally available at pins 4 and 5. This "error" amplifier and the reference circuit are powered via the V+ and V− at pins 12 and 7. Maximum supply voltage to the 723 must not exceed 40 volts, but the IC is protected against spikes of up to 50 volts that are no longer than 50 ms in duration. Sustained voltages greater than 40 volts will damage the IC.

Minimum supply level is about 9.5 volts; any lower than this will impair the reference voltage's accuracy and stability. Supply voltage must always be at least 2.5 volts higher than the maximum desired output voltage, due to common-mode voltage range limitations of the error amp.

The output of the error amplifier is connected to the base of an internal npn pass transistor. Both the collector and the emitter of this device are externally available at V_c and V_{out} pins 11 and 10. In most circuits, the V_c pin will be connected to the same supply as the V+ pin; indeed, these pins are side by side to facilitate such a connection. Having separate pins permits use of a separate output supply source, which can be an advantage under some circumstances. The internal pass transistor can pass up to 150 mA over the 723's full output voltage range. (Higher output currents can be obtained by using an external pass transistor.)

Also available at FC pin 13 is the connection between the error amplifier's output and the pass transistor's base. This connection is provided because the error amplifier isn't internally compensated like a 741. An external capacitor between pin 13 and either the inverting input or (more rarely) V− or ground stabilizes the amplifier.

A second internal npn transistor has its collector connected to the base of the pass transistor and has its base and emitter externally available at current limit (CL) and current sense (CS) pins 2 and 3. This transistor is the current-limiting sensor. The CL and CS pins are connected across a series output resistor. When current drawn from the output is sufficient to cause a 0.65-volt difference across the resistor, the sense transistor turns on and either reduces or cuts off the error amplifier's drive to the pass transistor. This limits output current flow to the selected level. Limiting is basically the same whether the internal pass transistor is used or an external pass device is added for up to 10 amperes or more of output current.

The only remaining element of the 723 is the zener diode connected to the pass transistor's emitter, with its anode available at V_z pin 9. The voltage rating of this diode is nominally the same as the reference voltage and is primarily used to offset the output voltage when the 723 is used as a negative voltage regulator.

Voltage Adjustment

Setting the output voltage of the 723 is simple, though from the application sheets, you would never know it. Of the three basic ways to set the 723's output, two are best suited to fixed-voltage regulation, and the third is the all-around best technique and is best suited to variable or adjustable output supplies.

With respect to voltage, the 723 has three inherent limitations. The first is the maximum 40-volt differ-

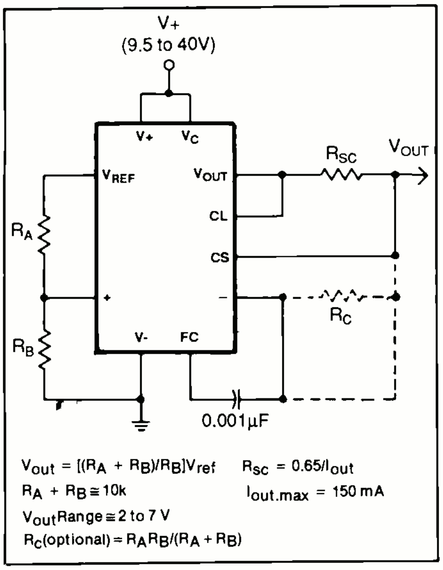


Fig. 2. The basic circuit for low outputs between about 2 and 7 volts.

ential that can be applied between the V+ and V− pins. There's no way to get around this, although the 723 can be used to regulate potentials up to 250 volts or more by offsetting its V− voltage.

Next is the 723's 2.0-volt lowest possible output referenced to the V− pin, which is due to common-mode voltage range limitations of the error amplifier. But an output adjustable to 0 volt is possible by offsetting the IC's V− pin by 3 to 4 volts below ground.

A final voltage limitation is that the maximum is about 2.5 volts below the V+ supply level, which is again due to common-mode limitations. Thus, for an output of 20 volts, V+ must be at least 22.5 volts. With a V+ of 40 volts, maximum output is about 37.5 volts.

Shown in Figs. 2 and 3 are the two most basic circuit configurations that are most suitable for fixed-output and limited-adjustability supplies. In all circuit configurations, V_{ref} is coupled to the error amplifier's + input and the output voltage is coupled to the amp's − input. To adjust the regulated output voltage, the reference voltage is divided before connection to pin 5 (Fig. 2), or the output voltage is divided down before connection to pin 4 (Fig. 3).

In Fig. 2, with the output voltage connected directly to the error amplifier's − input, the output voltage is held equal to the actual reference voltage at the + input. If the reference voltage is connected directly to this input (if R_A = 0 ohm), the output voltage will be equal to the reference, or about 7.1 volts. If R_A and R_B are equal, the reference voltage will be divided in half, and the output will be about 3.5 volts. Thus, it's the *ratio* of R_A to R_B that determines the output voltage, as the first equation in Fig. 2 shows. The total value of R_A and R_B should be about 10,000 ohms, but this isn't critical.

For maximum simplicity, the output voltage can be connected directly to the error amplifier's + input. However, for maximum thermal stability, resitor R_C should be added to the circuit. The value of R_C to have maximum stability is determined by dividing the product of R_A and R_B by the sum of their values in Fig. 2.

Since the output range of this circuit is from 2 (the error amplifier's lower limit) to 7 volts (the reference level), it's best used for low-voltage fixed-output regulation. (Ignore R_{SC} in this and the following figures for the time being.)

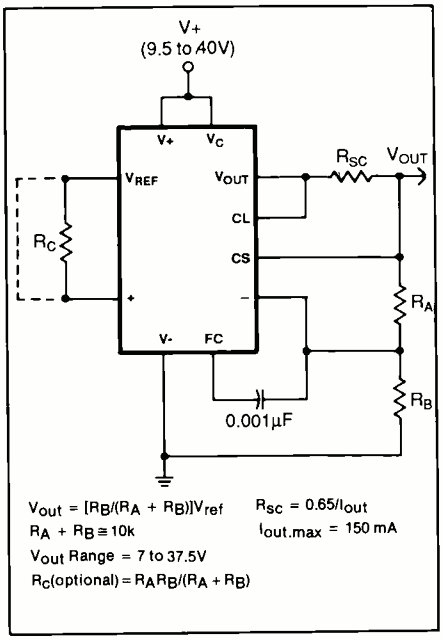
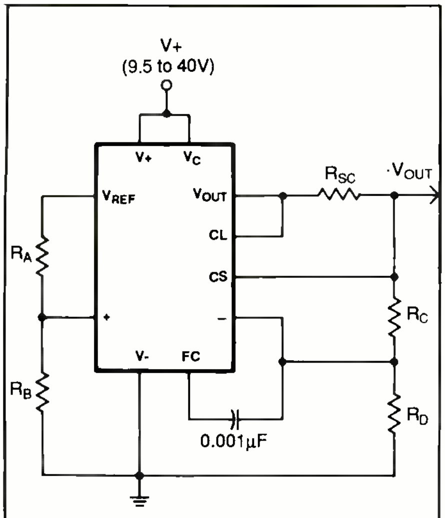


Fig. 3. The basic circuit for high outputs between about 7 and 37 volts.

Figure 3's circuit is the exact opposite of Fig. 2's. Here, V_{REF} is connected directly to the error amplifier, and the output voltage is divided down before reaching the amplifier's − input. With the output voltage connected directly to the error amplifier (R_A = 0 ohms), output voltage will be equal to V_{REF}, or about 7.1 volts. If R_A and R_B are equal, the output voltage will be divided in half before reaching the error amp and the absolute level will thus be double the V_{REF} level, or about 14.1 volts.

Here again, it is the ratio of R_A to R_B that determines the output voltage. The output range of this circuit is from about 7 (the reference level) to about 37.5 volts (assuming a 40-volt supply). As with the Fig. 2 circuit, R_A and R_B should total about 10,000 ohms, and R_C is optional but recommended for stability. This circuit is best used for higher-voltage, fixed-output and limited-adjustability supplies.

A major problem with the 723's data sheets is that they show only these two configurations, with no hint given as to how to bridge the 7-volt barrier. It's quite easy, as you might have guessed. All you have to do is divide down *both* the reference and output voltage inputs! This is illustrated in Fig. 4, where R_A and R_B divide V_{REF} down to any convenient level. The voltage thus delivered to the error amplifier's + input sets both the minimum output voltage and the "multiplier" for the output voltage divider string consisting of R_C and R_D and is used to vary the output voltage. Minimum output (with R_C = 0 ohm) is equal to the voltage at the − input, which cannot be lower than 2 volts. Maximum voltage, assuming a V+ of 40 volts, is 37.5 volts. Thus, this configura-



$V_{out} = V_{ref}[R_B/(R_A + R_B)][(R_C + R_D)/R_D]$

$R_A + R_B \cong R_C + R_D \cong 10k$

$V_{out.min.} = V_{ref}[R_B/(R_A + R_B)] \geq 2V$

$V_{out.max} = V+ - 3V$

$R_{SC} = 0.65/I_{out}$

$I_{out.max.} = 150\,mA$

Fig. 4. A configuration for any output between 2 and 37 volts.

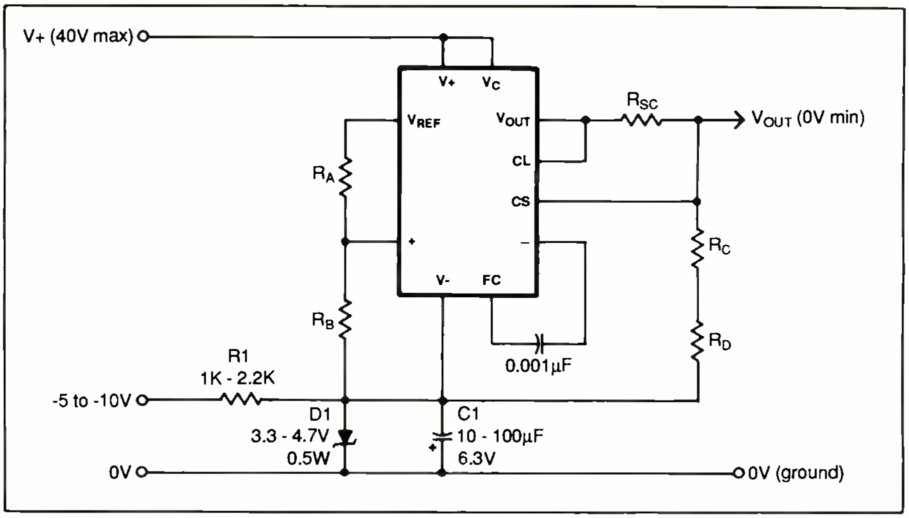


Fig. 6. A negative bias supply permits adjustment of 723's output down to 0 volt. Negative supply can come from an extra tap on power transformer.

tion can be used for a variable supply that can be swept from 2 to 37.5 volts with a single control.

One drawback is that R_A and R_C are difficult to optimize for maximum thermal stability. But this is a minor problem because the 723 has good stability even without optimization.

Note in Figs. 2, 3 and 4 the compensating capacitor connected between the FC and − input pins. Although the recommended all-around value for this capacitor is about 0.001 µF, it can range from 100 pF to 0.01 µF without causing difficulties.

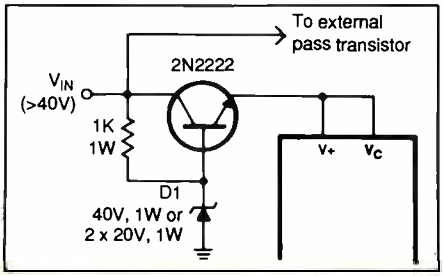


Fig. 5. Preregulator circuit used to protect LM723 against greater than 40 volts at V+ input terminal.

There is often a bit of a problem, particularly with high-voltage, high-current supplies, with keeping the supply to the 723 within the 40-volt limit. Although designing the supply transformer to suit the application is one way to go, a much easier approach for hobbyists is shown in Fig. 5. Here, a preregulator circuit is used to limit the 723's supply. A zener-resistor string biases a medium-power npn transistor to provide a limited and semiregulated supply to the IC.

A 40-volt zener diode would be ideal in the Fig. 5 circuit. Because this is not a common value two 20-volt zeners are used for *D1*. With the 0.7-volt drop across the transistor, the resulting supply to the 723 will be about 39.3 volts, assuming a 40-volt V+ supply. If necessary, exactly 40 volts can be obtained at the IC's inputs by hand-selecting the zener diode(s) or by adding a forward-biased 1N914 diode to the zener-diode string to exactly compensate for the 0.7-volt drop.

A limitation to the preregulator trick is that the preregulator transistor must carry the entire current that passes through the regulator and the internal pass transistor, which can be as high as 160 mA. This should not be a problem as long as a suitable transistor is used in the preregulator. Even so, there's a better way to accomplish your aim.

If an external pass transistor with a V_{CE} higher than the raw dc supply level is used, the preregulator can be used to provide power to only the 723 itself, and the raw dc is passed to the external transistor's collector. This drops the current required from the preregulator to about 5 mA or less.

Another voltage-related problem with the 723 is that its minimum output of 2 volts may be a drawback in some applications, particularly with variable-output bench supplies. Since the ony reason for the 2-volt minimum is the common-mode range limits of the error amplifier, the problem is easy to circumvent. As Fig. 6 shows, all you need do is offset the 723's V− level by a few volts negative with respect to power ground.

Raw dc of about −5 to −10 volts is regulated and stabilized by low-voltage zener diode *D1* and capacitor *C1*. All of the 723's negative connections (V− pin and the bottoms of the reference and output divider strings) are connected to the resulting −3 to −5-volt rail instead of to 0 volt. The common-mode limit of the error amplifier doesn't vanish; it's now offset

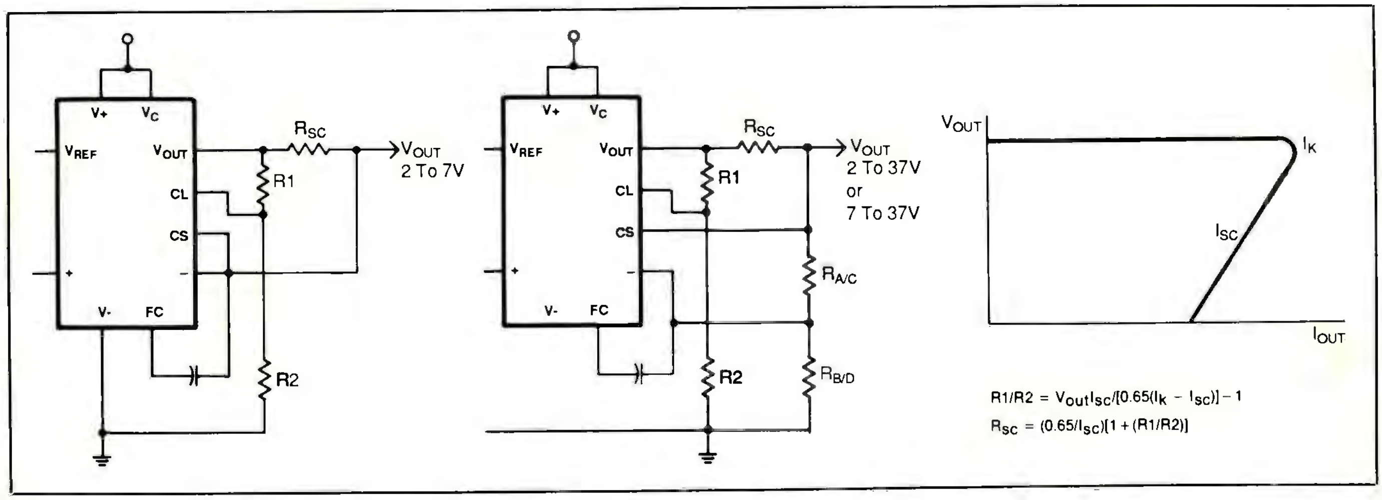


Fig. 7. Foldback current limiting, which gets its name from its voltage/current plot on a graph that appears to "fold back" on itself, requires slightly more complex circuitry than simple short-circuit limiting does. However, the forgiving nature of its limiting characteristic makes it ideal for test supplies.

below 0 volt, and the regulated output voltage can be reduced to 0 volt with respect to power ground.

It's important to note that resistor strings R_A/R_B and R_C/R_D *must* be selected so that it's impossible to adjust the output to below 0 volt. Otherwise, damage to the 723 may result.

Current Limiting

Setting the 723's short-circuit current level is a simple procedure. It's determined solely by the value of R_{SC} shown in most of the figures. Under no circumstances should R_{SC} be omitted. Although the 723 will operate without its over-current protection connected, even a momentary short-circuit in this mode will destroy the regulator IC and external pass transistor.

Setting the desired short-circuit current-limiting level is a simple matter of choosing a value for R_{SC} by dividing the base-emitter or turn-on voltage of the current sensor transistor (nominally 0.65 volt) by the desired current-limiting level in amperes. For example, with maximum output current using the internal pass transistor being 150 mA,, R_{SC} would equal 0.65/0.150 = 4.3 ohms.

You must take into account the power rating of R_{SC} as well. To determine the resistor's wattage rating, simply multiply the short-circuit current (I_{SC}) by the maximum output voltage to determine the maximum output power in watts. If the output is 20 volts and I_{SC} is 150 mA, output power would be 20 × 0.150 = 3 watts. In this example, a 4.3-ohm, 5-watt resistor would probably be the closest standard value you would be able to find.

Use of a simple short-circuit limiting resistor provides for only constant-current or shutdown limiting. If the load exceeds the I_{SC} level or if the output is shorted to ground, maximum current will flow while output voltage drops to nearly zero. While this kind of protection is adequate for most types of circuits, a slightly more forgiving type of limiting called "foldback current limiting" is also possible with the 723.

Foldback limiting is best suited to fixed-voltage supplies and limited-adjustability supplies, such as a nominal 12-volt supply that can be adjusted for output between 10 and 14 volts. This is because the current-limiting point changes with the output voltage with foldback limiting.

To design a 723 circuit with foldback current limiting, you must select three values. Choose output voltage V_{out} or the center point of the adjustment range. Then select short-circuit current level I_{SC}. Finally, select the maximum current that you want to flow before the output begins to "fold back" towards the short-circuit level. This peak level, called the "knee current," or I_k, is always higher than the short-circuit current. How much higher it is is up to you. Now that you have these figures, you can use the circuit and

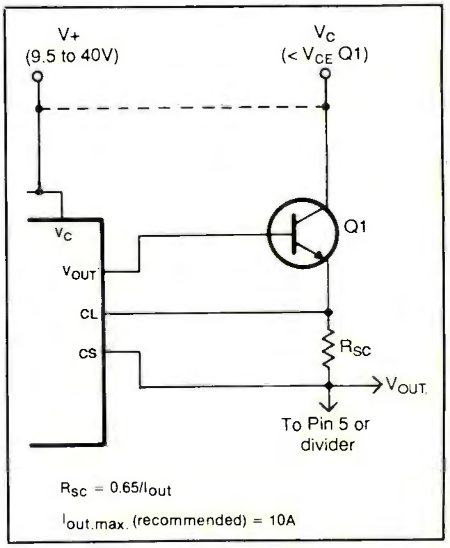


Fig. 8. Using a single external pass transistor with the LM723.

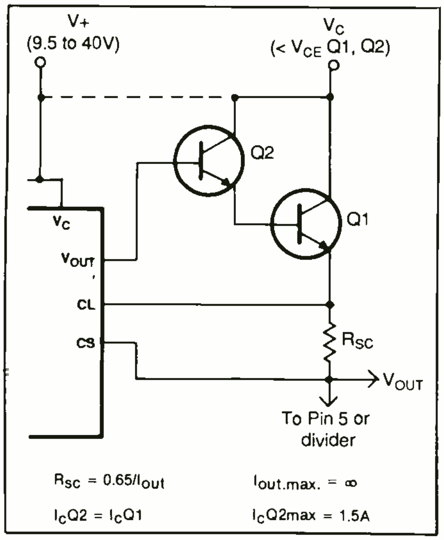


Fig. 9. Dual pass transistor arrangement is better than single transistor type and is recommended for all supplies with outputs greater than 5 A.

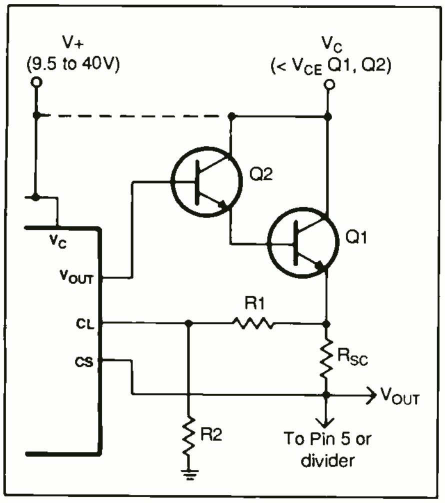


Fig. 10. Using foldback limiting with a pass transistor output.

equations in Fig. 7 to design a foldback limiting circuit.

Note that I_k must be less than 150 mA if the internal pass transistor is being used, or less than the I_C rating of an external pass transistor. It should also be evident from Fig. 7 that current-limiting circuitry R_{SC}, *R1* and *R2* remains the same whether the error amplifier's input is directly connected to the output or a divider string is used.

The first equation in Fig. 7 lets you determine the *ratio* of *R2*'s value to that of *R1*. (*R1* is temporarily assigned a value of 1). When you have the ratio, the next step is to find the nearest standard resistence values for *R1* and *R2* that add up to approximately 10,000 ohms while maintaining the ratio. For example, if the calculated ratio is 24.26:1, first add the two figures (25.26), divide the result into 1 (1/25.26 = 0.0396) and multiply this result by 10,000 to obtain *R1*'s value, which is 396 ohms. The value of *R2* would then be 10,000 − 396 = 9,604 ohms. The closest standard values to those calculated would be 392 (or 390) ohms and 9,530 (or 9,100) ohms.

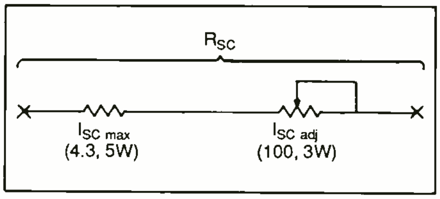


Fig. 11. A simple means of obtaining adjustable current limiting; use only without an external pass transistor.

The second equation in Fig. 7 is used to determine the value of R_{SC}. Note that I_{SC} remains the same for all output voltages, but the knee current increases as voltage increases. If you're designing a supply with an adjustable range of more than 2 to 3 volts, use the *highest* output voltage for design purposes—not the center voltage—to prevent an inadvertent overload. The power rating of R_{SC} is determined in this circuit by multiplying the *knee* current by maximum output voltage. Resistors *R1* and *R2* can be rated at ½ watt.

Pass Transistors

Since many power supplies must provide more current than the 723's internal capacity of 150 mA, an external pass transistor is needed. This is very easy to add, since only the transistor itself is required. Additionally, all phases of design remain exactly the same when using a pass transistor. The only change is that the rated collector current of the pass transistor now becomes the upper limit.

Figure 8 shows the 723 in a single external pass-transistor arrangement and illustrates just how simple this addition is to make. The transistor's collector can be connected either to the same supply as the 723, or (particularly when using a preregulator circuit) to the raw dc supply. The overall voltage rating (V_{ce}) of the transistor must be higher than the peak dc supply voltage, and the transistor's current rating (I_C) must be higher than the maximum current that will be required from the supply. A heatsink is required for almost all pass transistors.

Though a single pass transistor is adequate for any output current up to 10 amperes, a better design for all pass-transistor circuits, especially those to provide more than 5 amperes, is the dual-transistor circuit shown in Fig. 9. This circuit has a small buffer transistor between the 723 and the pass transsitor, and can be used for any practical current, even 50 amperes or more if a suitable pass transistor (or several paralleled transistors) is used. Buffer transistor *Q2* must have a V_{ce} and an I_C that are at least equal to the pass transistor's up to a maximum of about 1.5 amperes. Transistor *Q2* should not require a heatsink, except in very high-current supplies.

Figure 10 shows that foldback current limiting can be used with either a single or dual pass transistor, as well as with simple short-circuit limiting. The knee current of a foldback limiting circuit must be below the pass transistor's I_C rating, of course.

Selection of R_{SC} for high-current pass-transistor supplies is the same as for lower-current types, but a combination of very low values and high power ratings will be required. For example, a 5-ampere, 20-volt supply will require a 0.13-ohm, 100-watt resistor for R_{SC}. Wire-wound resistors with the necessary combination of ratings are relatively cheap, and smaller resistors can be paralleled to obtain the required resistance and power ratings. Wattage ratings in parallel-connected resistors add to each other. For example, connecting in parallel a 25- and a 50-watt resistor yields a combined power rating of 75 watts.)

Many variable-voltage supplies cannot produce the full designed output current at maximum voltage. For example, the supply shown in Fig. 13 will produce the full 3.5 amperes up to an output of about 20 volts, but current will fall off (at a rate depending on the supply's transformer, among other things) to about 0.75 ampere at the full 35-volt output. The point is that R_{SC} in this circuit doesn't have to be large enough to handle the theoretical maximum power (3.5 × 35 = 122.5 watts)—only the peak *actual* power of 3.5 × 20 = 70 watts. Using an oversized power resistor is never a bad idea, but the difference in size (and cost) between a resistor selected to meet an unobtainable theoretical maximum and one chosen to suit the actual maximum output power can be considerable.

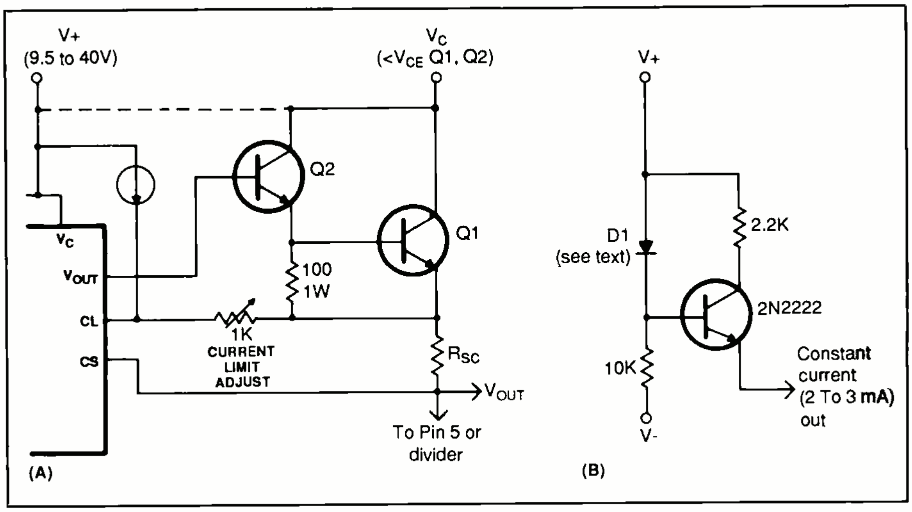


Fig. 12. An adjustable current-limiting scheme (A) that can be used to adjust limiting from near zero to maximum limit, even if upper limit is 10 amperes or more. Suitable constant-current source (B) for use with circuit (A) allows replacement of 2.2k resistor with trimmer to obtain fine adjustment of minimum current level.

Variable-Current Limiting

Most fixed-voltage power supplies will be adequately protected with fixed current limiting of either the constant-current or foldback type. However, most bench and test supplies will require adjustable current limiting to accommodate and protect a variety of experimental circuits and gear under test. Fortunately, smooth, effective variable limiting is easy to achieve with the 723.

The first variable current-limiting technique that may occur to you is something like that shown in Fig. 11, where a potentiometer replaces a fixed-value R_{SC}. Though this arrangement will work, it is limited in operating range by the 2-to-3-watt rating of most panel potentiometers. Higher power pots and rheostats are available, but they're bulky, expensive and inefficient.

The simple technique shown in Fig. 11 is suitable for use in circuits without pass transistors designed to deliver no more than 150 mA, since even ordinary panel pots can handle the maximum 3 watts of power produced. A fixed resistor should always be used in series with the pot, to protect it against overcurrent. If a 4.3-ohm, 5-watt resistor is used in series with a 100-ohm pot, minimum output current will be 0.65/104.3 = 6.2 mA, and maximum current will be 0.65/4.3 = 150 mA.

A far more satisfactory technique for variable current limiting is shown in Fig. 12(A). Here once again, R_{SC} is selected to set maximum output current. A 1,000-ohm panel pot is inserted between the emitter of the pass transistor and the CL pin of the 723, along with a 2-to-3-mA constant-current source connected to the CL pin. When the panel pot is set to minimum resistance, the constant-current source will be swamped by the current flowing from the pass transistor, requiring a full 0.65-volt difference across R_{SC} (full output current draw) to initiate current limiting. However, the farther advanced the pot, the stronger the influence of the current source on the CL pin and the smaller the differtial across R_{SC} (the smaller the current draw) will have to be to cause an *apparent* 0.65-volt difference to have current limiting to take effect. In fact, with the potentiometer set for maximum resistance, only a few milliamperes of output current are required to trigger current limiting.

Any sort of constant-current source can be used in this circuit—constant-current diode, op-amp circuit, etc.—as long as it can withstand the maximum supply voltage used in the circuit. A very suitable source is shown in Fig. 12(B). Here, the npn transistor is biased by a constant collector-base voltage (the drop across *D1*), regardless of the output voltage at its emitter. The diode should have a drop of between about 1.2 and 2.5 volts. Suitable diodes for this purpose include two 1N914s in series (1.4 volts), a red LED (1.5 volts), a yellow or orange LED (1.8 volts) and a green LED (2.0 volts). To fine-adjust the current, the 2,200-ohm re-

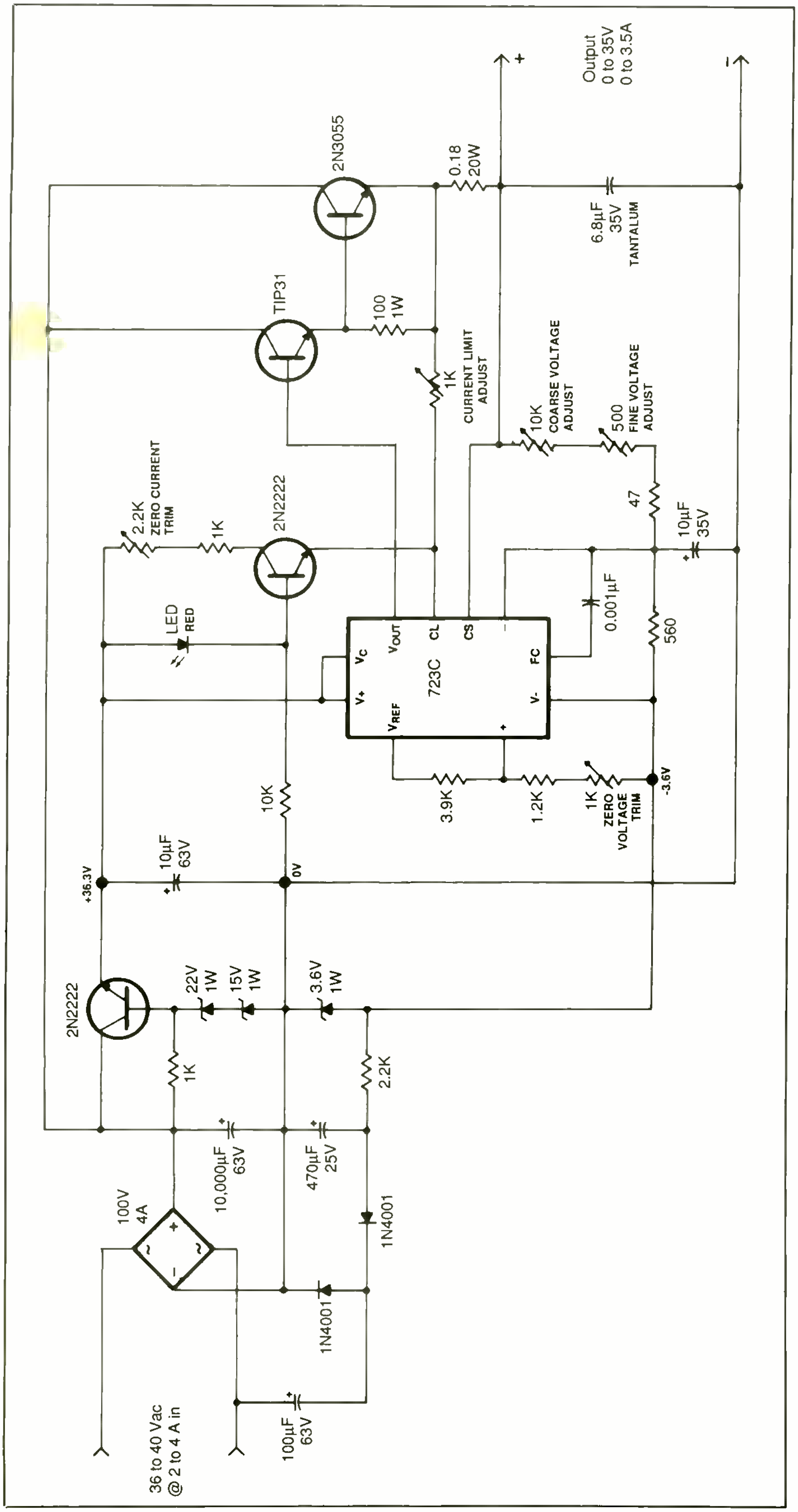


Fig. 13. An all-in-one bench power supply with 0-to-35-volt output at 0-to-3.5-ampere adjustable limiting. Trim points are provided to optimize circuit operation.

sistor can be replaced with a 1,000-ohm resistor in series with a 2,000-ohm trimmer potentiometer.

Figure 12(A)'s circuit can be trimmed to provide a smooth adjustment from zero to the maximum current set by R_{SC}, even if the upper limit is 10 amperes or more.

Practical Circuit

Shown in Fig. 13 is the schematic diagram of a complete variable bench-power supply that utilizes almost every element of design we've discussed above and features a variable output from 0 to 35 volts and adjustable current limiting from 0 to 3.5 amperes. The circuit is pretty straightforward, but two areas are worthy of discussion, beginning with the negative bias supply. Note that an ordinary single secondary power transformer is used, and no extra tap is needed to provide the negative voltage supply. Instead, a 100-µF capacitor and a pair of rectifier diodes are used to produce a raw dc of approximately 5 to 10 volts below ground reference. A 470-µF capacitor smooths the supply, and a resistor/zener-diode circuit produces a stabilized −3.6 volts. This trick works only with circuits like this one in which a minimal amount of current (5 mA) is all that's needed.

Since the 723 is now referenced to −3.6 volts at its V− pin, V+ must be reduced accordingly, which is done by lowering preregulation diodes from 40 to about 36 volts. Connecting a pair of 22- and 15-volt zeners in series as shown provides a supply of about 36.3 volts (22 + 15 − 0.7) to the 723's V+ and V_C pins. This gives the 723 a total maximum supply of about 39.9 volts. If you hand pick the zeners, you can bring this up to the full 40 volts.