

Power supplies and voltage regulators

In this first edition of our new Circuit File series, design consultant Ray Marston takes an in-depth look at practical power supply and voltage regulator circuits.

Ray Marston

TWO OF THE MOST common tasks facing the electronics designer or experimenter are those of designing basic power supply circuits to enable pieces of equipment to operate from ac power, and designing voltage regulator circuits to enable specific circuits to operate from well defined dc supply voltages over wide ranges of load current.

Both of these design tasks are reasonably simple. Basic power supply circuits consist of little more than a transformer-rectifier-filter combination, so all the designer has to do is select the circuit values, using a few very simple rules, to suit his own particular design requirements.

Voltage regulator circuits may vary from simple zener diode networks, designed to provide load currents up to only a few milliamps, to fixed voltage high current units for powering logic boards, etc, or to variable voltage high current units designed to act as general purpose pieces of test gear. We'll look at practical versions of all these examples in the next few pages.

Power supply circuits

Basic power supply circuits are used to enable pieces of equipment to operate safely from ac mains power (rather than from batteries), and are simply designed to convert the ac mains voltage into an electrically isolated dc voltage of the value required by the actual circuitry of the equipment.

The basic power supply circuitry consists of little more than a transformer-rectifier-filter combination; the trans-

former is used to convert the ac line voltage into an electrically isolated and more useful ac value, and the rectifier-filter combination is used to convert the new ac voltage into the appropriate dc value.

Figures 1 to 4 show the four most useful transformer-rectifier-filter combinations you will ever need. The Figure 1 circuit provides a single-ended dc supply from a single-ended transformer and bridge rectifier combination, and gives a virtually identical performance to the centre-tapped transformer circuit of Figure 2. The circuits in Figures 3 and 4 both provide 'split' or 'dual' dc supplies and, again, give virtually identical performance. The rules for designing these circuits are very simple, as you'll see in a moment.

Transformer-rectifier selection

The three most important parameters of a transformer are its *secondary voltage*, its *power rating*, and its *regulation factor*. The secondary voltage is always quoted in RMS terms at full rated power load, and the power load is quoted in terms of VA or watts (though VA is more widely used). Thus, a 15 V, 20 VA transformer will provide a secondary voltage of 15 V RMS when its output is loaded by 20 watts. When the load is removed (reduced to zero) the secondary voltage will rise by an amount specified by the *Regulation Factor*. Thus, the output of a 15 volt transformer with a 10% regulation factor (a typical value) will rise to 16.5 volts when the output is unloaded.

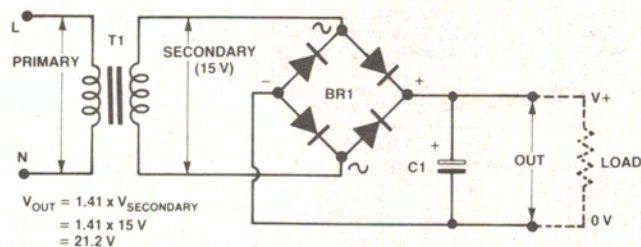


Figure 1. Basic single-ended supply using a bridge rectifier module.

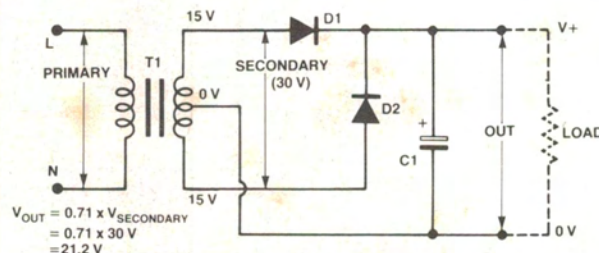


Figure 2. Basic single-ended supply using a centre-tapped transformer.

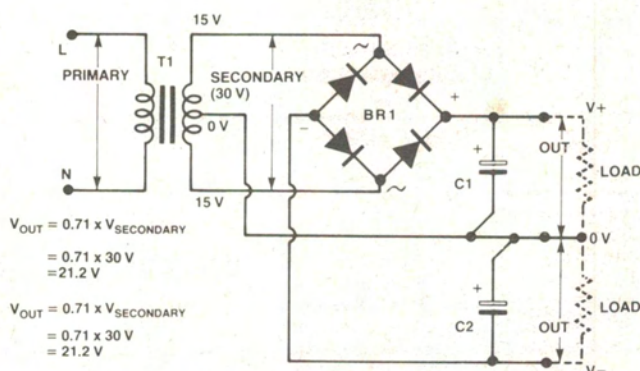


Figure 3. Basic dual supply using a bridge rectifier module.

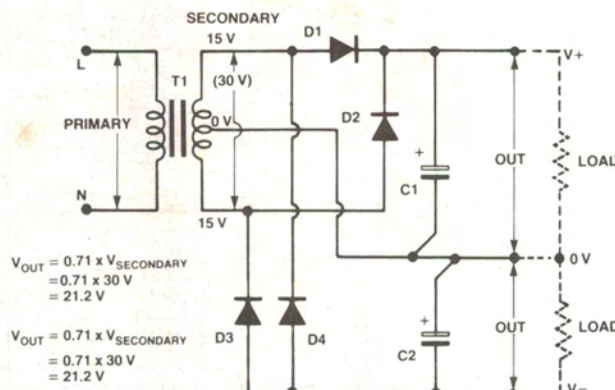


Figure 4. Basic dual supply using individual diodes.

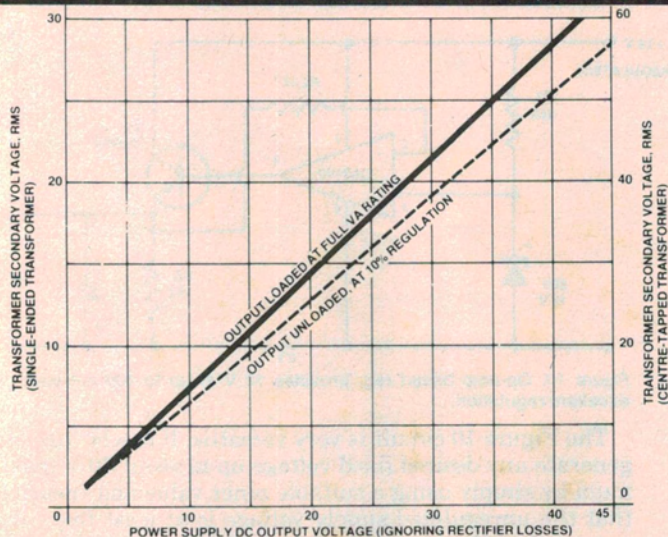


Figure 5. Transformer selection chart (see text).

Now, the most important point to notice here is that the RMS output voltage of the transformer secondary is *not* the same as the dc output voltage of the complete power supply. In fact, the dc output voltage of a fullwave rectified circuit is 1.41 (i.e.: $\sqrt{2}$) times the RMS transformer voltage (ignoring rectifier losses) that is feeding the rectifier, as shown in the graph of Figure 5. Note here that this voltage is equal to 1.41 times the voltage of a single-ended transformer. Thus our single-ended 15 V RMS transformer with 10% regulation will in fact provide an output of about 21 volts at full rated load (just under 1 amp at a 20 VA rating) and 23.1 volts at zero load.

When rectifier losses are taken into account, the output voltages will be slightly lower than shown in the graph. In the 'two-rectifier' circuits of Figures 2 and 4, the losses amount to about 600 mV, while in the 'bridge' circuits of Figures 1 and 3 the losses amount to about 1.2 volts. The rectifiers should, for maximum safety, have continuous current ratings at least equal to the dc output currents, but preferably greater.

Thus the procedure for selecting a transformer for a particular problem is very simple. First, decide on the dc output voltage and current that are required; the product of these two values (allowing for slight rectifier losses) determines the minimum VA rating of the transformer. Next, consult the graph of Figure 5 to find the transformer secondary RMS voltage that corresponds to the required dc voltage. Simple?

The filter capacitor

The purpose of the filter capacitor is to convert the fullwave rectified output of the rectifier — which consists of half-sinewave pulses — into a smooth dc output voltage. The two most important parameters of the capacitor are its *working voltage* and its *capacitance value*. The capacitance value determines the amount of ripple that will appear on the dc output voltage when current is being drawn from the circuit.

As a rule of thumb, in a fullwave rectified power supply operating from a 50 Hz power line, an output load current of 100 mA will cause a ripple waveform of about 700 mV peak-to-peak to be developed from a 1000 μ filter capacitor, the amount of ripple being directly proportional to the load current and inversely proportional to the capacitance value, as shown in the 'design guide' of Figure 6. In most practical applications, the ripple should be kept below 1-1.5 volts peak-to-peak under full load conditions. If very low ripple is required, the basic power supply can be used to drive a

three-terminal voltage regulator, which can easily reduce the ripple by a factor of 60 dB or so at very low cost.

Voltage regulator circuits

Voltage regulators may vary from simple zener-based circuits designed to provide load currents up to only a few milliamps, to fixed voltage high current circuits designed around 'fixed' three-terminal regulator ICs, or to variable voltage high current circuits designed around 'variable' three-terminal regulator ICs. We'll look at practical versions of all three types of circuit in the next couple of pages.

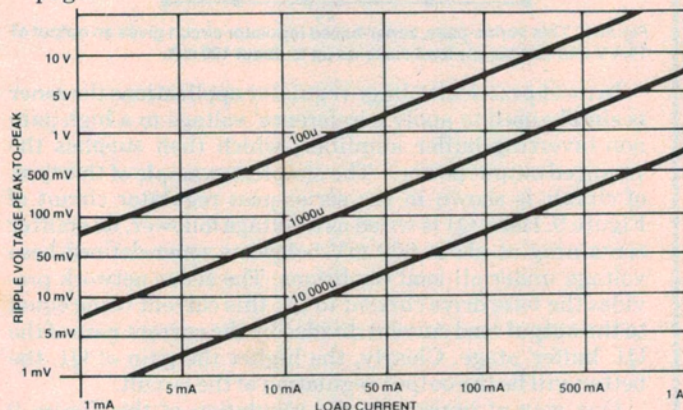


Figure 6. Filter capacitor selection chart (see text).

Zener-based circuits

A zener diode can be used to produce a fixed reference voltage simply by using the connections shown in Figure 7. Here, a current of roughly 5 mA is passed through the zener diode from the supply line via limiting resistor R. Often, the supply voltage (V_{in}) may be subject to fairly wide variations, causing the zener current to vary over a similarly large range. So long as V_{in} is always more than a few volts

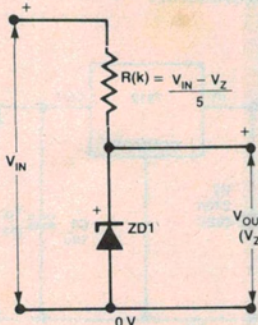


Figure 7. Basic zener reference circuit. Bias is about 5 mA.

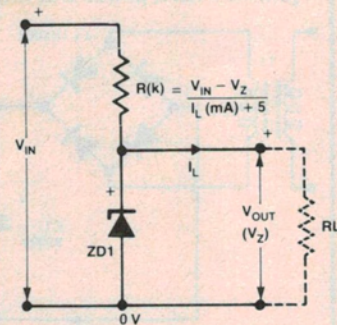


Figure 8. Zener reg. can supply load currents up to a few tens of mA.

greater than the zener voltage and provided that the zener power rating is not exceeded, this variation has only a moderate influence on the output voltage of the zener, which typically has an effective output impedance of only a few tens of ohms.

A zener can be used as a very simple voltage regulator, providing maximum load currents up to a few tens of milliamps, by merely selecting the value of 'R' as shown in Figure 8. Here, when the designed maximum load current is being drawn only 5 mA flows through the zener; when zero load current is being drawn the zener passes 5 mA plus the maximum designed load current, and thus dissipates maximum power. It is important to ensure that the power rating of the zener is not exceeded under this 'no load' condition. ▶

circuit file

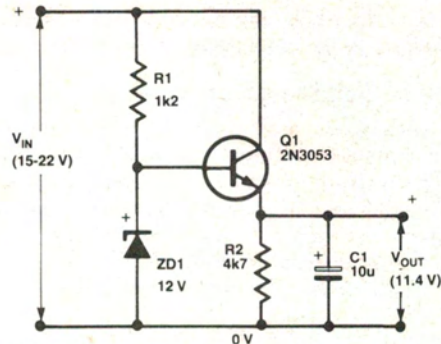


Figure 9. This series-pass, zener-based regulator gives an output of 11.4 V and can supply load currents up to about 100 mA.

In most practical voltage regulator applications the zener is simply used to apply a 'reference' voltage to a high gain non-inverting buffer amplifier, which then supplies the required output power. The simplest example of this type of circuit is shown in the series-pass regulator circuit of Figure 9. Here, Q1 is wired as a voltage follower, its emitter remaining at about 600 mV below its zener-defined base voltage under all load conditions. The zener network provides the base drive current to Q1, this current being equal to the output load current divided by the current gain of the Q1 'buffer' stage. Clearly, the higher the gain of Q1, the better will be the output regulation of the circuit.

One way of improving the regulation of the Figure 9 circuit would be to use a Darlington or super-alpha pair of transistors in place of Q1. An even better solution is to use the op-amp plus transistor buffer stage shown in Figure 10. Here, the op-amp and Q1 are wired as a unity gain non-inverting dc amplifier with a near-infinite input impedance and near-zero output impedance. The output voltage tracks within a few mV of the zener reference value. The safe output current is limited to about 100 mA by the power rating of Q1; higher currents can be obtained if Q1 is replaced with a power Darlington transistor.

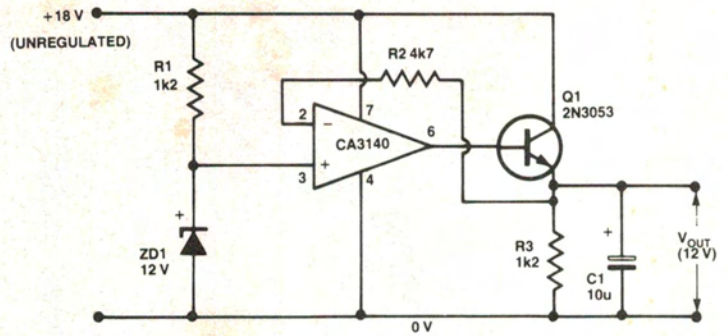


Figure 10. Op-amp based reg. provides 12 V at up to 100 mA with excellent regulation.

The Figure 10 circuit is very versatile. It can be made to generate any desired fixed voltage up to about 30 V maximum by simply using a suitable zener value and ensuring that the unregulated supply voltage is at least five volts greater than the zener value (up to 36 volts maximum). The circuit can be used as a variable voltage supply by simply wiring a potentiometer across the zener, with its slider taken to the non-inverting input of the 3140 op-amp; this op-amp can accept inputs all the way down to zero volts, enabling (for example) a 0-25 V supply to be easily implemented.

Fixed three regulator circuits

Fixed voltage regulator design has been greatly simplified in the last decade by the introduction of three-terminal regulator ICs such as the '78xx' series of positive regulators and the '79xx' series of negative regulators. These ICs incorporate features such as built-in foldback current limiting and thermal protection. A wide range of three-terminal fixed voltage regulator ICs is available; standard current ratings are 100 mA, 500 mA, 1 A, and 3 A, and standard output voltage ranges are 5 V, 6 V, 8 V, 12 V, 15 V, 18 V and 24 V.

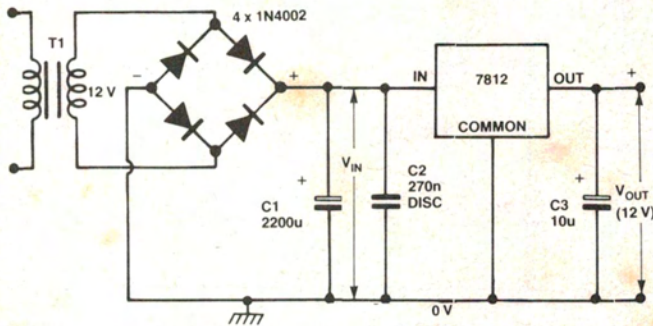


Figure 11. Circuit employing a common three-terminal positive regulator.

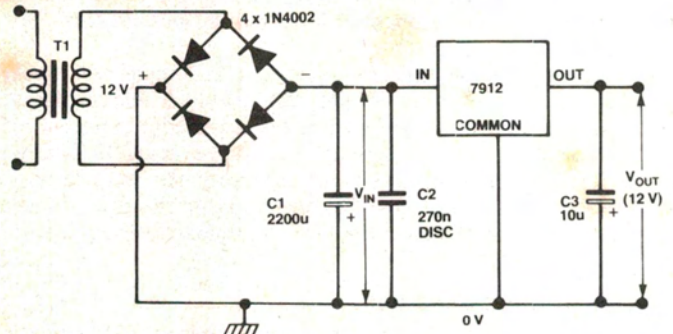


Figure 12. Circuit using a common three-terminal negative regulator.

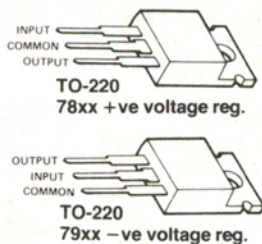


Figure 13. Complete circuit of a dual supply using three-terminal regulators. This supply delivers +/− 12 V at up to 1 A.

Three-terminal regulators are remarkably easy to use, as shown in the basic circuits of Figures 11 to 13, which show the connections for making positive, negative and dual regulator circuits respectively. The ICs shown in these examples are 12 volt units with current ratings of 1 A, but the basic circuits are valid for all other voltage ratings, provided that the unregulated input voltage is at least three volts greater than the desired output voltage.

If the connection between the regulator's input and the rectifier's filter capacitor is more than 50 mm in length, then a capacitor is needed across the regulator's input terminals to maintain stability. Generally, all that is necessary is a 200n or greater value disc or plate ceramic capacitor, mounted right at the regulator's terminals using short leads. Alternatively a 2u2 or larger value tantalum could be used. You often see a capacitor connected across the regulator's output, too. Although not always necessary, a capacitor in this position reduces high frequency noise and improves transient response. A 100n or greater ceramic capacitor is recommended, or an electrolytic of 1u to 10u or so.

The output voltage of a three-terminal regulator is referenced to the 'common' terminal of the IC, which is normally (but not necessarily) grounded; most regulator ICs draw quiescent currents of only a few mA, which flow to ground via this 'common' terminal. The regulator output voltage can thus easily be raised above the designed value by simply biasing the 'common' terminal with a suitable voltage, making it easy to obtain 'odd-ball' output voltages from the regulator. Figures 14 to 16 show three ways of achieving this.

In figure 14 the bias voltage is obtained by passing the IC's quiescent current (typically about 8 mA) through RV1. This design is adequate in most applications, although the output voltage obviously shifts slightly with changes in quiescent current. The effects of such changes can be minimised by using the circuit of Figure 15, in which the RV1 bias voltage is determined by the sum of the quiescent current and the bias current set by R1 (12 mA in this example). If a fixed output voltage is required other than the designed value, it can be obtained by wiring a zener diode in series with the common terminal, as shown in Figure 16, the output voltage then being equal to the sum of the zener and regulator voltages.

The output current capability of a three-terminal regulator can be increased by using the circuit of Figure 17. Resistor R1 is wired in series with the regulator IC. At low currents, insufficient voltage is developed across R1 to turn Q1 on, so all the load current is provided by the IC. At currents of 600 mA or greater sufficient voltage (600 mV) is developed across R1 to turn Q1 on, so Q1 provides all currents in excess of 600 mA.

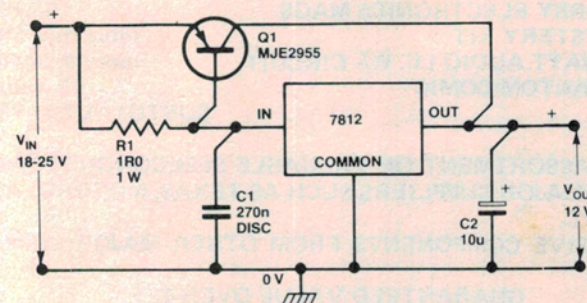


Figure 17. Increasing the output current capacity of a three-terminal regulator. This will deliver 5 A at 12 V.

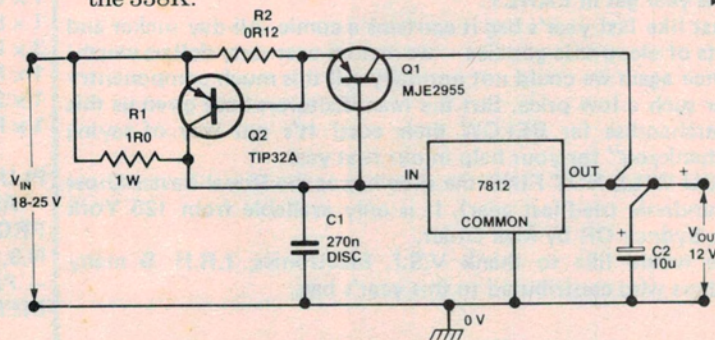


Figure 18. Providing overload protection for the Figure 17 circuit. Q2 'robs' Q1 of base current when load current goes above 5 A.

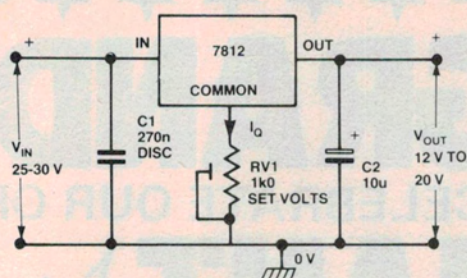


Figure 14. Simple method to vary output voltage.

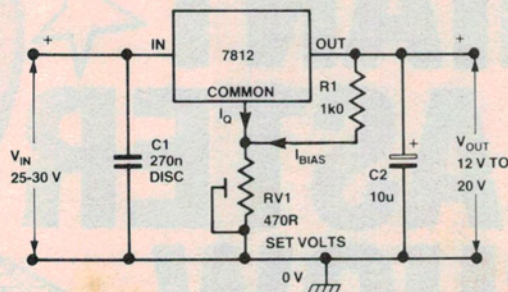


Figure 15. Improved method of varying output voltage.

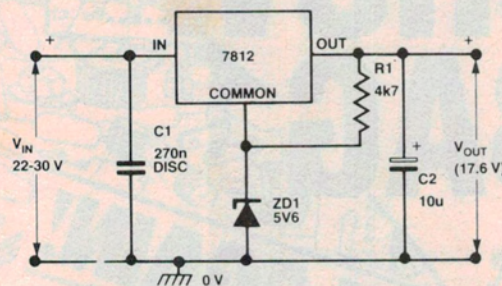


Figure 16. 'Jacking up' the output voltage using a zener.

Finally, Figure 18 shows how the bypass transistor of the above circuit can be provided with overload current limiting via an 0R12 current-sensing resistor (R2) and turn-off transistor, Q2.

Variable three-terminal regulator circuits

We've already seen that the outputs of '78xx' regulators can be varied over limited ranges by simply applying suitable variable voltages to their common or reference terminals, even though these ICs are designed as fixed regulators. If, however, you need to vary the output voltages over fairly wide ranges, a far better solution is to use one of the special variable three-terminal regulator ICs, such as the 317K or the 338K.

circuit file

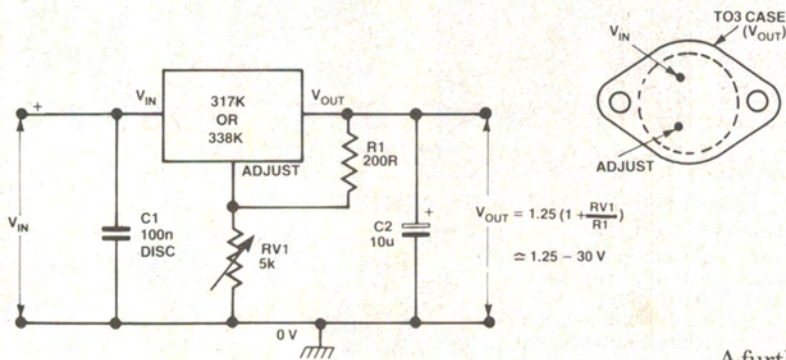


Figure 19. Case outline, basic data and basic application circuit of the 317K and 338K variable-voltage three-terminal regulators.

Figure 19 shows the outline, basic data and the basic variable-regulator circuit that is applicable to these two devices. Both devices have built-in foldback current limiting and thermal protection and are housed in TO3 packages, the major difference between the devices being that the 317K has a 1.5 amp current rating compared to the 5 A rating of the 338K. The major feature of both devices is that their 'output' terminals are always 1.25 volts above their 'adjust' terminals, and their quiescent or adjust-terminal currents are a mere 50 μ A or so.

Thus in the Figure 19 circuit, the 1.25 volt difference between the 'adjust' and 'output' terminals causes several mA to flow to ground via RV1, thereby causing a variable 'adjust' voltage to be developed across RV1 and applied to the 'adjust' terminal. In practice, the output of the Figure 19 circuit can be varied over the approximate range 1.25 to 30 volts via RV1, provided that the unregulated input voltage is at least 3 V greater than the maximum output voltage. Naturally, alternative voltage ranges can be obtained by giving R1 and/or RV1 alternative values, but it should be noted that for best stability the R1 current must be at least 3.5 mA.

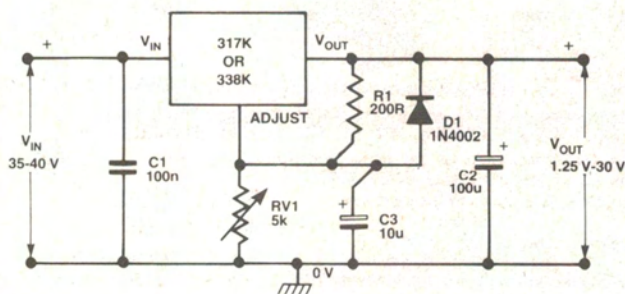


Figure 20. This version of the variable-voltage regulator provides some 80 dB of ripple rejection.

The basic Figure 19 circuit can be usefully modified in a number of ways. The basic ripple rejection factor of the Figure 19 circuit, for example, is about 65 dB, but this can be increased to 80 dB by wiring a 10 μ F bypass capacitor across RV1, as shown in Figure 20, together with a protection diode connected as indicated, to prevent the capacitor discharging into the IC if the regulator output is short-circuited.

PARAMETER	317K	338K
INPUT VOLTAGE RANGE	4-40 V	4-40 V
OUTPUT VOLTAGE RANGE	1.25-37 V	1.25-32 V
OUTPUT CURRENT RANGE	1.5 A	5 A
LINE REGULATION	0.02%	0.02%
LOAD REGULATION	0.1%	0.1%
RIPPLE REJECTION	65 dB	60 dB

A further modification of the Figure 20 circuit is shown in Figure 21. Here, the transient output impedance of the regulator is reduced by increasing the C2 value to 100 μ F; diode D2 is used to protect the IC against damage from the stored energy of this capacitor if an input short occurs.

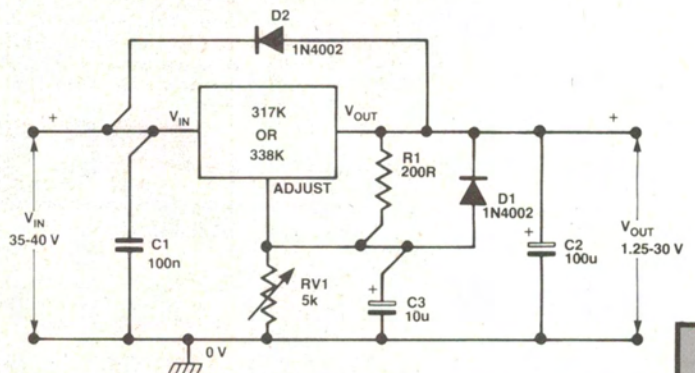


Figure 21. This version has 80 dB ripple rejection, a low impedance transient response and full input and output short circuit protection.

The minimum output voltage of the Figure 19 to 21 circuits is 1.25 volts. If you want the voltage to vary all the way down to zero, the circuits must be configured so that the adjust terminal goes to -1.25 V when RV1 is reduced to zero ohms. Figure 22 shows how this can be achieved, using a 35 V negative rail and a pair of series-connected diodes to clamp the low end of RV1 to -1.25 V.

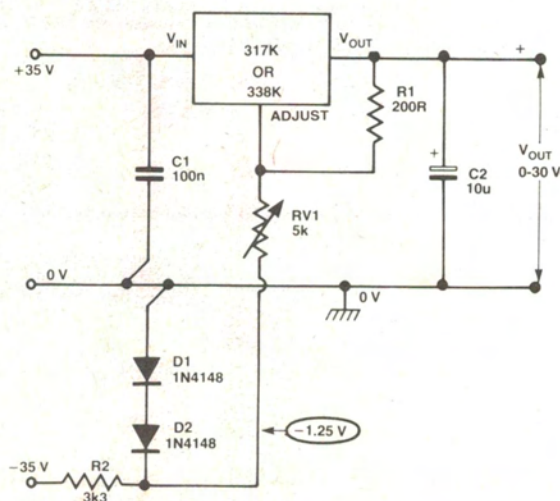


Figure 22. How to provide variable output that goes from 0 V to 30 V.

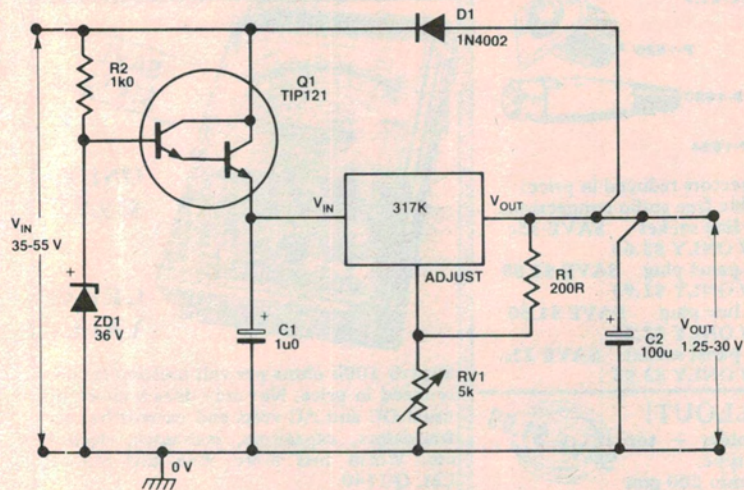


Figure 23. This variable voltage unit uses a pre-regulator (Q1) to give input over-voltage protection and improved ripple rejection.

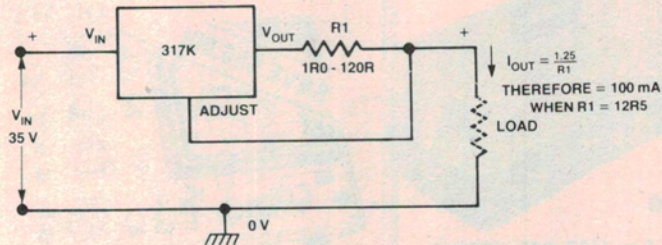


Figure 24. A method of using the 317K as a precision current limiter or constant current generator.

If you want to get the maximum possible voltage out of one of these regulators, you'll need to make sure that the input voltage does not exceed the 40 V rating of the IC. The best way to do this is to use a simple Darlington-plus-zener pre-regulator circuit, as shown in Figure 23, which enables you to use any unregulated input in the range 35 to 55 volts. Note that as well as giving input over-voltage protection, this pre-regulator also gives a further improvement in ripple rejection. If you want to use this circuit with a 5 A 338K regulator, you may need to reduce the value of R1 and beef up the power rating of the zener diode.

Finally, to complete this look at regulator circuits, Figure 24 shows how you can use the 317K as a precision current limiter or constant current generator in which the output current is determined by R1 and is virtually independent of the external load values. By suitable choice of R1, the constant-current magnitude can be set at any value between approximately 10 mA ($R1 = 120R$) and 1.25 A ($R1 = 1R$). Not bad for a two-component circuit!