# Basic Regulator circuits

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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 requirement for a regulator most of the time can be filled by just using a 7800 or 7900 series IC, and little or no other effort. You will most likely seldom build regulator circuits, unless your project is a large, high powered power supply or other item such as a very high powered audio amplifier. And power supplies and high power amplifiers are often better and more cost effective if purchased ready made. Many companies provide such items at reasonable cost, often less than you would have to pay for just the large transformers, filter capacitors, and heatsinks needed. You will also need to obtain PC boards, small parts, meters, and case. Power supplies are staple, off the shelf items. 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 todays’ wheelmakers and wheel engineers will stop designing, improving, and making wheels. They may get bored doing it, or decide to do something else, and eventually they must retire, grow old, and die off. If there are no other wheelmakers and designers to replace them, eventually there will be no more wheels. The wheel will then have to be invented all over again. 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 wont become another technical whiz who cannot solder, use an oscilloscope, and whose electronics (?) knowledge is limited to trendy pseudoscience, the latest in stereos, and whats hot at the computer store or software emporium. This point made, we will discuss simple and 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 a big topic 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 disguises.

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 a 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. As an 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 across each lamp so 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 todays Christmas decorations, where 25 to 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 and hopefully avoiding the job of searching for the defective lamp. 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, as in a current limited power supply, in which the supply supplies 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 than 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 to 90 percent or better. In addition, the elimination of heavy, expensive, and large 60 Hz transformers will reduce cost size and weight. This is achieved with somewhat greater circuit complexity and greater circuit noise due to switching transients. This often limits the use of switching regulators in applications where noise may cause problems (i.e. low level audio and RF circuits operating at frequencies in the noise spectrum of the power supply). 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 usually will 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 to 24 volts at currents from 100 ma up to several amps are readily available and cheap, and can easily be interfaced to higher power bipolar or FET devices for high current supplies. These are commonly 3 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 mfd, and only need these 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 from several manufacturers. These low cost regulators and converters make it practical and a no-brainer to supply individual circuits with special voltages not supplied by a systems main power source, such as higher or opposite polarity voltages. This 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 maintaing 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 figure 1. A zener diode is generally used, although gas discharge devices (Were 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 maintain this voltage.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 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 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 ampere 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 5V 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 must never fall below this voltage, or regulation will be lost. This mimimum 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 ten or twenty milliamperes 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. This can be a large power transistor capable of handling several amperes of current. The load current consists of the collector current, which is the lions 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 ampere, the collector current would be $\beta$ / ($\beta$+1) of 1 ampere or 50/51 amperes and the base current would be 1/($\beta$+1) Or 1/51 of an ampere. This is a little less than 20 milliamperes. The current flow is shown in Fig 2a. Fig 2b shows how an intermediate transistor can be used to 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. (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. There is also a small drop in output voltage due to the base-emitter drop in the pass transistor (0.6 to 0.7 volts per transistor typically). There is also additional resistance drop in the potentiometer if used for varying the output voltage. Some loss in regulation is caused by this. The regulator cannot “know” if there is a drop in the output voltage. What is 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 implies a feedback or servo system that will act to control the output voltage. We will show a very basic way to do this with a few additional parts.

Fig 3 shows a very basic feedback regulator in which the output voltage has some say in its exact level. 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 tend to be turned off, drawing less current through bias resistor R4. The collector voltage will tend to rise, increasing the voltage at the base of pass transistor Q2 and therefore the emitter of Q2, which happens to be the power supply regulator output terminal. 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.

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 to 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 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:

1) Output voltage cannot be less than the zener voltage plus the base-emitter drop in Q1
2) No means of current limiting or short circuit protection exists
3) Maximum regulated output voltage is limited, as there will always be a voltage drop across R4
4) Regulation progressively poorer as output voltage increases, since feedback factor R2 / (R1+R2) decreases
5) 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 dealt with with circuit changes and additional components.. (1) can be dealt with by using 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. A resistance can be placed in series with the input and the voltage drop across this, a function of load current, used to control the regulator output. Additional transistors or an op amp can be used to get more open loop gain

Fig 4a shows one method by which current limiting can be added. R4 is in series with a PNP transistor, Q3 acting as a current source. R4 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 0.7Ω for 1 ampere, 0.35Ω for 2 amperes, etc.

Fig 4b shows 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 go down to zero volts output, as may be needed in a laboratory power supply.

Fig 4c shows a way to improve transient regulation of the regulator in fig 4. 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 are often 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 suden removal of the input voltage, this capacitor can discharge back into the regulator, possibly damaging the pass transistor emitter-base junction due to reverse overvoltage. A protection diode is often added across the pass transistor to guard against this type of fault.

Fig 5 shows 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 complianceThis principle is widely used inside ICs where a high impedance current source is needed. Fig 5b shows the use of a 5 volt regulator IC to produce a constant current source. The 3 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 milliamps 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. Fig 5c shows the use of an op amp to produce a constant current. 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 Vin/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 possible safe nondestructive testing.

Since ICs can have many transistors and resistors built in, additional regulator features are easily added. Many manufacturers publish data sheets for their IC devices that show some or all of the internal circuitry. In many cases it is 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 hold of 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 ever you are expecting to do anything original. Working blind may get you into problems and hours of futile effort. This can often be avoided if you know what is happening.

A lot can be done with cheap and inexpensive 3 terminal regulators. Fig 6a,b,c shows a few circuits using the 7805. This is probably one of the easiest to get, most widely used regulator IC chips 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 amperes. 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, or your other suppliers have a minimum order, or you have plenty of 5 volt units and refuse 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 3 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. It is recommended to use 2 resistors as shown and run 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. But, 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. So you will get some small loss of regulation using this circuit, but it is not serious for most applications and saves money and having to stock 8 volt units. You can get up to about 10 volts with still excellent performance, although higher voltages are possible if some fall-off in regulation is allowable. For higher voltage use the LM7812 is very common, cheap, and widely available, and can be used for outputs in the 12 to 24 volt range. 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.

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. Fig 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 V (± 0.35 V for LM723C version). By selecting a few resistors the output voltage can be programmed 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, and provides current limiting action via internal circuitry. C1 is a compensating capacitor in order to maintain 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 be also very close to 7.15 volts, (assuming high error amp gain). Therefore, for 12 volts output, the voltage divider made up of R1 and R2 must provide 7.15 volts at the junction of R1 and R2. R2 is not critical and almost any reasonable value can be used. Practically, 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 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. 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. Q1 must be adequately heat sinked, since at 12V output and 20V input as much as 4.8 watts will be dissipated in Q1 (8 volts drop at a possible 600ma). 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 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 can occur also when the DC input supply is shut down. Load regulation with the 723C in this circuit should be 20 millivolts or better, no load to full load (500 ma), with about 2-3 millivolts change during a 5 volt change in input voltage (15 to 20 volts). As can be seen, quite good performance can be obtained with few components and a simple circuit. It is highly recommended to consult the manufacturers application notes and data sheets (You can usually download these on their websites) as there are many other configurations and applications of these devices.

By using auxiliary power transistors and adequate heatsinking, power supplies delivering commonly used supply voltages (12, 24, or 32 volts) at up to 50 amps or more may be constructed. 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, worst case is full load current at minimum output voltage, since this 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 be used to 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 than power supplies than has been 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 save some money.

# SIMPLE REGULATOR CIRCUITS

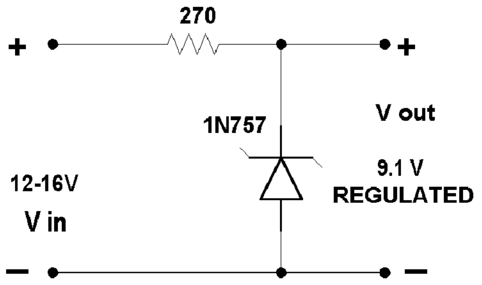



FIG 1
BASIC SHUNT
REGULATOR

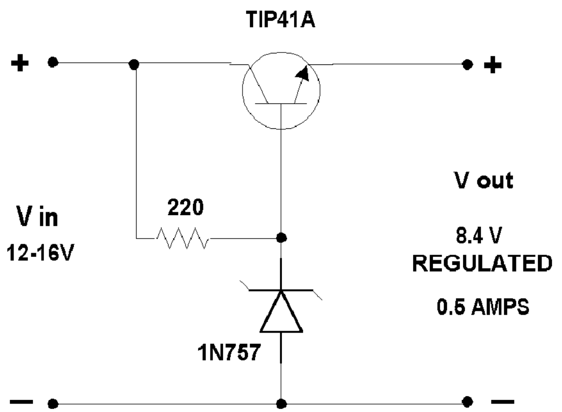



FIG 2a
SIMPLE REGULATOR

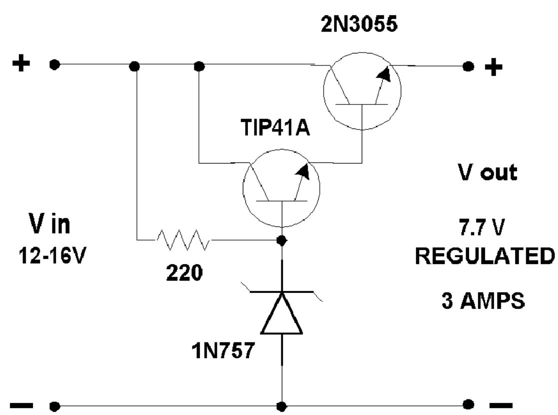



FIG 2b
SIMPLE REGULATOR
FOR HIGHER CURRENT

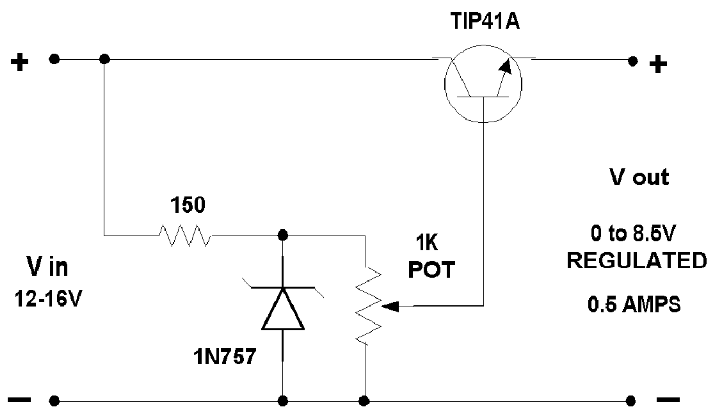



FIG 2c
SIMPLE ADJUSTABLE REGULATOR

**IMPORTANT:**

**PASS TRANSISTORS SHOULD BE ADEQUATELY HEAT SINKED**

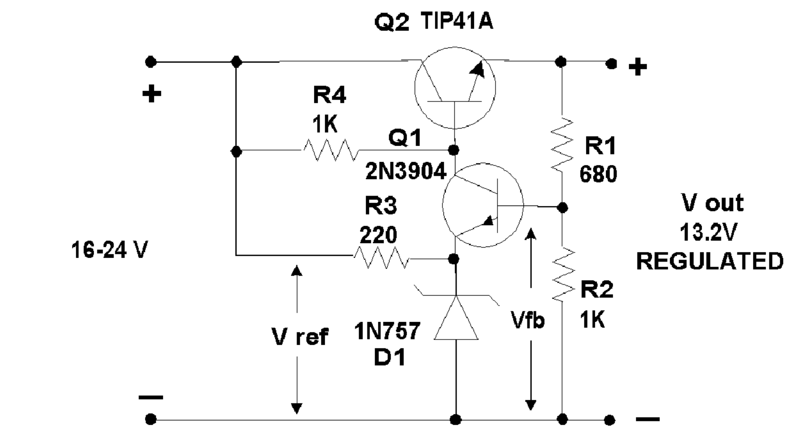



FIG 3

SIMPLE FEEDBACK REGULATOR WITH SINGLE TRANSISTOR ERROR AMPLIFIER

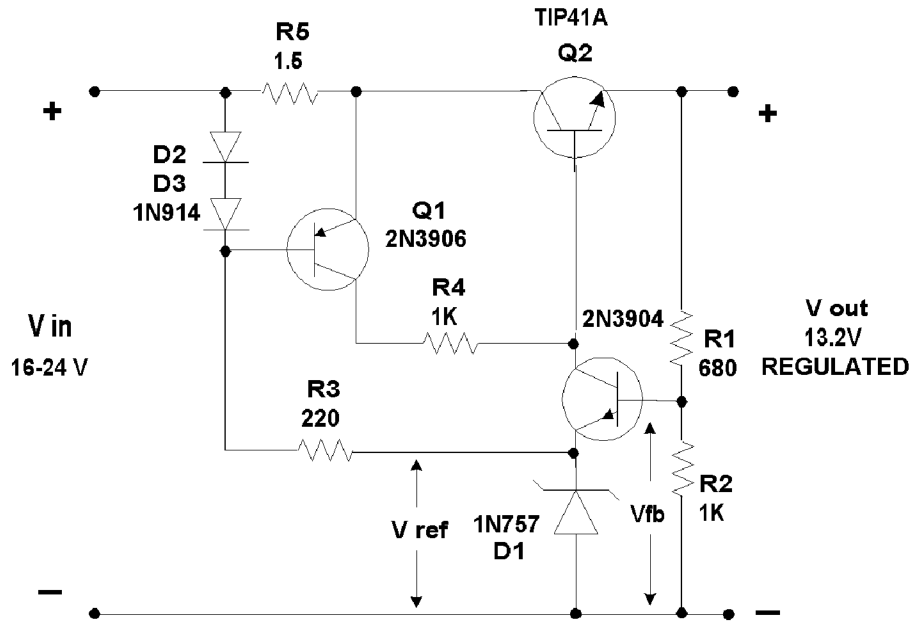



FIG 4a
SIMPLE FEEDBACK REGULATOR WITH CURRENT LIMITING

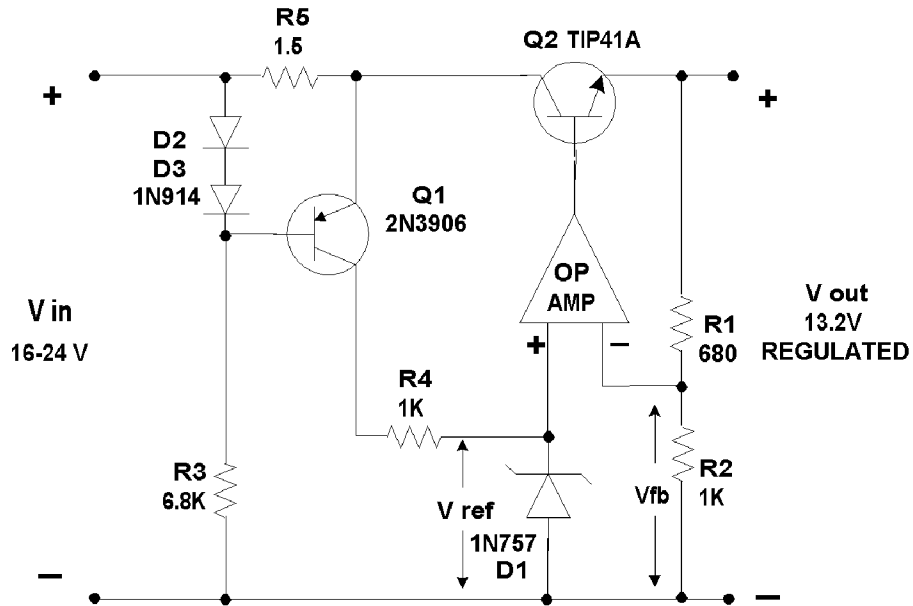



FIG 4b

USE OF OP AMP AS ERROR AMPLIFIER

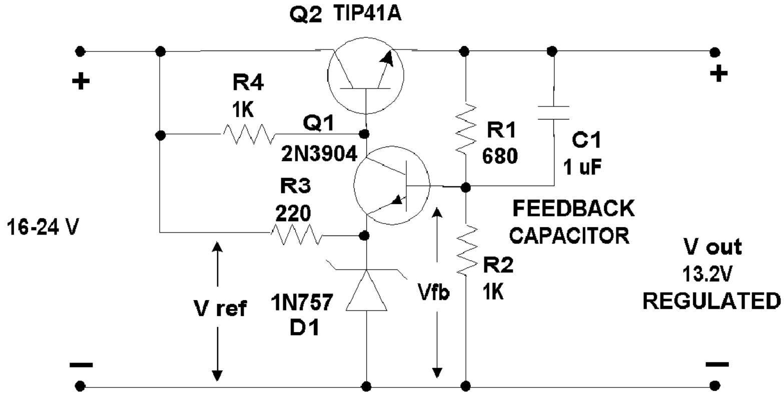
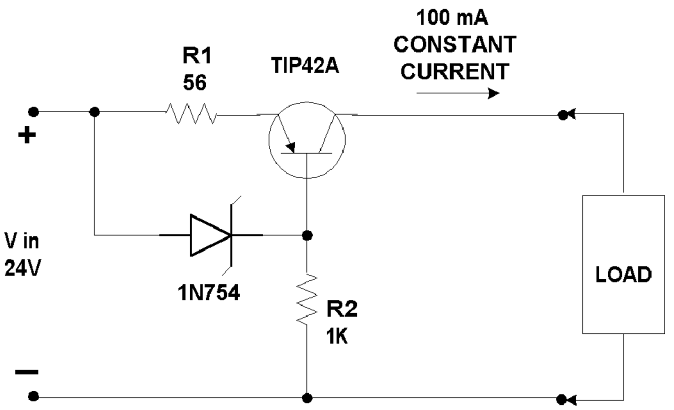


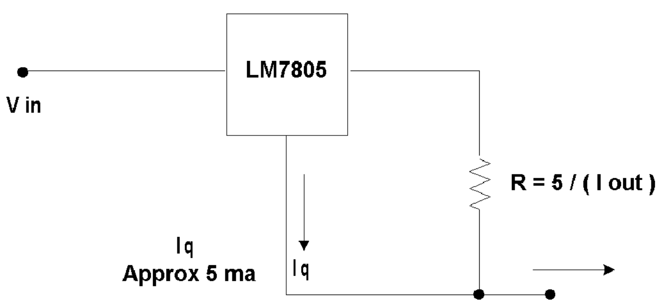

FIG 4C

SIMPLE FEEDBACK REGULATOR
WITH FEEDBACK CAPACITOR TO
IMPROVE TRANSIENT RESPONSE

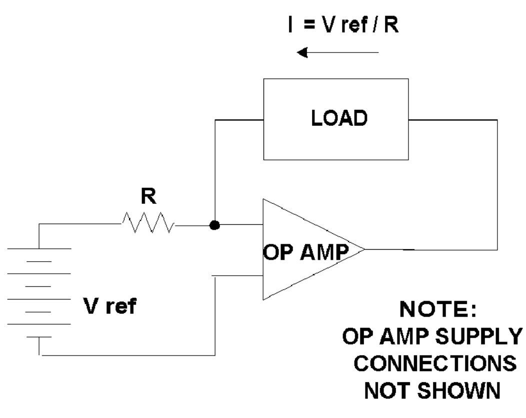



TRANSISTOR
CURRENT
REGULATOR

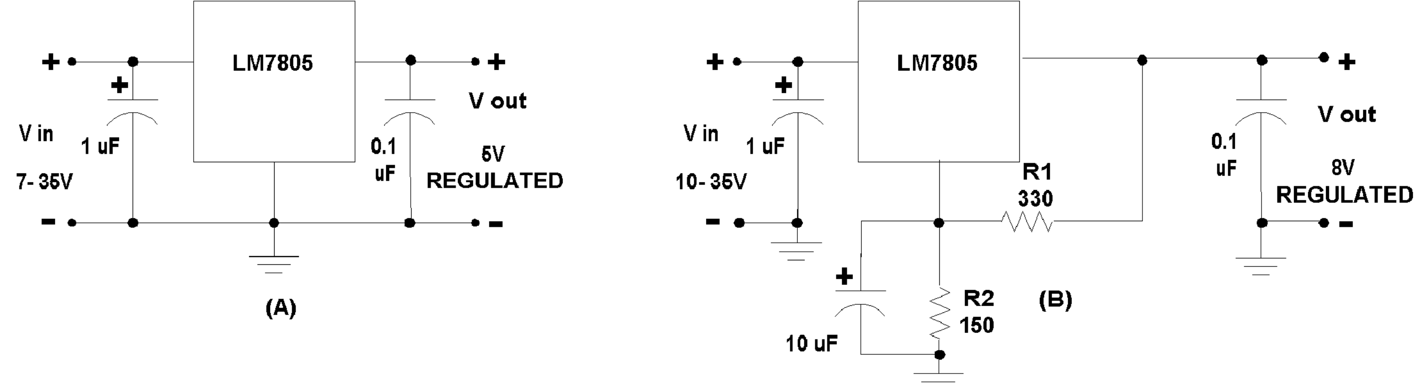
FIG 5
CONSTANT
CURRENT
REGULATORS

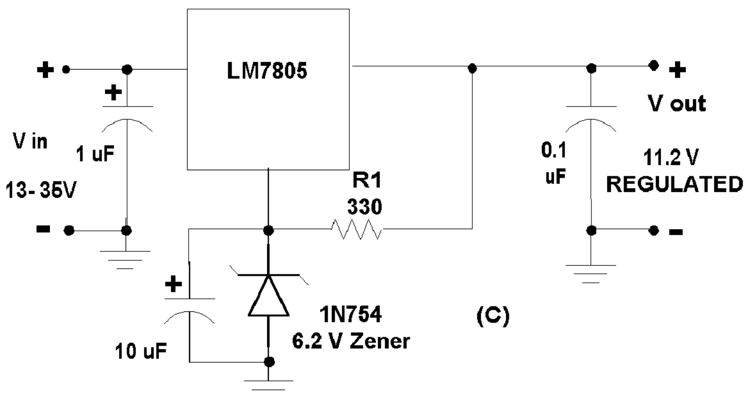



USE OF LM7805
AS CURRENT
REGULATOR

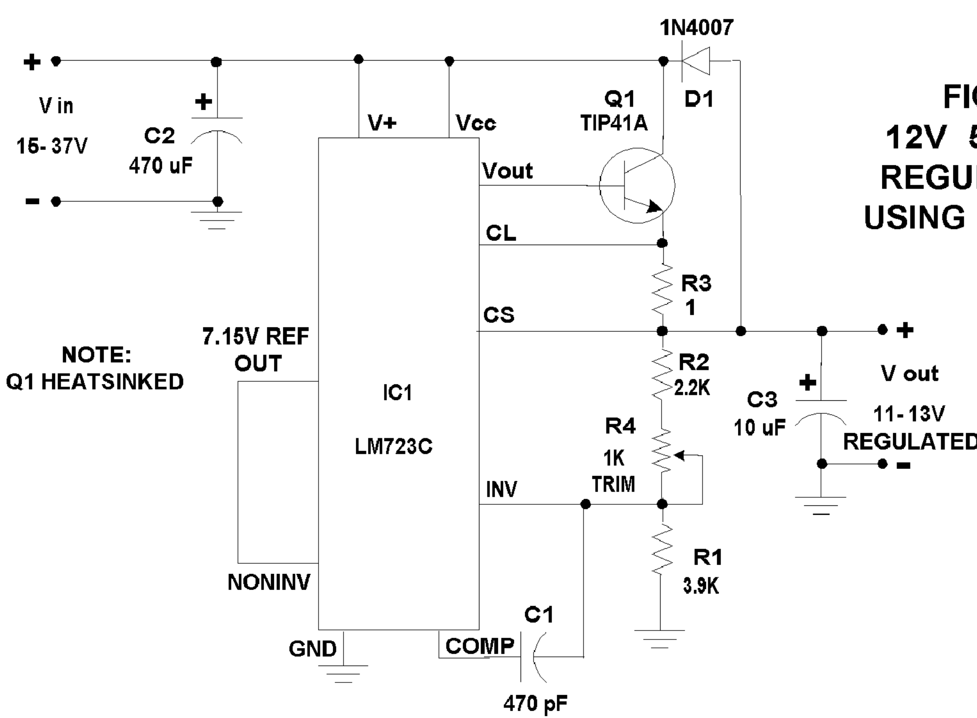



USE OF OP AMP
AS CURRENT
REGULATOR




# FIG 6 a,b,c LM7805 CIRCUITS




# FIG 7 12V 500 Ma. REGULATOR USING LM723C

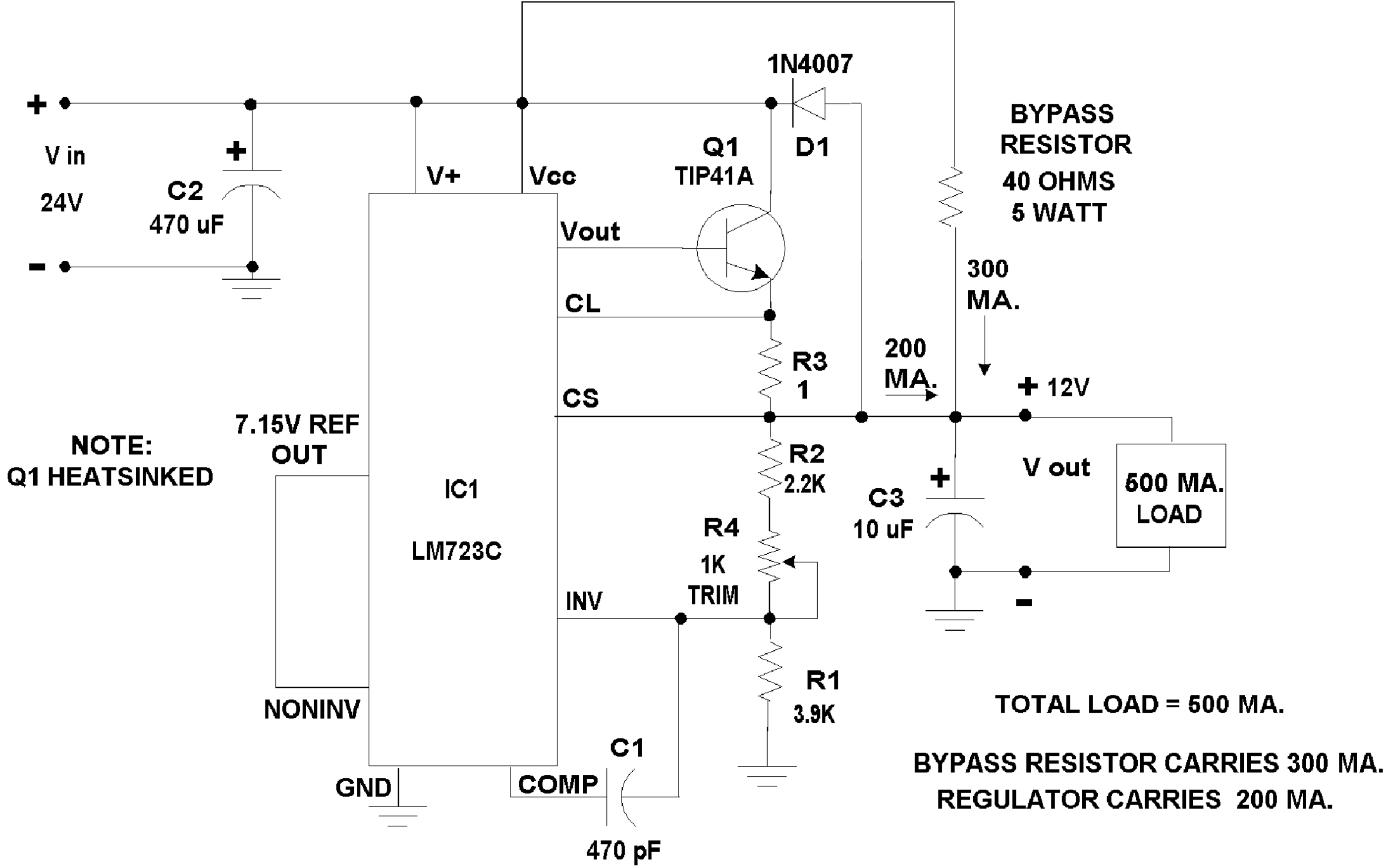



**FIG 8**
**LM723C REGULATOR**
**WITH BYPASS RESISTOR**