Power Supplies and Voltage Regulators

Designing linear supplies, and looking at the 732, 317, 78XX and 79XX

Linear Power Supplies

The DC power supplies used for electronics and computers are of two main types, switching and linear, both supplied from the 120V AC mains. Switching supplies include a regulator, and are a special study, so they will not be mentioned further here. The linear supply is relatively simple and inexpensive, and in many cases is completely adequate. For some applications, a regulator is not required, either because the load is constant or because small variations in the output voltage do not matter. The basic ideas of linear power supply design will be presented here, and you should make a small supply just for the experience, if you have never done so before.

A linear supply consists of transformer, rectifier, surge-limiting resistor, filter capacitor, and bleeder. The transformer should have separate primary and secondary windings so that the output is isolated from the power-line ground. It is very dangerous otherwise, so isolation is important. A transformer cannot usually take a DC current through a winding, but if a winding is center-tapped, equal DC currents can flow from the center tap to the ends of the windings without inconvenience. Small currents can, of course, be tolerated. The rectifier is usually a full-wave bridge of silicon diodes, though two diodes at the ends of a center-tapped winding can also be used. The capacitor is a large aluminum electrolytic, up to 10 000 μF, and a voltage rating of 450 V. For higher voltages, capacitors may be used in series (halving the equivalent capacitance but doubling the voltage rating); the leakage in the capacitors will equalize the voltages. A resistor is used in series with the capacitor to limit the surge of current in the first half-cycle of operation, when the capacitor is uncharged. To handle the sharp power pulse, a wire-wound power resistor is required, though after the turn-on surge, it hardly dissipates any power at all. The bleeder resistance is connected across the capacitor to discharge it when the supply is turned off. It should carry up to 10% of the rated output current, and helps to stabilize the operation of the supply, eliminating any rises in voltage at very low currents that may occur. For high-voltage (> 50V) supplies, a bleeder resistor is essential to remove the hazard of an unexpected voltage in the filter capacitor when the supply is turned off. The bleeder resistor should be rated to dissipate the necessary power in steady operation.

The AC input should be fused, using a slow-blow fuse of about two or three times the normal input current. The purpose of this fuse is to save the power transformer if a filter capacitor fails, usually by becoming a short circuit, or if the rectifier fails, also usually by presenting a short circuit. This can happen even if the output is protected against a short by a voltage regulator. Usually, insufficient current flows in this case to open the protective device of the line, which may be 15 A or more, and is designed to prevent fire. The current may be more than sufficient to burn out the transformer primary, if it is rated for an ampere or less. The transformer is usually the most expensive part of the power supply, and is worth saving. The fuse may be in a fuse block inside the chassis; it is not worth much to have front-panel access to the fuse. It is also nice to have a pilot light to show when power is applied to the transformer primary, across which the pilot light should be connected. A neon lamp with dropping resistor is very satisfactory for this purpose.

It is not necessary to have a polarized plug unless the chassis is grounded to one side of the line--in that case, a polarized plug is mandatory. A metal chassis or box should be grounded to the green wire of a 3-conductor power cord for protection against shock. Any fault to the hot wire should trip the protective device of the AC supply circuit in this case. It is general practice to put a switch only in the hot wire, but with an unpolarized plug, both wires should be switched using a DPST switch to make sure the hot wire is switched. The white wire should never be directly connected to the chassis, even if it is ground. If the chassis is grounded, then it is safest to connect one side of a high-voltage DC output to the chassis, so that no fault placing the chassis at high voltage can occur. For voltages over 500 V, special care must be taken with protection, since such voltages can be lethal. For voltages less than 50 V, practically anything goes, since the shock hazard is minimal.

Low-voltage (below 50V) transformers, and the other components, are easily available. High-voltage transformers are difficult to locate, especially in smaller ratings, and can be quite expensive. The secondary voltage is specified as the rms value; the peak value will be 1.414 times greater. The no-load output voltage will be this peak value, and the output voltage will drop as the current supplied increases. If a regulator is used, the difference in voltages will cause a power dissipation that is greater, the greater the voltage difference. At maximum load, the output voltage need only be enough greater than the output voltage to operate the regulator. The series of 1A diodes, 1N4001 to 1N4007, have peak inverse voltage ratings from 50 V to 1200 V, and easily handle most modest rectifying tasks. Their peak surge current is 25 A, and you should analyze the circuit and choose the surge-limiting resistor accordingly.

The capacitor is sized on the basis of the permissible *ripple* in the output. To estimate the ripple, consider that the capacitor supplies the maximum output current I continuously, and is "topped up" to the output voltage every 1/120 s for a full-wave rectifier, and every 1/60 s for a half-wave. The charge drawn by the load is then I/120 C (full-wave) and this equals C?V, where ?V is the amplitude of the ripple. Therefore, C = I/120?V. The large values of C that usually result from this equation are easily supplied by modern electrolytic capacitors. This is called the "brute force" approach to reducing ripple. Older designs for high-voltage (300 V) supplies often used a pi-section filter of two shunt capacitors separated by an iron-core inductor of a few henries. This gave good filtering with much smaller capacitors. However, big capacitors are cheaper than filter chokes these days.

An important parameter in estimating the surge current is the quantity ωRC = 377RC for 60 Hz, where R is the resistance of the transformer secondary plus the surge resistor. If this quantity is less than 1, the filter capacitor charges up rapidly during the first half-cycle, and is almost fully charged by the end, 8 ms later. The maximum surge current is considerably less than the value E/R in this case, where E is the peak AC voltage, and occurs early in the cycle. On the other hand, if this quantity is large, several cycles are required to charge the filter capacitor, and the peak current approaches the value E/R more closely. As a very rough guide, if the quantity is about unity, then the peak current is about E/2R.

The differential equation governing the charging is iR + q/C = E sin ωt, with the initial conditions that i = q = 0 at t = 0. The solution of the equivalent equation i' + i/RC = (E/R) cos ωt is easily found by using the integrating factor exp(t/RC). The solution can be put into the form i = A[cos θ - exp(-D θ)] + B sin θ, where θ is the phase angle in degrees, A = (E/R)[k/(1 + k^2], B = kA, D = (π/180)(1/k), where k = ωRC. This formula can be evaluated numerically by a program on an HP-32 calculator (for example) in any particular case to estimate what the surge current will be. Such a program is shown in the box on the right, the program with the label A. At the top, the storage of the parameters is shown. To execute the program, enter the value of θ and press XEQ A. For example, if E = 850 V, R = 10Ω and C = 50 μF, we find k = 0.1885, and the maximum current to be about 14 A (much less than E/R = 85 A!).

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A← A          E← E
B← B          F← R
C← D          X← E0
X← θ

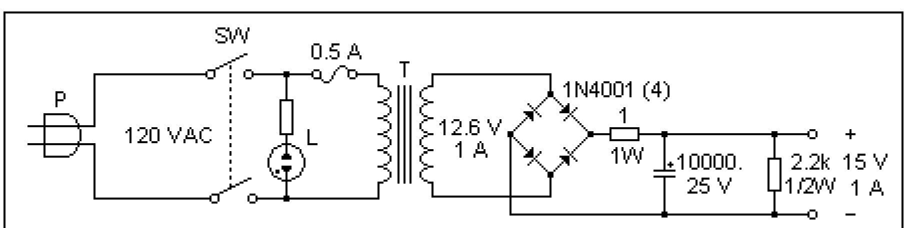
LBL A         LBL B         -
STO D         STO D         √
COS           RCL E         X↔Y
RCL D         ÷             -
RCL C         ASIN          2
*             →RAD          *
+/-           π             π
e^x           2             ÷
-             ÷             RCL F
RCL A         X↔Y           ÷
*             -             RTN
RCL D         RCL D
SIN           *
RCL B         RCL E
*             x^2
+             RCLD
RTN           x^2
```

HP-32 Programs

Moreover, the capacitor is charged to 834 V when conduction ceases. If E = 170 V, R = 10Ω and C = 1000 μF, k = 3.77, the maximum current is about 13.5 A.

Once the filter capacitor is charged to the output voltage, the rectifier supplies a pulse of charge each time the transformer secondary voltage E goes above the output voltage E_o. The current is $i = (E - E_o)/R$, and the charge is the integral of this from the phase angle $\theta_1 = \sin^{-1}$ (E_o/E> to 180° minus this angle, or twice the integral from $?_1$ to π/2. The charge is equal to the average output current I times T/2, where T is the period (1/60 s), for full-wave rectification. Therefore, the average output current $I = (2/\pi R)[\sqrt{(E^2 - E_o^2)} - E_o(\pi/2 - \theta_1)]$. Program B at the right evaluates this expression for any E_o. For E = 170 V and R = 10Ω, the output voltage is 160 V for 146 mA, 155 V for 269 mA, and 150 V for 414 mA. Note that the surge limiting resistor has an important effect on the power supply *regulation*, which is the change in output voltage caused by a change in output current.

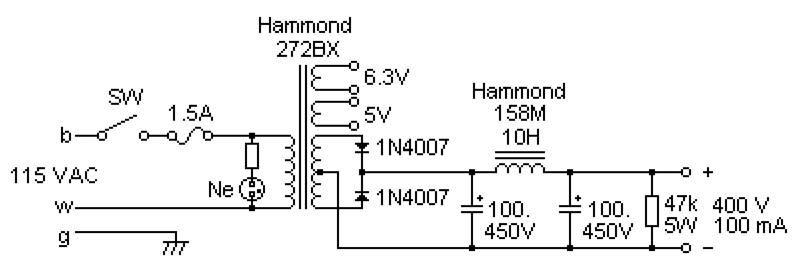
A typical low-voltage power supply is shown below. The power-line switch is shown as a DPST, which isolates the supply when OFF. If the plug is polarized, an SPST switch in the "hot" or black lead can be used. Do not put a switch in the white wire only, which may leave the supply "hot" when the switch is off, if the plug is reversed. A pilot light is shown across the AC supply to indicate when the supply is turned on; this is an NE-2 lamp in series with a 150k resistor, a very satisfactory pilot light. A fuse could be added if desired, which should be slow-blow to handle the turn-on surge. For small supplies, the fuse is inconveniently small, and is often omitted. Most voltage regulators handle output shorts quite well.



Brute Force (Linear) Power Supply

A supply may be constructed on perfboard, using terminal strips or press-in terminals as necessary. A TO-220 regulator should be mounted flat on the board with its heat sink, and not allowed to wiggle on its leads. Cover the AC wires; a cord switch can be used for economy. It is not necessary to enclose low-voltage power supplies, but high-voltage supplies should always be enclosed, either in a nonconducting box, or in a grounded metal box. If a metal box is used, a three-conductor power cord is appropriate, with the grounding wire (green) connected to the box. If there is nothing to ground, a three-conductor cord is redundant. If you do not already own a 5V, 1A power supply for digital logic, it is a good exercise to make one. A 6.3 V transformer will do, with a 7805 regulator. Everything else is the same as in the figure.

A high-voltage linear supply is shown below. Supplies like this were used for the B+, or plate, supplies for vacuum tubes. It is a full-wave rectifier using a center-tapped secondary, since bridge rectifiers were inconvenient with vacuum diodes. In this circuit, silicon diodes have replaced the vacuum diodes that were typically used. Note that the inverse voltage rating must be larger than the total secondary voltage, not just half of it. The transformer is rated 600 V CT at 100 mA, and also supplies low-voltage AC, at 6.3 and 5.0 V, for vacuum tube cathode heaters. The 5.0 V was used for the rectifier diode, the 6.3 V for the other vacuum tubes. The secondary resistance is about 200 Ω, enough to limit surge currents without an extra resistor. The filter is a passive LC filter--a pi-section, capacitor input filter--that works very well, giving scarcely detectible ripple in the output. The choke must be designed to handle the DC current without saturating (100 mA in this case). I use the supply as a variable high-voltage supply, feeding it from a Variac, to obtain voltages between about 150 V and 450V. The ratings of the diodes, capacitors, and the choke insulation are all closely approached. When plugged into full 120V without a reasonable load, a dummy load of 10k or so (25W!) should be used to avoid excessive voltage, which can rise to about 500 V. Nothing fails at this voltage, but it is best to stay below it. All the components are currently available, and the total cost is about $100.



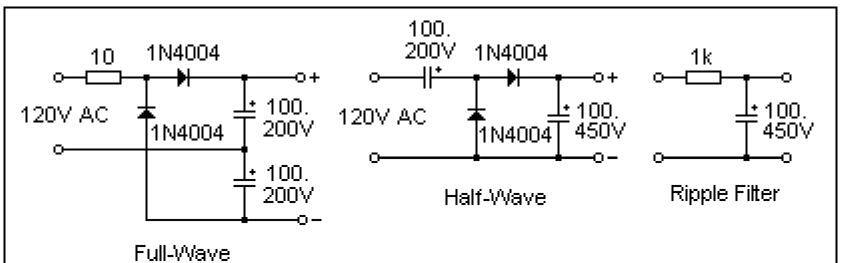
DC B+ Supply (40 W)

Other DC supplies are mentioned in the page on Vacuum Tubes, and the use of isolation transformers is discussed.

Voltage Doublers

We will see in the page on switched capacitors that we can create a negative supply from a positive one, or produce multiples of a given voltage, by charging capacitors in one configuration and discharging them in another, using CMOS switches. We can let an alternating current do its own switching, with the aid of diodes, to produce a similar effect. The most useful is the *voltage doubler* that produces a DC voltage twice what a straightforward rectifier would produce. These circuits were used with vacuum-tube radios to avoid the expense of a power transformer, which often cost as much as all the rest of the radio together. These AC/DC radios represented a shock hazard because of the grounding of the household supply. If the plug went in the right way, then the radio's ground was also the supply ground, which was actually ground, and all was well. If the plug was reversed, then the chassis became 120 V "hot" with respect to things like radiators and pipes. The chassis was usually still "hot" even when the set was switched off. Today's polarized plugs reduce the hazard considerably, provided everything is wired correctly. Another use of a voltage doubler is to get higher voltages than a transformer may conveniently give, for things like cathode-ray tubes.

Voltage-doubler circuits are shown below. There are two varieties, called "full-wave" and "half-wave" although in each case the ripple frequency is equal to the line frequency (not double it, as in a true full-wave rectifier). The diodes must withstand the doubled voltage, but the voltage rating of the capacitors depends on the circuit. The half-wave circuit has the great advantage that there is a common conductor, which can be taken as ground. An interesting safety modification is to use only one conductor in the line cord, to be connected to the hot wire. The other conductor is tied to a pipe or other ground, guaranteeing that the chassis will be ground. If the plug is reversed, there will be no current.

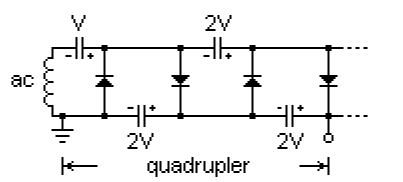


Voltage Doublers

The ripple is calculated the usual way, by considering the constant current drain on the capacitor charge. The circuits shown yield a bit more than 300 V. The ripple of either circuit will be around 0.15 V (in the full-wave circuit, the ripple of the two capacitors is in antiphase). An RC ripple filter as shown will reduce the ripple by 95%, at a load current of 10 mA. For larger currents, simply increase the size of the capacitors. Also, it is a good idea to add a surge resistor to limit the inrush current to less than 15 A when the circuit is turned on. This requires about a 10Ω, 3W resistor in series with the

AC supply, as shown. Do *not* use a 1/4 W resistor because the average dissipation is small. If you do, it will disappear in a flash of glory when you turn the switch on!

These circuits can be investigated at lower voltages by using the function generator as a source. The full-wave doubler is also a bipolar supply, where ground is taken at the junction of the capacitors. For an input voltage of 6.64 V (rms), the full-wave circuit gave 14.11 V, the half-wave 13.85 V, with a load of 10k (about 1.4 mA). The capacitors were 470 μF.



Voltage Multiplier

The doubler principle can be extended to arbitrary multiplication, as shown in the circuit at the left. The half-wave doubler will be recognized at the left-hand end, near the transformer. The transformer is shown grounded so that voltages of 2V, 4V, and so forth, can be picked off. If it is grounded on the other side, we have available V, 3V, 5V, and so forth. As the number of sections increases, insulation is an increasing problem, and the current that can be supplied becomes smaller. Quite large voltages can be obtained; this principle was used in the Cockroft-Walton accelerator for charged particles.

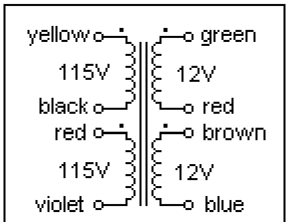
A voltage multiplier is an attractive high-voltage, low-current supply, as required for cathode-ray tubes and photomultipliers. An example of a voltage sextupler is described in Photomultipliers, as well as a cheap high-voltage supply based on an electromagnetic buzzer. The existence of silicon diodes makes the multiplier much easier to realize than when thermionic diodes had to be used. The multiplier is easy on the voltage ratings of components, which must resist only the stage voltage, not the total voltage.

Transformers with Multiple Windings

One frequently sees transformers with dual primaries, so they can be connected for 115 or 230 V, and with dual secondaries, to offer flexibility in output voltage and current. These transformers offer further possibilities, in which the secondaries may not actually be used. They can be connected as step-up or step-down autotransformers, or as an isolation transformer, and are specially applicable when the power required is small.

Transformers are designed on the basis of volts per turn, which ensures that the magnetic flux does not reach saturation. Therefore, a transformer should not be used at a higher voltage than its rating. If it enters flux saturation, the magnetizing current will increase and the transformer will overheat. The same thing happens if the transformer is used at too low a frequency, but there is seldom an opportunity for this. So far as transformers are concerned, 50 Hz and 60 Hz are about the same thing. A transformer can always be used at a lower voltage or a higher frequency than intended by the designer. If a transformer runs hot, say 85°C or so, it is being abused, and its life will be short. Small transformers typically run warm, so do not be put off by this. The heat comes from core losses as well as from copper losses, so it appears even if the transformer is not loaded.

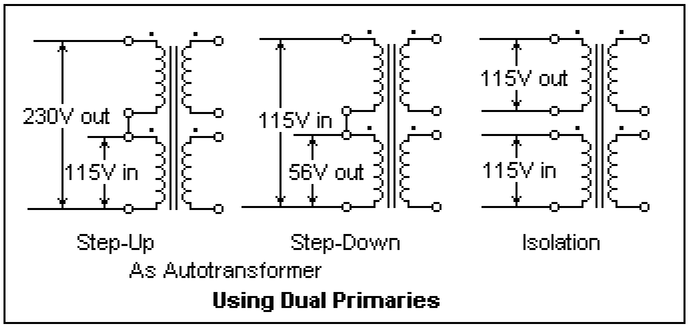
If you have a transformer but no specifications, the power rating can be estimated from the weight of the transformer, comparing it with others of known rating. The DC resistance of the windings gives some clue as to their current ratings, and shows what is connected to what. Center taps can be identified. An AC voltmeter or an oscilloscope can be used to estimate the turns ratio and phasing of the transformer. Use a function generator instead of the power line, for safety and convenience. If the intended primary voltage is known, then the transformer can usually be satisfactorily specified and safely used.



Talema 62062-P2S02

An interesting and useful small transformer is represented by the 25 V-A Talema 62062-P2S02, whose connections are shown at the right. It is quite reasonably priced ($13). The polarity dots for each winding were determined with the oscilloscope. A positive voltage applied to one gives a positive voltage at the others. This transformer has well-identified colored leads, which is excellent practice. The permissible rms primary current is 25 / 230 = 0.109 A, in each primary winding. It is suggested that the primary be fused for 160 mA. The secondaries are each rated at 1.041 A.

This is a *toroidal* transformer, in which the core is an iron toroid, surrounded by the windings. In the more familiar small transformer, the iron surrounds the copper (for convenience, not completely), while here it is the other way round. Classically, transformers were called *shell* or *core* types, depending on whether the windings were on the same or separate legs of the core. A toroidal transformer seems to be an ideal type of core transformer. The efficiency of the transformer is given as 84%, which is good for such a small machine. It can be mounted with a 1/4" bolt through the center.



The different ways the primaries can be connected and used are shown at the left. We can have a step-up to 230 V, or step-down to 56 V. In either case, the output circuit is not isolated from the input, as is typical with autotransformers. Note that this connection is made possible because the two windings link the *same* magnetic flux. Two separate transformers cannot be used in this way. An isolation transformer is also possible, and is useful because such transformers are not common in small ratings. In all of these circuits, the secondaries are not used, and are left open.

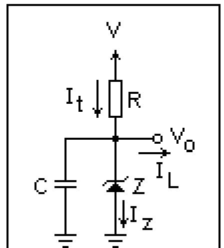
Two separate transformers can provide isolation if their secondaries are connected together. This should work fairly well if the demands are modest, but the combination will not have high efficiency. However, it may be an inexpensive solution to the problem.

Voltage Regulators

Suppose you have a load taking 50 mA at 5 V, but a 12 V supply. A resistance (12 - 5)/0.05 = 140Ω in series will drop the voltage appropriately. If the load is absolutely constant, such as an LED, then a series dropping resistor is quite satisfactory. There is some power loss in the resistor, 350 mW, so we'd better use a 1/2W resistor in place of the usual 1/4W one, but this is not serious. We can think of this as a 5V source with an internal resistance of 140Ω (presuming the 12V supply ideal), which is really not a very good voltage source, which should have a low internal resistance so the output voltage does not change much if the current changes.

If our load is constant on the average, but has sharp current spikes (like digital logic circuits), the matter can be handled by a capacitor in parallel with the supply. This has to have a pretty large capacitance in most cases, since its reactance should be much less than the internal resistance of the source it is de-spiking. In this case, if we expect spikes that are shorter than about a millisecond, a capacitance greater than about 1/(2π)(140)(1000) = 1.1 μF would do. For larger capacitances, electrolytic capacitors are normally used. The best are tantalums, but aluminum electrolytics will do if they are made somewhat larger (they are worse at high frequencies than tantalum). Some say that 1 μF in tantalum is equivalent to 25 μF in aluminium. Take care with the polarity, since electrolytics cannot stand reverse polarity. The supply internal resistance and the capacitor form a low-pass filter. If the supply has a small internal resistance, a series resistor is usually added so the capacitor does not have to be impracticably large. Of course, for an ideal (low-impedance) supply, no spike filter is necessary anyway.

If 140Ω is not small enough for you (it would not do if you were supplying digital logic, which has a narrow supply range) there are alternatives. A good one is the Zener diode. This is a PN junction used with reverse bias. At some reverse voltage, the junction breaks down and thereafter the current increases very rapidly with applied voltage. Therefore, the voltage across the diode is roughly constant whatever the current through it, and we have something that can keep the voltage constant. For narrow junctions with their low breakdown voltages, breakdown is by quantum-mechanical tunneling across the narrow barrier, called the Zener effect. For wider junctions and higher voltages, the breakdown is by electron avalanche, which occurs when the voltage is high enough to give the electrons enough energy to knock other electrons into the conduction band. The diodes are called Zener diodes, however, whatever the mechanism. They are commonly available with voltages from 3 to 50 V.

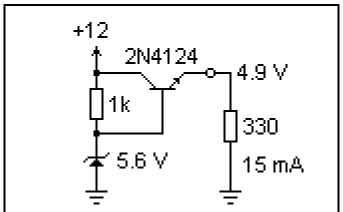


Zener Regulator

A Zener regulator is shown in the diagram. The dropping resistor R is an essential component, its value given by $(V - V_o)/I$, where I is the desired output current plus 10%. The current in this resistor is constant as long as the supply voltage V is constant, and is shared between the Zener and the load. When the load is removed, all the current passes through the Zener, and with the maximum load, the Zener current only consists of the 10% extra. If the Zener current drops to zero, then it ceases to regulate and we have an ordinary voltage divider. Therefore, we allow about 10% extra to make sure this does not happen. The power dissipated in both the dropping resistor and the Zener diode must be considered, and suitable power ratings applied. Small Zeners are available in 1/2W and 1W sizes. The 1N4733 is a 1W Zener, while the 1N5231 is 1/2W; both have a Zener voltage of 5.1V.

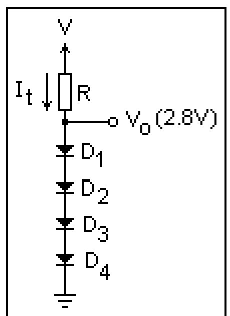
If you set up a 5.1V regulator with R = 100Ω (1/2 W!) and a 1N4733, you can measure the output voltages for a range of load resistances from infinity down to 100Ω, which correspond to currents of 0 to 51 mA. The current in R is about 69 mA in this case. If you connect a 51Ω (1/2W) resistor as a load, you will see that the voltage is no longer held at about 5 V. The voltage drops somewhat at the higher load currents, because the Zener voltage changes slightly with current (as the load current increases, the Zener current decreases, and so does the Zener voltage). The slope is expressed as the

Zener resistance, which is the change in voltage divided by the change in current. In this case, I measured about 5Ω (which is really the Zener resistance in parallel with R). This is a pretty good voltage source. It is drawn with a despiking capacitor, which is not necessary for the experiment here. The input voltage to the Zener regulator can also vary, without affecting the output voltage. Only the total current is changed in this case.



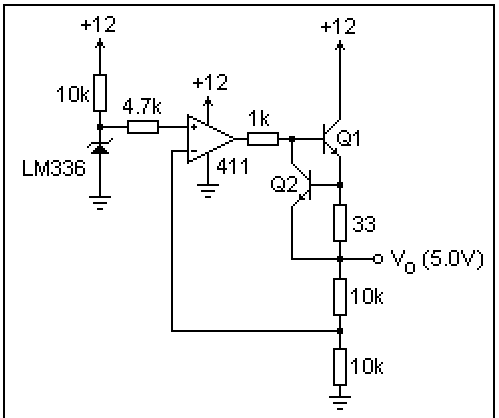
Zener with Pass Transistor

For more output current, or to save Zener dissipation, the Zener can be helped out by a *pass transistor* that actually does the job, the Zener establishing its base voltage. The output voltage is the Zener voltage less the drop in the emitter of the transistor. A 5.6 V Zener is about right for a 5 V digital supply (they don't seem to make a 5.7 V Zener). A test circuit is shown at the left, that is supplying about 15 mA to its load, while the Zener dissipation is only about 36 mW. The circuit could supply more current, say 85 mA, without difficulty, except that the power dissipation in the pass transistor would be 600 mW, near its limit. For more current, a power transistor with heat sink would do. A 470Ω dropping resistor instead of 1k would give up to 10 mA base current, enough for an output of 400 mA or so, with a Zener dissipation of only 76 mW. A power Darlington could also be used as a pass transistor, with a greater forward drop, but requiring very small base current. A large electrolytic capacitor from the base to ground can solve noise problems, if there are any. The drawback to this circuit is that there is no current limiting in case of an output short, and the addition of a current sensing resistor on the output side would hurt the voltage regulation. A fuse is probably the best answer to this problem. The idea of using a pass transistor is applicable to most power supplies, as we shall see below.



Diode Regulator

Should you require a smaller voltage, less than 3 V, one possibility is a string of diodes, as in the figure. These diodes are biased in the forward direction. Since the current increases rapidly with voltage, they can be used as a voltage regulator. The incremental resistance of each diode is about 50Ω/I, where I is the diode current in mA. In a transistor, 25Ω appears instead of 50Ω--diodes are made somewhat differently, and the actual figure is somewhere between 25 and 50, depending on the diode. In this case, we choose a diode current of 20 mA, so the internal resistance of this regulator is 4 x 2.5 = 10Ω, in parallel with the dropping resistor. Either signal or rectifier diodes can be used. The 1N4001 will handle diode currents up to 1 A. The reverse breakdown voltage, usually an important parameter, is of no consequence here.



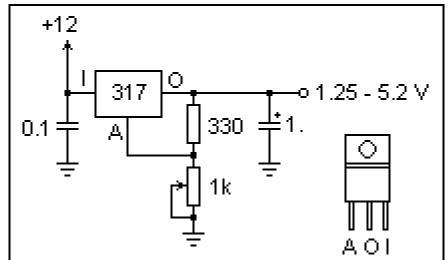
Voltage Regulator with Current Limiting

We can do very much better with feedback, and achieve a nearly perfect voltage source. The principle is shown in the circuit at the left. The output voltage is compared with an accurate voltage source, such as the 2.5V LM336, using a voltage divider either on the output or the voltage reference to get the desired voltage, and the difference drives an operational amplifier that acts to reduce it to zero, by controlling a pass transistor. This circuit has the added feature of current limiting, which protects against a shorted output. When the voltage across the current-sensing 33O resistor rises sufficiently to turn on Q2 (about 0.7 V), Q2 draws extra current from the op-amp output. The op-amp tries to maintain the output voltage, but eventually saturates, and then the output voltage can drop. The 1k resistor is there to help the amplifier to saturate when this happens (it would saturate anyway, since the output can only source about 20 mA, but the resistor does it more gently). Practically all advanced voltage regulators include current-limiting, as well as other protection against unfortunate events. One example is the output "crowbar" which shorts the output (bringing current limiting into action) if the voltage rises too high, for example if the pass transistor should fail. This can be done with an SCR.

Construct this voltage regulator example, and test it for various loads, noting the current-limiting action, which is set here for about 20 mA. Up to a load of 220Ω (23 mA) the output voltage was steady at 4.94 V all the way from no-load. With 150Ω the output voltage dropped to 3.76 V, and to 2.69 V for a 100Ω load. Check to see that the op-amp is saturated when the voltage begins to drop.

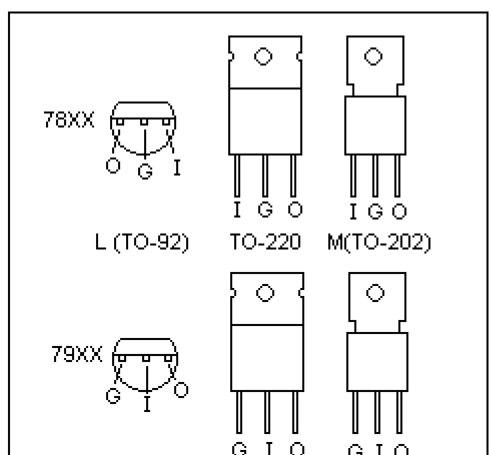
A similar vacuum-tube voltage regulator is described in the page on Vacuum Tubes, under Power Triodes, which gives a regulated 144V from a 175-275V input.

The 723 voltage-regulator integrated circuit contains all the items necessary to make such a regulator, except for the external resistors and a frequency compensation capacitor. The voltage standard is 7.15 V, and the output can range from 2 to 37 V. There is a high-voltage version for somewhat higher output voltages. The maximum current of the internal pass transistor is 150 mA, but an external pass transistor is easily connected as a Darlington to provide any current desired. This IC is well covered in The Art of Electronics.



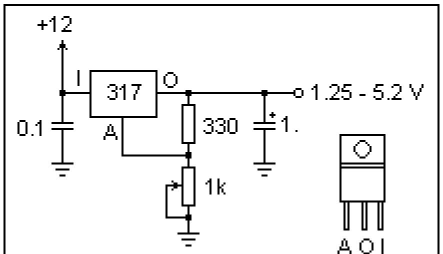
Variable Supply

Even easier to use are the three-terminal regulators, which look like transistors and have, not surprisingly, three terminals. One is the input, one the output, and the remaining one is an adjusting input. The LM317 comes in a TO-220 power transistor package, with the tab connected to the output terminal. It can be used up to a difference of 40 V between input and output, and supplies up to 1.5 A. The circuit for a variable output voltage regulator is shown at the right. Internal circuitry holds the voltage between the adjustment terminal A and the output terminal O at 1.25 V (actually, somewhere between 1.2 and 1.3 V). Whatever current passes through R_1 also passes through R_2 (except for the 50 to 100 μA that the adjustment terminal requires) and sets the output voltage. This is given by $1.25(1 + R_2/R_1$ V, and the current through the resistors should swamp the adjustment current. There is a minimum output current of about 3.5 mA required for the internal circuitry to work properly, and this can be supplied by the voltage adjustment resistors. A potentiometer is not generally used, and these troublesome components are not recommended. The 317 is the choice when you need an arbitrary, nonstandard voltage. Capacitors are recommended at input and output, as shown in the figure, to enhance stability. The 1 μF is a tantalum; use 25 μF if it is aluminum. Above 25 V output, a diode should be connected between output (A) and input (K)to allow the capacitor to discharge safely if the input is shorted, instead of going through the 317. If a large capacitor is used to bypass the adjustment terminal to suppress ripple, a diode is also needed in this case between the adjustment terminal and the output. The diodes have nothing to do with the operation of the regulator.



Three-Terminal Regulator Connections

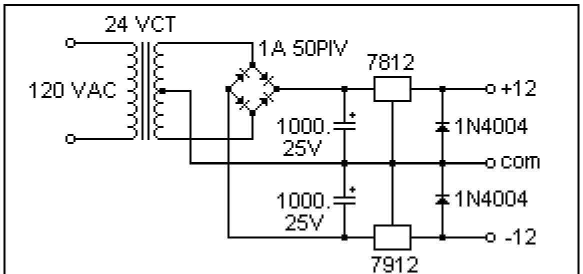
For voltages of 5, 12 and 15 special three-terminal regulators are available that require no external resistors at all. The adjustment terminal is simply a ground terminal. The connections of these regulators are shown in the figure. The L versions (TO-92) supply up to 100 mA, the M versions (TO-202) 500 mA, and the regular versions (TO-220) up to 1 A. All are protected against excessive dissipation as well as against a short circuit. They will give more current if properly heat-sinked, and all except the L versions should generally be arranged with good heat sinks. The 78XX series are positive regulators, while the 79XX are negative regulators, so that regulated bipolar supplies can easily be constructed. Curiously, the pinouts are different in the two series, as can be seen from the figure, and should be carefully observed.



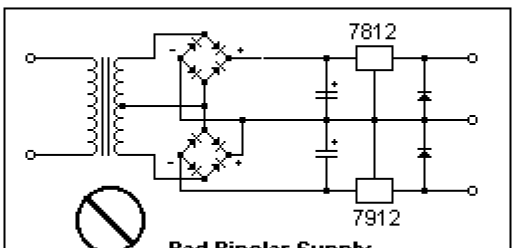
Variable Supply

Positive and negative regulators are connected as shown in the figure. Note that the connections are quite different, and that one of the terminals is "ground.". A negative voltage, one below ground, is applied to the negative regulator. A positive regulator cannot the turned around and used as a negative regulator, in any case. The output capacitor is optional, but improves transient response. The input capacitor is needed only if the regulator is far from the unregulated supply.

Bipolar supplies are often required, for op-amps and other circuits with signals that swing above and below ground. They are usually symmetrical, such as ±5 V, ±12 V or ±15 V. Such supplies can be made from independent supplies connected in series, with the common terminal serving as ground. In this case, negative regulators are not needed. You may wish to use a center-tapped secondary on the power transformer for this purpose. The correct way to do this is shown at the right. A ± supply is first made using a single bridge rectifier, which is then connected to the regulators. The diodes protect the regulators in case of a short between the outputs, which otherwise would have a nasty outcome.



Bipolar Suppy from Center-Tapped Secondary



Bad Bipolar Supply

A way NOT to do this, suggested by the use of independent supplies, is shown at the left. Each half of the transformer secondary has been used to make an independent supply, using a negative regulator to reference the negative output to ground. This supply does indeed produce ±12 V as expected. Unfortunately, there is also a short circuit for the secondary through the diodes. If you test the circuit, the diodes can probably stand the short, but the transformer cannot, and there is soon heat and smoke. Trace the short circuit from one end of the secondary to the other. The problem is that we have connected the plus and minus supplies at two points, which are incompatible. Such educational surprises crop out in electronics from time to time.

Fuse Protection

This is a reasonable place to discuss various forms of *protection* of electronic apparatus. One very common type of protection is from failures in the apparatus itself, that cause it to draw excessive current. The purpose of this protection is to save expensive components that otherwise might be ruined, such as power transformers. The AC power line includes its own protection against overcurrent, so we do not have to worry on this score. Overcurrent protection is provided by *fuses*, which are heated by the current and melt, breaking the circuit. The fuse is heated by I^2R loss, and loses heat by conduction to the supports and by conduction and radiation into the air surrounding it. Fuses generally operate rather slowly, but, it is hoped, more rapidly than the protected apparatus heats up.

A fuse has not only a current rating, but also a voltage rating. The voltage rating should not be exceeded, or the fuse might not break the circuit properly. Alternating currents are easy to break, and most fuses are used with alternating current supplies, with a rating, say, of 250 V. The same fuse might have a DC rating of only 50 V, showing the greater difficulty of breaking a DC circuit. Unless there is better information, this factor of 5 will give a guide.

The commonest fuse sizes for electronic apparatus are 3AG, 1/4" x 1-1/4", or the somewhat smaller "metric" size of 5 x 20 mm. These will usually break up to 250 VAC, and come in current ratings of up to 10 A or so. The smaller 2AG size, 0.177" x 0.57", is also available. These fuses will remain intact at their rated current for an indefinite time. At 110% of the rating, they will not open in less than 4 hours. At 135% of the rating, however, they will open within 1 hour. At 200%, they will open in roughly 5 seconds. A "fast-blow" fuse will open in less than 5 s, while a "slo-blow" fuse will open in more than 5 s, at this overload. At 4 times the current rating, a fast-blow fuse may open in 10 to 300 ms, while a slow-blow fuse will take 0.15 s to 3 s. At higher overcurrents, any kind of fuse will open sooner, and there is not much difference between slow-blow and fast-blow. A fuse will require at least 10 ms to open in any case, so sensitive components like chips and transistors will not be protected well by fuses. At least the connecting wires will not melt.

A slow-blow fuse has some extra thermal mass that is effective at moderate overloads, so the fuse will not blow during a turn-on transient. It seems that even a normal-blow fuse will survive the turn-on surge of tungsten lamps (I have not verified this, but plan to). Motors start somewhat more slowly, and generally require slow-blow fuses. Power supplies with large filter capacitors may also have a turn-on surge while the capacitors charge, that occupies 100 ms or so, and also require slow-blow fuses.

Surge Protection

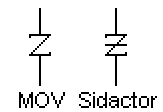
The other protection challenge comes down the wires into the apparatus, and fuses are of little help here. Generally, there is a voltage surge for a short period. The AC power line can experience surges of 1 kV or so from switching transients. Although these protection devices are often called "lightning arresters," there is little that can be done against actual lightning. Much more common, though are surges resulting from earth currents, nearby lightning strikes, and so forth. Any wires that run outside the building are subject to these surges, as was soon found out when telegraph lines were constructed.

The first protection device was a sharp point connected to the line near a grounded conducting plane. When the air gap broke down with a spark, a low-resistance path was created for a short time between the line and ground, bypassing the surge. Some inductance was usually provided between the protector and the apparatus to encourage the surge to leave the equipment alone. These protectors worked quite well, and (in some form) are still necessary on the telephone lines entering a building. Spark gaps will not protect against the smaller, but still damaging, surges on power lines.

Another device was a carbon lightning arrester. Apparently, this kind of device had a path that was normally of high resistance, but became a low-resistance shunt when excessive voltage was applied. I cannot find any such devices in current catalogs, so have no details to mention. However, they work much like the modern surge absorbers mentioned below.

A gas discharge tube, consisting of two electrodes in a bulb filled with some gas at low pressure, would act just like a spark gap, but breaks down at a lower voltage. When the discharge is established (which requires some milliseconds), a low-resistance path is created to bypass the surge. Such devices were used in a military field telephone system, since they responded to the ringing voltage, giving a visual indication, as well as providing surge protection to the telephone. Even an NE-2, which breaks down at 60-70 V, can provide some protection when connected between a line wire and ground. There should be no series resistor, of course, since this would defeat the protection.

Back-to-back Zener diodes provide very good protection. They operate rapidly, but cannot absorb a great deal of power. PNPN devices, known under the trade name of Sidactors, are more rugged and can be obtained with breakdown voltages of 60-660 V. Note that such triggering devices will be automatically restored at the zero crossings of an AC signal.



Surge Protector Symbols

A very useful protective device is made from ceramic metal oxides. The general term for such devices is *varistor*, which describes resistors whose resistance depends on the voltage across them. They are also called MOV's (Metal Oxide Varistors) or ZNR's (Zinc Nonlinear Resistor), by different manufacturers. Zinc oxide and Strontium Titanate are typical materials used. They may resemble ceramic capacitors (except that the coating is shiny, not matte) and test open by DMM, so they may be confused with capacitors. Usually, they are bilateral, and are not polarized. Symbols found for these devices are shown at the right. One really should use the symbol for a nonlinear resistor, but I have not seen this used yet.

Test a low-voltage MOV, such as a V8ZA2 (from Hosfelt), by connecting it in series with a 1k resistor. Measure the voltage across the MOV as the voltage to the series combination is varied, and make a V-I plot for the MOV. Up to about 5 V, the MOV was simply an open circuit. Then, the current curve bent rapidly upwards between 7 and 8 V, as the resistance dropped quickly. This is an almost ideal protector characteristic. MOV's operate in 50 ns, according to Panasonic, which is certainly fast. The MOV is simply connected directly across the power lines. A V130LA20B turns on at about 175 V, so it is just right for 120 VAC power lines. It can stand surge currents of 100 A and 70 J energy. Here is excellent protection for less than a dollar. Connect it on the line side of any RFI filter that you may be using (series inductance and shunt capacitance to filter out high frequencies on the power line).

Source: http://www.co-bw.com/DIY_Power_Supplies.htm