CRYSTAL SETS TO SIDEBAND © Frank W. Harris 2025, REV 16

Chapter 8

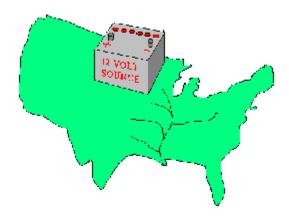
POWER SUPPLIES

Once you progress past crystal sets, electronic projects almost always need a power supply. Low power projects, like a small receiver, can be powered with flashlight batteries or even a little 9 volt "transistor" battery. Other convenient sources of low power DC are *adapter plugs*. These are the black cubes a few inches square that plug into the wall and have a long, skinny cord that plugs into your recorder or small appliance. They deliver 6, 12 or other DC voltage at a few watts. Adapter plugs have the safety of a battery with the convenience of wall power. On the other hand, their voltage may have high AC (50 or 60 Hz) ripple noise and need to be filtered to make pure DC like a battery.

Power supply requirements

If you plan to power your QRP with household power, you'll need more than a few watts. A 5-watt transmitter needs at least 10 watts of power with good voltage regulation to get rid of the ripple. Otherwise AC ripple on the DC will go right out over the air as a hum or buzz. When you decide to plug a homebuilt circuit into the wall, you must confront some significant safety issues. Line-powered power supplies convert 120 volts AC into DC voltage at the required levels of voltage and current. (In much of the world 220 volts AC at 50 Hz is standard.) Actually, a transmitter can also be thought of as an energy conversion device. It converts direct current into radio frequency current. In this chapter I'll describe some power supplies you could use for your QRP and higher power transmitters.

The ideal power supply is called a *voltage source*. An ideal "voltage source" is a power supply that can supply infinite amounts of current without the slightest change in the voltage. For example: As every northern resident knows, starting a car can be difficult when the temperature is below zero. A cold battery does not supply as much current as a warm battery. So, when you turn the ignition key on a frigid morning, the battery voltage crashes.



On the other hand, if you had a battery the size of North Dakota, the voltage would not drop a microvolt when you started the engine. Moreover, you could start all the other cars in

Minnesota simultaneously without voltage drop. Of course, there are also other practical issues here. For example, your battery would need zero resistance battery cables, zero resistance connectors, etc. Well, you get the idea: The ideal voltage source should not lose any voltage, no matter how much power it supplies. Using ham radio vernacular, a good power supply is a "stiff" supply.

Lab power supplies

A reliable, line-powered laboratory DC power supply is useful for building and testing circuit boards. Every well equipped electronics labs needs one. A big advantage of commercial lab supplies is that the voltage is adjustable from zero to some relatively high level like 20 volts DC. Meters show you the current and voltage at every moment, so you know what is happening. Variable voltage allows you to power up a new circuit *CAREFULLY*. You can start with a few tenths of a volt and see what happens. If the circuit is shorted, you can find out with one volt applied to the circuit board, rather than blasting it with 12 volts right away. This helps you avoid burning up expensive transistors.

Many lab supplies put out two or even three separate supply voltages at once. Some supplies, like the old Heathkit shown below, can be configured to produce simultaneous, equal, positive and negative DC voltages. This is useful for powering operational amplifier circuits which work with analog waveforms referenced to zero volts. Some lab power supplies automatically limit the available current to some maximum that you select.



This old Heathkit supply above has 3 supplies in the same enclosure. If needed, I can wire them in series for a total of 45 volts. Bench power supplies are quite generic and you don't need a modern one for reliable service. If you like, you could build your own from the designs presented in this chapter.

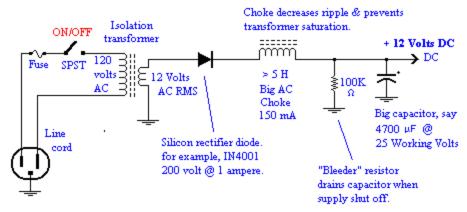
Power supply needed for a QRP

To power your QRP you need at least about 1.0 ampere at 12 volts DC. A typical modern, transistor QRP transmitter runs on a 12 volt power supply but its efficiency is only about 50%. Therefore, the bare minimum you will need is

10 watts = 12 volts x 800 milliamperes

Homebuilt power supplies for use with rechargeable batteries or line power are described below. If you aren't familiar with power supply design, a discussion of the basic principles follows.

Simple wall-powered supplies using 120 Volts AC



SIMPLE LINE-POWERED 12 VOLT POWER SUPPLY.

(NOT SUFFICIENT FOR QRP)

The diagram above illustrates the simplest, safe, generic, line-powered power supply you can build. Unfortunately, this supply is too poorly regulated to power a transmitter. However, it illustrates the minimum safety features and it's easy to explain.

The following discussion assumes that the reader lives in North America where the standard household line voltage is 120 volts AC RMS @ 60 Hz. The safety issues explained here are applicable to other regions of the world. However, voltages, connector types, wire color codes and ground configurations are often different. For example, in Europe the standard is 220 volts AC RMS @ 50 Hz.

Power supply safety

Metal enclosures. The supply should be enclosed in a box to insure that children (and you) won't get fingers across the 120 volts AC. Ideally the box should be made of <u>metal</u> so that, in case of a short circuit, a fire is highly unlikely.

Another safety design philosophy is called *double insulation*. In this scheme the electronics are housed in a *plastic* box and extra effort is made to insure that the internal wires are properly protected so that shorts and loose wires are highly unlikely. A double insulated plastic box does not necessarily need a ground wire in the line cord. However, for ham applications, metal boxes also shield circuitry from stray radio waves and are usually the best choice.

Line cord. The line cord should be the modern, three-wire type with the (green) ground wire securely connected to the metal box. In case a loose wire in the box causes the hot side of the AC line to touch the metal box, the ground wire will safely shunt the AC current to ground.

The line cord should pass into the metal box through a *rubber grommet* so that the metal edge can't cut through the insulation on the wire and cause a short circuit. Once inside the box, the cord should be held captive by a clamp, properly known as a *strain relief*. The strain relief insures that if the power supply is ever yanked by its cord, the live wires will not be ripped loose and short out.

The wires in a line cord are usually color-coded. The "hot" wire usually has *black* insulation while the "neutral" or return wire is *white*. The third *green* safety wire is connected to power line ground. It should be connected directly to the metal chassis. The neutral wire is also supposed to be connected to the house ground buss out in the circuit breaker box. Looking at a North American household three-prong socket, the round pin is the "ground" and is connected to the green wire. The wider, flat pin is the neutral side and the narrower flat pin is the "hot" pin. Unfortunately, sometimes wall sockets are wired wrong, so it's better not to bet your life on the orientation of the flat pins. In previous revisions, I had the narrow and wide pins reversed. Nate Bargman, NØNB, set me straight. The lesson for us old guys is ... don't trust your memory!

Fuse. The first destination of one of the two power wires, preferably the "hot" black lead, should be a *fuse*. As you probably know, fuses are little pieces of solder-like lead mounted in a glass tube. When the current exceeds some calibrated level, like one ampere, the lead melts and the circuit opens. Fuses, of course, can only be blown once and can't be reused. A fuse is represented on the diagram by the squiggle in the diagram labeled "1A," meaning "one ampere." The electrical standards allow a fuse to be considerably larger than necessary. For example, 5 ampere fuses are OK even though only 20% of that much current is expected.

Small *circuit breakers* serve as reset-able fuses and are available in low current levels such as 3 or 5 amperes. Some large circuit breakers are incorporated into ON/ OFF power switches. The safest ones switch and protect both sides of the power line.

Switch. The power switch can switch just one side of the line, such as the single-pole, single-throw (SPST) switch shown above. Or, it is even safer to switch both sides of the power line at once using a double-pole, single-throw switch (DPST). The switch for a QRP supply should be rated for at least 125 volts AC and 3 amperes.

The transformer

After the power switch, the line current usually goes to the primary winding of a transformer. The transformer has two functions: first, it *isolates your power supply from the household supply* and from ground. This makes electrocuting yourself much less likely. As explained earlier, the AC lines supply 120 volts AC referenced to ground. The transformer secondary winding delivers AC power that has no relation to ground at all.

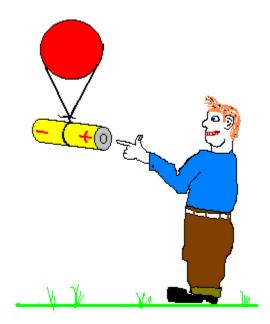
For example, I don't recommend actually trying this, but suppose you were to plug a well-designed transformer into a wall socket. And suppose that this transformer has high voltage secondary wires left dangling open circuit: Because of the isolation, you could touch either secondary wire without being shocked, even if your other hand were hanging onto a grounded water pipe. Of course if you touch *both* high voltage wires simultaneously, they will blast you.

Even the best designed power line transformers have some capacitive "leakage" through the isolation barrier. In medical equipment the concern is interference with a patient's heart rhythm. Less than 10 microamperes of 60 Hz leakage, a very small current, is considered safe.

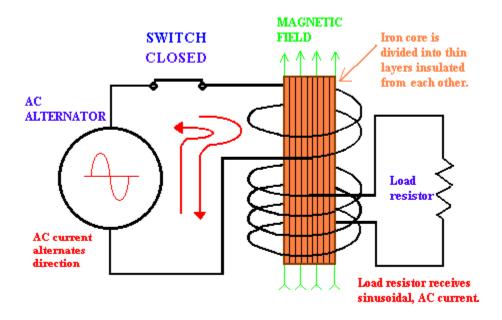
A secondary winding is isolated from ground - like a battery floating in mid-air

Think of isolation as a battery hanging from a balloon. Electric circuits require a closed loop in order for current to flow. For the dangling battery, the current can only flow from one end of the battery to the other. There is no relationship to ground. If a person standing on the

ground reaches up and touches the battery, no circuit loops are completed, so no current flows.



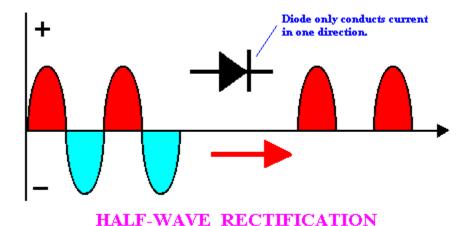
As explained in Chapter 2, *transformers can change the ratio of current to voltage* in proportion to the number of turns of wire around the core. To convert 120 volts AC to 12 volts AC, the turns ratio between primary and secondary coils would be 10:1. Or, if you needed to generate 1200 volts AC for an oscilloscope Cathode Ray Tube (**CRT**), the turns ratio would be 1:10.



Transformers are not 100 % efficient. They are made from copper wire that has a significant resistance and iron that dissipates a small amount of energy as heat every time a

magnetic field is generated or its polarity is reversed. In general, the larger the transformer and the larger the diameter wire used for the windings, the higher the efficiency will be. Large low frequency transformers are built of layers of iron, insulated from other layers by a thin coating. If the transformer were one continuous mass of iron, it would act like a shorted winding on the transformer and divert the magnetic energy into heating the iron.

Iron has a definite and abrupt limit on how much magnetic field it can support. Once all the iron has been magnetized, the iron will contribute no more magnetic field, no matter how much more current flows through the primary. Obviously, the larger the iron core, the more energy the iron can pass on to the secondary before the iron saturates. As a general rule, the larger the transformer, the more power it can pass through its windings.



(Only one half of wave is exploited.)

Rectification

Most electronic devices require smooth, continuous DC voltage to work properly. AC is converted to DC by means of rectifier diodes. Rectifiers are high-power, high-current, high-voltage versions of the small diodes used in crystal sets. Referring to the simple power supply shown earlier, the transformer is followed by a rectifier diode. *The diode only passes positive current flow in the direction of the arrow*. This means that current leaving the diode is in the form of "humps," or half sine waves. Only half of the sinewave is allowed to pass, so a single diode rectifier is called a *half-wave rectifier*. By definition these humps are "DC" since they have only one polarity. Unfortunately, for most electronics applications, bumpy, intermittent sine-wave halves are grossly inadequate. For example, if you use them to power a CW transmitter, your signal will sound like an unpleasant buzz and it will take up 120 Hertz of bandwidth. In the 1920s this was often done deliberately to modulate Morse code and make it audible in a receiver without a BFO (Beat Frequency Oscillator). If you tried to run a computer microprocessor on these humps without filtering, the processor would reset 60 times per second.

Peak Volts, RMS volts and DC volts

Sinewaves don't stand still at any one voltage, so how are they measured? The positive voltage seems to cancel the negative voltage so that the arithmetic average of any sinewave

voltage is zero. Also, the sinewave output from a rectifier reaches peaks of over 12 volts, but most of the time the voltage will be much less than 12 volts. Calling the output "12 volts DC" does not accurately describe the available power.

Rules are needed to describe sinewave voltage and current. As you might expect, *peak voltage* is the voltage difference between zero and the most positive extreme of the waveform. *Peak-to-peak* or *PP* voltage means the voltage difference between the most negative peak and the highest positive peak.

RMS sinewave measurement

RMS measurements are a way to express voltage and current sinewaves that can be used in calculations of Ohms law and power. In other words, RMS measurements are equivalent and compatible with DC measurements of voltage and current.

As you may know, the voltage that comes out of North American wall sockets is officially named *120 volts AC RMS*. During my lifetime American line voltage has also been nominally called "110 volts AC," "115 volts AC," "117 volts AC," and now it is called "120 volts AC." At my house I measure it more like 123 volts AC. Confusing, no? Anyway, the two power wires coming into your house from the power pole out in the alley nominally have 240 volts AC across them. Of course it was formerly called two times 110 volts AC or 220 volts AC. Some people still call it 220 volts. Line voltage is designed so that each of the two wires from the power pole is at 120 volts AC with respect to ground.

As explained in Chapter 2, inside your circuit breaker box these two wires are connected to two big metal "buss" bars. There is a third, grounded metal bar that runs down between the two active buss bars. The individual circuit breakers snap onto these bars like cars on a railroad track. Heavy power circuits for your electric stove and clothes drier clip clear across the ground buss to engage both hot lines for a total of 240 volts. Small circuit breakers just clip from one side to the ground bar to obtain 120 volts for ordinary low-power circuits.

The *RMS* or *Root Mean Square* of a sinewave voltage is defined as the peak voltage divided by the square root of two. *RMS voltage can be thought of as "the effective average voltage."* RMS values allow us to use Ohm's law for calculating AC RMS current, AC resistance and power. For example, 120 volts RMS is a sinewave with a peak voltage of 1.414 times the RMS voltage. In other words:

Peak voltage = RMS x $\sqrt{2}$ = RMS (1.414)

 $120 \text{ V RMS } \times \sqrt{2} = 120 \times 1.414 = 169.7 \text{ Volts Peak}.$

Therefore, ordinary household line voltage could be expressed as 120 Volts RMS, 170 Volts Peak or 340 Volts Peak-to-Peak.

Filter capacitors - filtering out the ripple

The half sinewave bumps, which are properly known as "ripple," must be smoothed out into a continuous DC voltage. This is accomplished by means of a *low pass filter*. In this case low pass means that the filter only passes frequencies well below 60 Hz. Of course DC is zero Hertz, which is the lowest frequency possible. The half-wave rectified supply illustrated earlier is equipped with an L-C, "L" filters. L- filters are simply two-element filters that represent the two

legs of the letter "L."

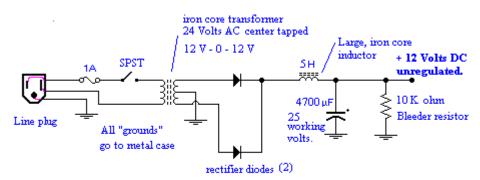
Capacitors conduct AC and prevent the flow of DC. Inductors conduct DC but resist the flow of AC current. In an effective DC filter for line voltage the component values will be huge, like 10 Henries and 5,000 microFarads. This is because the frequency we want to filter out, 60 Hz, is extremely low and big components are needed to have an effect on such a slowly changing sinewaye.

Bleeder resistor across the capacitor

The purpose of the bleeder resistor across the filter capacitor is to discharge it when the supply is not in use. Remember that high quality capacitors will hold their charge for many hours, sometimes days. Bleeders usually aren't important with a low voltage supply like 12 volts. But if this were a 500 volt supply, a person could get a nasty jolt or burn if they were to touch the capacitor. This can happen even though the supply is no longer turned on or plugged in.

If you were to build the half-wave supply shown earlier and put a 10 watt load on it, if you used an excellent transformer and a really huge capacitor, perhaps the DC voltage will at least be continuous. However, there will still be a 60 Hz sinewave ripple or waves impressed on top of it. If you used it to power a transmitter, the tone of the Morse code would have a distinct rough sound as the DC level varies at 60 times per second. When hams gave you a signal report for CW they use three numbers called the **RST**, **Readability**, **Strength and Tone**. The numbers range from 000 to 599, respectively. A scale of 1 to 5 is used for readability. Scales of 0 to 9 are used for strength and tone. If your DC supply had a lot of ripple on it, your contact might send "UR RST 593." "3" implies a really harsh tone rather than a pure audio sinewave BFO (Beat Frequency Oscillator) whistle. Because of the ripple problem, transmitter power supplies always use dual rectifiers to produce *full-wave rectification*.

Full-wave rectifiers



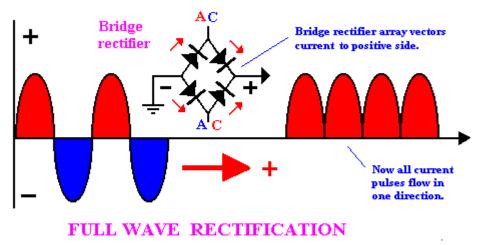
FULL - WAVE RETIFICATION USING A TAPPED POWER TRANSFORMER

Full-wave rectifiers convert both halves of the sinewave into useful DC current. The DC voltage is now a succession of "humps" with no "off" intervals. With twice as many "humps" per second, the voltage is much easier to filter. Full-wave rectification is a big step toward producing a DC source that resembles the smooth continuous voltage available from a battery.

There are two ways to achieve full wave rectification. The circuit above uses two diodes.

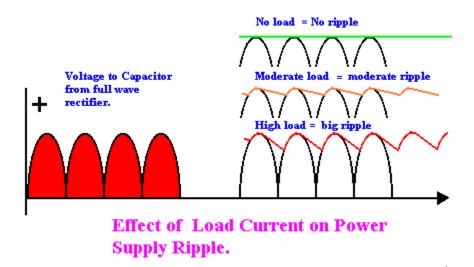
What you probably didn't notice at first is that the secondary of the transformer has *TWO* 12 volt RMS AC windings. By having two separate windings and wiring them in series, one of the windings can be positive at all times. This allows positive current to flow through one of the two diodes at all times and greatly decreases the ripple. Notice that, if we wanted, we could reverse the polarity of the diodes and produce the same waveform with the opposite polarity. That is, if we wanted a *NEGATIVE DC voltage source* referenced to ground, reversing the diodes would do that. Notice that the positive end of an electrolytic capacitor would have to be grounded because ground is now positive. If you don't reverse the capacitor polarity, the capacitor will soon corrode internally and fail - usually with a dramatic bang.

Bridge rectifiers



(Both polarities of sinewave are exploited.)

The second way to achieve full wave rectification is to use a bridge rectifier made from four individual diodes. This configuration allows us to get full wave rectification from a single secondary winding. The four diodes are soldered in a diamond pattern as shown above. The AC voltage source is applied across the top and bottom of the diamond. The two diodes on the right are pointed so that the <u>positive</u> current will always flow to the positive side. The left side is wired to ground and the diodes point in such a way that the <u>negative</u> current is always vectored toward ground. To say it another way, the positive current always flows "UP" from ground.



Ripple

Because the rectifier is supplying current in the form of "humps," the voltage output across the capacitor will also vary up and down. If the capacitance is large the voltage will not drop to zero during the "valleys." However, it can drop fairly low if the current drain from the supply is large. The more current that is sucked out of the capacitor, the lower the voltage "valleys." This is illustrated in the drawing above. If the large inductor or "choke" is large enough, it will work with the capacitor to smooth out the height of the voltage peaks and raise the level of the valleys dramatically.

Like capacitors, inductors also store energy. The current through an inductor can't change instantly. Therefore, when the voltage of each "hump" starts downward, the current charging the capacitor will persist longer, thereby reducing the output ripple.

With no load current, output voltage charges to the peak voltage

Notice that, if the power supply is not connected to an external load, the output voltage will rise up to the maximum voltage that comes through the rectifiers. For a 12 volt RMS transformer output winding, this is approximately the square root of two (1.414) multiplied times 12 volt RMS volts, or about 17 volts DC. Referring to the diagram, with no external load the only load on the capacitor is the tiny one milliampere current passing through the bleeder resistor. This means that the variation in voltage between the humps will be extremely small. In summary, if there is no load on the power supply, to a voltmeter it looks like a "regulated" 17 volt power supply with essentially no ripple. If your 12 volt circuit might be damaged by 17 volts, you must not connect a supply like this to your circuit.

When you first turn it on, the voltage will be 17 to 18 volts for a moment before the load current flow is established and the choke and capacitor pull the peak voltage down. RMS (Root Mean Square) refers to the *AVERAGE* voltage of the rectified sine wave "humps." If the output from the big capacitor were fed directly into your QRP without a regulator, the capacitor would charge toward the peak voltage of the "humps." Depending on how much current your QRP was drawing, 17 volts might destroy some of the components in your QRP. As the load on the power supply is increased, the output voltage would drop down toward the rated RMS voltage, 12 volts. As the rated transformer load, say 3 amps, is exceeded, the DC voltage will probably drop below

12 volts.

Power transformer saturation

A second purpose of the "choke" (series inductor) is to prevent the peak current from the transformer from exceeding the current rating of the transformer. If the choke were not located between the rectifier and the capacitor, the current from the "humps" would only flow into the capacitor when the voltage from the rectifiers is higher than the voltage already stored in the capacitor. It is like a tidal pool alongside the ocean. The pool can only fill with water when the tide rises higher than the level of the pool. The result of these pulses of charging current is that the power transformer must provide much more peak current than it may be rated for. If a transformer is rated for, say 10 amperes RMS, and these surges of current are drawn in bursts just a few microseconds long, then the peak current might be 100 amperes. Because the transformer doesn't have enough iron for that, the iron saturates and the transformer inductance momentarily collapses. Suddenly, the transformer will act like a few turns of copper wire shorting out the AC source. Saturation causes the windings and the transformer to heat rapidly and perform poorly.

The current through the filter inductor cannot change instantly. Consequently, even though the rectifier voltage drops below the voltage stored in the capacitor, the inductor will continue to supply current into the capacitor to maintain the current. Current will continue to flow until the magnetic energy stored in the inductor is exhausted. This more constant current flow reduces the current surges in the transformer and prevents saturation and heating.

Substituting big chokes with small, cheap resistors

In the real world, most low voltage power supplies like this solve the problem with a cheap resistor instead of a large, expensive iron core inductor. Resistors waste energy, but what the heck! You can use the resistor with an extra-large filter capacitor that costs less and weighs much less than a choke with the equivalent filter value. Or, as we'll see shortly, a linear voltage regulator can put a load on the capacitor all the time so that the current flow is not just in short bursts.

Direct line-powered power supplies

Transformers seem like a lot of bother. Since we plan to reference the DC power to ground anyway, why not dispense with the power transformer? If we needed 120 Volts DC, we could just rectify it directly off the power line. There was a period in the 1950s and 1960s when small table radios were built this way. These vacuum tube radios used 120 volts DC on the tube plates. The tube filaments ran on 120 volts AC. The 5 or 6 tube filaments were usually strung in series, like Christmas tree lights, to add up to 120 Volts.

Direct line power design has limitations. The power wires coming into the radio are 120 Volts AC and ground. There is no out-of-phase 120 volt line so, unless you power it with 240 volts AC like a kitchen stove, the DC coming out of the rectifier must be half wave and will have a strong ripple. A table radio draws little power, so it isn't too hard to filter out half-wave ripple. A high power application, such as a big stereo, has always used a power transformer even during the vacuum tube era.

If you connect a single rectifier diode directly to the AC line it will work as described earlier in the illustrative power supply. Now, what would happen if you tried to connect a bridge

rectifier diode array directly to the AC line which has one side grounded? Draw the diagram and think about the voltages on each component as the sinewave progresses. If you actually try this, you better protect your bridge rectifier with a low amperage fuse!

There are such things as direct line-connected high power, low ripple power supplies. This is done by using a bridge rectifier but not referencing it to ground. That is, the positive and negative DC output wires float and are both insulated from ground. This isolated, rectified DC voltage is then filtered and chopped into a high frequency AC (20 KHz to 100 KHz) using high power transistors. Because the frequency is high, the high frequency AC can drive a transformer that is surprisingly small. The sinewave cycles are so brief, it takes little iron to store the energy in each half cycle. The transformer can have one or more isolated output windings which are then rectified full-wave and filtered as shown earlier.

Regulators

To provide pure DC at a constant voltage over a wide range of load current, you need a regulated power supply. The regulator's first task is to "trim off" unwanted peak voltage and provide a DC voltage equal to (or similar to) the transformer rated RMS voltage. Regulators solve the 17 volt over-voltage problem described above. Its second purpose is to maintain constant voltage even when the load resistance is changing continuously or during a line voltage brown out. A regulator circuit is usually added to a power supply like the one above. There are two basic kinds of regulators, *linear regulators* and *switching regulators*.

Linear regulators are a sort of automatic variable resistor placed in series with the output of a simple supply like the ones we have been discussing. The regulator uses feedback from the voltage across the load to change the size of the "automatic resistor" and hold the load voltage constant. For example, in the above power supply the regulator input voltage might vary from say 15 to 18 volts, but the regulator would change its resistance to hold the output constant at 12 volts DC. A linear regulator not only insures that the load voltage is always the same, it also "trims" off the ripple.

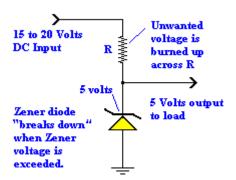
Switching regulators are more complex circuits that usually involve inductors (or transformers) and switching transistors. The advantage of switchers is that they waste far less energy and run much cooler. Switchers can raise or lower DC voltages at as much 90% efficiency. Switchers start with unregulated DC and turn it into high frequency AC power. This AC power is then passed through a small, high-frequency transformer to generate whatever voltage is needed above or below the original DC voltage. In an equivalent method, the unregulated DC is pulsed through an inductor to generate higher or lower voltages. Some switching regulators work directly off the household line. In other words, the 120 volts AC is rectified without a transformer and results in roughly 120 volts DC that is then converted into high frequency AC to drive a small, high-frequency transformer or a step-down inductor. For amateur radio applications, switchers usually make radio noise that you will hear in your receiver. Yes, commercial ham radio equipment sometimes use switchers in their designs, but in my experience, getting rid of the switching noise is extremely difficult.

In contrast to switching regulators, some switchers just boost or lower the voltage, but don't regulate the output voltage. They do not use feedback to control output voltage. These are often called *charge pumps*. The RF noise from these unregulated charge pumps can be insignificant because they only switch at one frequency. They don't "dither" back and forth trying

to hold the output voltage constant. To summarize, *regulated switchers are noisy*. It is difficult to suppress the switching noise for use in a ham receiver. Also, if used to power a transmitter, a switcher may also give the Morse code a slightly rough tone. *Charge pumps only make RF noise at specific harmonics of the switch frequency*.

Zener diode regulators

The simplest DC voltage regulator is made from a **Zener diode**. It is a "**linear regulator**" because there are no abrupt pulsed signals involved and it works entirely with DC. It dissipates the unwanted voltage and energy as heat. A Zener diode is a modified silicon diode subtly different from the rectifiers used in the power supplies above. Zener diodes are made from silicon that has been doped (contaminated) with extra ions. The extra ions cause the diode to break down at a specific lower reverse voltage when a high reverse voltage is applied. Zener diodes are deliberately manufactured to be inferior rectifiers, but when used as regulators, they are quite useful.



Why ordinary rectifiers don't behave like Zeners

Diodes rectify because the reverse voltage is insufficient to force electrons through the P-side of the P-N junction that has no free electrons. However, when enough voltage or "electrical force" is applied, the P-N barrier breaks down in an *avalanche breakdown*. When this breakdown happens at high voltage and high current, the sudden heat generated usually ruins a diode (or bipolar transistor). At low voltage levels, such a breakdown doesn't destroy the diode provided that the diode doesn't overheat. The *Zener voltage* level can also be used as a voltage reference.

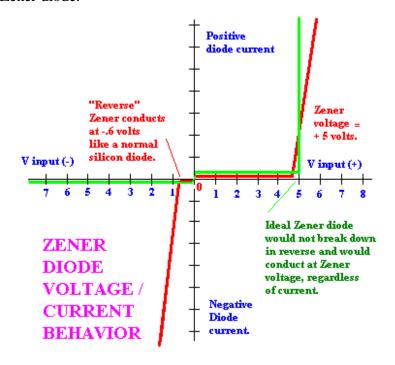
Doping silicon diodes makes Zeners

When big, tough, modern 400 volt silicon diodes are "doped" with extra ions mixed into the semiconductor, the avalanche can happen at lower voltages anywhere below 400 down to as little as 3 volts. The crude diodes I built in Chapter 4 were made from raw metal sulfide ore, straight from the mountain. Heaven only knows what extra ion contaminants they contained. They broke down at about 1 volt. Because the load voltage is low, the load resistance usually limits the avalanche current to a safe level. With a low voltage, the heating in the silicon can be mild enough that the diode survives the breakdown. In practice, commercial Zener diodes are available from about 3 to 50 volts. 50 volt Zeners must be capable of dissipating a great deal of heat or they will be easily destroyed.

In the circuit shown above, the Zener diode breaks down at 5 volts. If one of these diodes is placed across a load, the Zener diode will clamp the voltage to 5 volts so the voltage across the load never rises above 5 volts. Of course the input voltage must always be higher than 5 volts and the unwanted voltage will be dissipated across the resistor in series with the power supply. Ohm's law tells us that much of the resistor current must also pass through the Zener on its way to ground. So the Zener diode itself is often dissipating as much energy as the intended load. As you can see, Zener diode regulators have poor energy efficiency.

Real versus ideal Zeners

If a Zener diode behaved "perfectly," the voltage across it would be the Zener voltage, no matter how many amperes flowed through the diode. This is illustrated by the **green** curve in the graph below. Unfortunately, the Zener voltage rises with large currents as shown below on the **red** curve. A 5 volt Zener regulator diode is shown. Notice that when the Zener diode is wired backwards, it acts like a normal, forward-biased silicon diode. Conduction starts at about 0.6 volts. What is called "forward" conduction for a normal diode is called reverse conduction for a Zener diode.

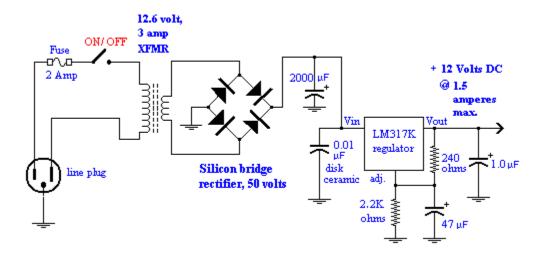


Zener diodes are impractical for heavy current regulation. They not only dissipate energy in the series resistor R, they also burn up energy in the diode. Moreover, as the diode current rises, the Zener voltage can be significantly different from its nominal value. In practice, Zener regulation is used for light loads over a narrow range of input voltage. As you will see later, Zeners can be used as **VOLTAGE REFERENCES** to control a transistor regulator. In this way, the regulation can be reasonably good and energy isn't wasted.

Using Zeners as reference voltages is illustrated in applications later in this chapter.

A homebuilt, line-powered power supply for a QRP

Now let's be practical: The 12 volt supply below worked well for me and can be assembled entirely from parts from Jameco.com or other vendor.



This 18 watt regulated line-powered supply should be built in a metal chassis. The round ground pin from the line cord should be connected to the chassis. In that way, if the "hot" black wire should break and touch the chassis, the metal would not become dangerous to touch. A 2 to 5 ampere fuse in series with the line input protects the supply. The ON/OFF switch should be rated for 250 volts DC and at least 1 ampere. The line cord should pass through a rubber grommet on its way into the chassis. Once inside, the line cord should be clamped to the chassis. This insures that, if someone picks up the power supply by the cord, the force will be on the clamp and not on the solder joint where the line cord is fastened to the fuse and switch.



The transformer is rated at 12.6 volts RMS at 3 amperes. I used Radio Shack part # 273-1511. The rectifier is a generic silicon bridge rectifier rated for at least 50 volts @ 3 amperes. Alternatively you could use 4 individual rectifiers arranged as shown above. The filter capacitor following the rectifier just needs to be large and greater than about 25 working volts. The other three capacitors serve to stabilize the output and prevent oscillations and ripple. Adding a 12 volt dial light so you will know when it is turned on is a nice touch.

The LM317K programmable voltage regulator

The LM317K regulator chip is packaged in a TO-204 (TO-3 packages are similar) metal case and can deliver 1.5 amperes. To dissipate the heat, the TO-204 case should be bolted to the

metal chassis and insulated by means of a mica washer and silicone grease. Mounting kits for this purpose are also available at mail order vendors such as Jamecom.com, Mouser.com or Digikey.com. The LM317K regulator chip works by regulating the voltage between the V_{out} terminal and the "adjustment" lead on the regulator. The regulator regulates this voltage difference to 1.2 volts. This low voltage allows the designer to regulate voltages equal to or higher than 1.2 volts. In this 12 volt application, the regulator passes current through a 240 ohm resistor and regulates the voltage across the 240 ohm resistor to 1.2 volts. This results in a "current source" that drives a constant current through the 2.2K resistor to ground. This increases the total regulated output voltage from 1.2 up to 12 volts. In other words, 240 ohms is about 10% of the sum of 240 ohms plus 2200 ohms.

The LM317K "clips off" any voltage above 12 volts so your QRP will never see a higher voltage. Notice that the LM317K is a *linear regulator* in a large TO-3 case. This means that any input voltage that is above the regulation voltage is dissipated as heat. This seems wasteful, but linear regulation makes no radio noise and produces a flat output voltage with no ripple. Notice that the multi-Henry inductor "choke" (or a resistor) is not necessary. This is because the regulator is drawing current from the capacitor nearly all the time. Consequently the transformer iron will not be saturated by high current pulses.

Below is a picture of the same circuit made with the "T" version of the regulator, the LM317T. It has the T-220 case which doesn't have as much mass to dissipate heat, but is designed to be used with a heat sink.



Because you can "program" the total regulated voltage, this same regulator can be used to regulate voltages from 1.2 volts up to about 20 volts. Notice that if the 2.2K resistor were a variable resistor, a potentiometer, the output voltage could be continuously adjustable from 1.2 to 12 volts. A 4,000 ohm variable resistor would be adjustable up to 20 volts. If you wanted, you could expand this design into a homebrew laboratory bench supply. All you would need to add are the potentiometer, a volt meter and a current meter in series with the output.



I modified an LM317K regulated 12 volt supply to make the output variable between 8 and 12.5 volts for a specific project. Since I didn't need to make it variable down to 1.2 volts, a 1K Ω pot just varies the upper 40% of the 2.2K Ω "programming resistance."

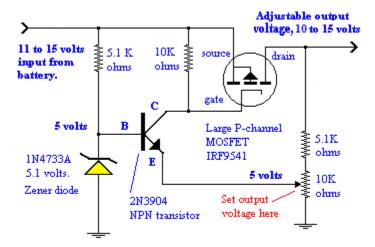
The LM317K regulated supply is good, but not great

This simple regulated supply may not be ideal for QRPs that generate 5 watts or more of RF output. The voltage during a long CW dash sometimes drops about 1/4 volt. This can cause the frequency to shift slightly and the fellow you're talking to might hear your tone drop at the end of a dash. Specifically, I got an RST 567 signal report from a fellow. I could not reproduce this effect running the transmitter into a 50 ohm dummy load. However, when I listened to my own signal loaded into a real dipole antenna, I found the tone of the CW signal often shifted, just as the fellow reported.

This power supply violates my goal to never use integrated circuits. If there are purists who share my aversion to integrated circuits, the "low dropout" regulator shown below can be substituted for the LM317K regulator. A larger power supply than this would be more versatile and could power a bigger transmitter. Obviously, the higher the power level, the more difficult the regulation becomes. Running a 100 watt transmitter requires at least a 200 watt regulated power supply. I avoided this project for many years by running my entire ham station on a solar-charged 12 volt battery. Deep discharge batteries and a 200 watt supply are described at the end of this chapter.

A low dropout voltage regulator for use with a battery

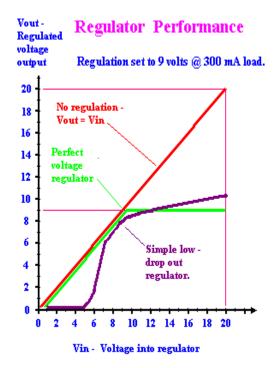
As you will read shortly, two 6-volt lead-acid golf-cart batteries make a terrific, high-current 12 volt power supply. Unfortunately, running your transmitter on batteries means that, when the battery is ready to be recharged, its voltage will drop down to 11 or even 10.5 volts. This means that (ideally) your QRP should be tuned up to run on 10.5 or 11 volts and then regulated to that level. Remember that *a linear regulator can only deliver LESS than its input voltage*. So if you're running on a 12 volt battery, you need a regulator that wastes as little voltage as possible. This waste voltage is called *dropout*. The regulator shown below receives nominal 12 volts from a battery. The active regulation element is a big P-channel MOSFET transistor. The bigger the transistor, the less voltage it will waste across its internal resistance and the lower the "drop out." Multiple transistors can be wired in parallel to make the internal resistance even lower.



The P-channel **MOSFET** transistor turns on (conducts current) when its gate voltage is pulled downward toward ground. So when the battery voltage drops, the gate voltage must be pulled down (toward zero volts) to turn the MOSFET more on. When the battery input voltage rises, the gate voltage must be raised to turn the transistor more off and restore the output to the set voltage.

Low Dropout 12 Volt Power Supply

The gate voltage control is done with an NPN bipolar transistor. The transistor compares the reference voltage across a 5 volt Zener with a fraction of the output voltage across the sense resistor pot on the lower right. The slider on the sense resistor potentiometer contacts the resistance at a level that produces about 0.6 volts less than 5 volts. As the output voltage rises, the voltage on the sense resistor rises. This in turn increases the 2N3904 emitter voltage. The difference in voltage between the base and emitter drops, causing the drive to the NPN transistor to drop. As the NPN transistor turns more off, the gate voltage on the MOSFET rises toward the battery voltage and turns the MOSFET more off and lowers the regulated output voltage.

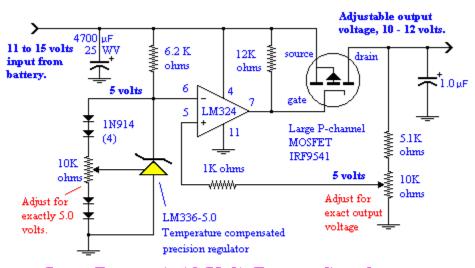


The **purple** plot on the left shows the performance of this simple power supply when it has been set to 9 volts with a 300 milliampere load. The red line shows the voltage the load would receive if there were no regulation. In other words, Vin = Vout. The green line illustrates the performance of an ideal or perfect linear regulator. If the transistors had infinite gain and the Zener diode always produced precisely the same reference output voltage, then the green curve is what you would get. As soon as the regulator is given 9 volts input, it would deliver exactly nine volts, no matter what the load was. As you can see, the simple regulator isn't radically different from the ideal, but it is far from perfect.

A precision, temperature-compensated, low-dropout regulator

Much better regulation can be achieved by replacing the NPN transistor with an operational amplifier. Operation amplifiers, "op-amps," are integrated circuits composed of many or even dozens of transistors. Op-amps perform as though they were nearly perfect transistors. Similarly the LM336 voltage reference is an integrated circuit made from bunches of transistors that perform as though they were a nearly "perfect" Zener diode. As the voltage across the regulator is varied, the voltage across the Zener remains constant within one or two thousandths of a volt.

If you go to the trouble to build this regulator for your QRP, the voltage regulation will be at least ten times more precise than the supply built from a LM317K which I diagrammed earlier. My QRP draws about 12 watts of power. The LM317K supply dropped about 0.25 volt when I keyed my QRP. I replaced the LM317K regulator chip with the more complex regulator circuit shown just below. Now the output voltage drops about 0.025 volts, one tenth as much. My crystal controlled QRP worked the same with both supplies with the QRP connected to a dummy load. But as explained earlier, with a real antenna I had complaints about the tone of my CW signal shifting with the LM317K supply. I assume my antenna has an extra reactive component (capacitance or inductance) that requires more voltage than the dummy load.



Low Dropout 12 Volt Power Supply with Precision Regulator

The op-amp is the triangle symbol in the center. This op-amp has 14 pins and the numbers shown are the pin numbers. This particular chip contains four op-amps. Only one is used in this circuit. Pins 6 and 5 are the inputs. The input pins function in such a way that the op-amp changes the output voltage (pin 7) to "try" to keep the two input pins at the same voltage. That is, so long as the voltage on pin 6 is identical to the voltage on pin 5, the output remains constant. When the **positive** pin 5 has a higher voltage than the **negative** pin 6, the output pin will shoot positive as high as it can go. When the negative pin 6 is higher than pin 5, the output pin will zoom negative as low as it can go.





If you build this, be sure to leave the unused three output pins open circuit - no connections. You may ground the positive input pins on each op-amp to insure that the op-amp doesn't decide to oscillate. The output pins will remain at zero volts and the chip will only draw significant current by the active op-amp. If you like, you may wire 2 or more op-amps in parallel. This will increase the current capacity of the outputs. Also, if your application involves a higher voltage, e.g., more than 15 volts, wiring all the op-amps in parallel will help distribute the heating inside the chip. This over-15-volts problem is discussed in more detail in the later article which describes a 200 watt supply.

Some authors do not recommend wiring the op-amps in parallel. They say that the op-amps are very similar but cannot be identical. Therefore the op-amps will fight each other and dissipate extra heat. I wired mine in parallel, but I haven't seen any evidence to confirm or deny this concern.

Ordinary transistors, like the 2N3904, have current gains as high as 100. That is, 1 milliampere of base current will produce 100 milliamps of collector to emitter current. In contrast, the op-amp has nearly infinite voltage and current gain. Gains like 100,000 or a million are common. Also, the inputs draw essentially no current. They have nearly infinitely high input resistance. This means that op-amps are ideal to "monitor" some condition, such as the output voltage from the power supply. The op-amp output can then change the op-amp output pin voltage in order to restore the supply to equilibrium. Looking at the diagram, pin 6, the negative input, always rests at 5.00 volts, so long as the battery voltage input to the LM336 is above 5 volts. The output voltage pot at the lower right is adjusted to produce the desired output voltage. The big MOSFET transistor will remain turned on to the exact degree to deliver the voltage you set. This set point is the place where 5 volts appears on the pot. As soon as the op-amp "sees" that pins 5 and 6 have the same voltage, the output voltage on pin 7 holds still and stops changing.

A precision Zener diode

The LM336 precision Zener diode is not only extremely accurate, it will maintain its accuracy over a wide temperature range. They are primarily intended as a *voltage reference* and are most accurate when supplied with about 1 milliamp through the chip. It is available in two

voltages, 5.0 volts and 2.5 volts. They are not intended to power variable loads like the Zener supply discussed earlier. However they can be used as regulators if the load current is tiny, such as the oscillator in a VFO.

VFOs should draw as little power as possible to prevent heating. Speaking of temperature change, don't forget to bolt your MOSFET to a big heat sink. At high input voltages and big load currents, you may expect the MOSFET to get hot without a heat sink. Keeping it cool keeps its internal resistance low and improves the regulation. The metal flange on the transistor should be insulated from the heat sink and metal chassis with a mica insulator and silicone grease. There are modern silicon rubber insulating pads that can substitute for the mica and supposedly do not need the messy grease.

As we shall see in Chapter 10, building a variable frequency oscillator that reaches modern standards of frequency drift requires the use of a super-regulated power supply. This in turn will require you to use regulators made from integrated circuits. Sigh. Of course you could prove me wrong by building a precision regulator with discrete parts.

Better precision from ordinary Zeners

If you don't happen to have any LM336s around, you can make a fairly good precision reference by using 2 or even 3 Zener diodes in a cascade. For example, the first Zener might turn on at say, 10 volts. The first diode then powers the 2nd Zener diode which might turn on at 8 volts. This in turn can power a third Zener that conducts at 5 volts. The resulting regulated reference voltage will supply hardly any current, but its only purpose is to deliver a voltage to the input of an op-amp to serve as a comparison voltage for the sense resistor voltage. Unlike the LM336 integrated circuit precision reference, this more primitive reference doesn't have the adjustable temperature regulation and will produce slightly higher or lower voltages as the temperature changes.

Packaging power supplies

The photo below shows the underside of the mainframe of my all-transistor CW transmitter. It is uses modules described in Chapters 6, 10, 11 and 12. The low dropout 12V QRP power supply is located just to the left of the center. The circuitry is mounted on a commercial perforated circuit board. This circuit board is standing on edge but the blue trim pots that adjust the LM336 and output voltage can be seen. The black-colored, P-channel power MOSFET that controls the output is just above the board. The transistor is insulated from the chassis with a plastic screw and a gray silicon pad.

My excuse for the messy wiring is that this chaos evolved as I made changes and additions. There is one coax cable visible that carries RF from the VFO. All the other wires carry DC currents. RF currents should never be carried more than a fraction of an inch by simple wires. This chaotic wiring is ugly, but it works!



The perf-board circuit at the upper right with the three capacitors large is the precision supply for the VFO. two large The TO-204 transistors mounted vertically (upper left) are the Morse code (CW) keying transistors for the 50+ watt linear amplifier. The black relay at upper left is a DC relay that engages the 12 volt battery during transmit.

Each module is electrically mated to the circuit with either Molex plastic connectors or RCA audio connectors so that it may be easily repaired or replaced. RCA connectors are convenient for use as feed-through connectors wherever needed.

CHEAPSKATES AND OLD BATTERIES

What to do with old alkalines

One of my pet peeves is that small, hand-held devices are rarely designed to use all the energy contained in the batteries. When my GPS, flashlight or hand-held 2 meter transceiver quits, I measure the voltage of each alkaline cell and discover that that they still read 1.2 to 1.3 volts. I happen to know that these batteries still contain 40 to 60% of their original energy. Being cheap, I save them, always hoping to find ways to extract the last milliwatt-hour. Eventually I collected a big bag of them.

I used to work for a company that made small, hand-held devices. They were powered by either alkaline 9 volt "transistor" batteries or 1.5 volt AA cells. When I studied alkaline batteries under load, I observed that the battery voltage per cell declines from 1.6 volts down to 1.0 volt in a fairly linear fashion. During the entire discharge the current was robust and able to power our devices at full power. Below 1.0 volt, there is essentially no energy left in the battery cell and the voltage abruptly crashes and the device goes "dead." Unlike most companies, we designed our products to function properly over the entire useful voltage range.

Recharging alkalines?

As you know, the alkaline batteries are not designed to be re-charged. Our company service department was plagued with units returned to us with their battery compartments clogged and corroded by dried yellow gunk. Yes, you can recharge alkalines. But if you don't pull them off the charger at exactly the right moment, they swell and will leak goo into your unit when you begin to discharge them. Recharging is least likely to damage the battery if they are only partially recharged, perhaps to 1.4 volts per cell. If there is the slightest degree of swelling after charging, discard them. Never use swollen batteries in your device.

By the way, **the good news** was that during my tests Duracells really did have slightly more energy than Energizer. **The bad news** was that the Duracell metal cases were thinner and more likely to leak. There is no free lunch. If you insist on recharging your alkalines, Energizers are (or at least used to be) preferred for charging because the stronger cases were less likely to leak.

Powering a 2 meter hand-held with alkalines

I own an ancient 2 meter Kenwood TH-21 hand-held transceiver. The replaceable battery packs contained six AAA rechargeable Ni-Cad batteries These worked poorly in cold weather and only stored 20% as much energy as alkaline AAA cells. I unsoldered the Ni-Cads and replaced them with alkalines. This worked well for use as an emergency radio that I could carry around in my backpack. The alkalines do not self-discharge and perform well in below-zero temperatures.

Then I began to use the hand-held to check into the local weekly club roundtable. First I put up a 2 meter vertical antenna on my roof. It's just like the verticals described in Chapter 5, except very much smaller. I quickly began to drain the AAA cell batteries and, as is usual for battery-powered gizmos, my hand-held died when the battery open circuit voltage dropped below 1.2 volts per cell.

Like most old guys, my parents were survivors of the Great Depression, 1930 to 1940. Depression veterans never waste anything. They saved string, plastic bags, rubber bands, paper clips and anything that might be reused. For better or worse, I inherited the habit.



My solution to buying AAA batteries every month was to build an external battery box. The blue battery box has an ON/OFF switch and contains Radio Shack battery holders for 3 and 4 AA cells. Instead of six AAA cells, the hand-held is now powered by *SEVEN* "dead" AA 1.2 volt alkaline batteries. Even with "dead batteries," the extra cell insures that I have at least 8 volts, enough to power the hand-held. I own an extra Kenwood battery pack for the hand-held, so I took out the original AAA cells and connected the pack to the blue Radio Shack enclosure using some thin flat line, as shown above. Now I rarely buy new AAA batteries and I don't worry if they will last for an entire roundtable. I just check my battery box every couple weeks to be sure it is delivering at least 8 volts.

When it is my turn to serve as the net control station, I open the blue box and measure each cell. If any of them are below 1.2 volts, I replace them with my "freshest dead batteries." It

is embarrassing when your transmitter dies and you are supposed to be talking to a large group. In summary, it works and I don't fill the trash with dozens of alkaline cells. Best of all, I finally have a use for all those old alkaline AA cells! (My parents would be proud.)

HEAVY DUTY POWER SUPPLIES

The beauty of batteries

As I mentioned earlier, I often run my whole station on solar power stored in a 12 volt battery. I know this sounds like tree-hugging, liberal silliness, however my solar powered station came about quite logically and has many advantages for a homebuilt station. There are lots of hams who do this - and no wonder! A lead-acid storage battery is a wonderful power supply. It puts out huge currents whenever you need them and the voltage regulation is excellent. The best advantages are that batteries make no switching power supply RF noise and there's no waste heat from a big linear regulator.

My return to ham radio began in 1997 when I hauled my 1967 homebuilt mobile ham rig down from the attic and blew off the dust. Once upon a time it had been mounted in my car. Since my old rig runs on 12 volts, I couldn't even try it out without a heavy-duty 12 volt power supply. I considered building or buying a supply but after 10 seconds I decided that was ridiculous. I happened to have some 6 volt golf cart batteries in the garage. I hauled two of them down to the basement and put on an automotive 12 volt trickle charger. After a day, the batteries recovered and I could fire up the rig. AM phone was extinct, but there was nothing to stop me from getting on CW, which I did with good success. Well, that's not entirely true. My adventures included a drifting VFO and eventually a blown 200 watt charge-pump switcher, but those problems had nothing to do with the power source.

My old vacuum tube rig was a power hog. The receiver drew 3.5 amperes at 12 volts. That's 42 watts just to listen! The transmitter was much worse, of course, but it wasn't dramatically worse than a transistorized rig. After all, a transmitter can't radiate big power if it doesn't consume big power. Moreover, a modern, linear class AB transistor rig can be *less* efficient than an old Class C vacuum tube transmitter. Either way, my transmitters draw 6 to 20 amperes.

Compared to a golf cart or an automobile starter motor, a ham rig is a low power device. 20 amperes should be plenty of current. A deep-discharge storage battery is best, but there's no reason you can't use an old car battery. Those of us who live in snow country routinely discard car batteries when they can no longer supply 300 amperes on a frigid January morning. But even an old car battery will usually supply 20 amperes for five minutes without appreciable voltage drop. All you need to do is keep a small, one-ampere charger on it continuously. For anyone on a budget, a free used car battery is a free high current power supply.

Requirements for a line-powered 20 ampere, 12 volt DC supply

I used golf cart batteries for many years but eventually I got around to building an equivalent line-powered power supply. I've had poor luck running ham equipment on switching power supplies. If the switcher is more than just a charge pump and actually regulates the output voltage, then it will make RF noise. You'll hear the static in your receiver and it may be obvious

on your transmitted signal. I've had previous experience with this problem:



A 1967 homebrew all-band transmitter with a switching power supply running on 12 volts DC

The 150 watt switching supply is at the left rear. Unlike a modern transistorized transmitter, a vacuum tube 50 watt transmitter typically needs 500 volts DC for the power output tube. Originally the supply was a simple charge pump that used 2 germanium power transistors. It consisted of a free-running multivibrator (square wave oscillator) circuit that drove a voltage step-up transformer with no feedback. Although unregulated, the supply worked well and didn't produce audible hash on my signal.

Then one day one of my germanium transistors blew and I was unable to find a suitable replacement. Germanium transistors seem to be extinct in the modern world. They simply can't compete with power MOSFETs. I rebuilt the supply using a modern pulse width modulator, switching regulation system and MOSFET power transistors. An elegant feature of the new switcher was that the output voltage was adjustable. Just by turning a knob I could vary the transmitter output power from 20 to 80 watts.

Unfortunately, the switcher and the RF amplifier stages "talked to each other." That is, when the load increased, the supply increased the pulse width modulation to compensate, but not without a slight delay. This subtle ripple or "jitter" was hard to see on a scope, but no matter how much I filtered the DC high voltage, the jitter appeared as a slightly rough note on the CW signal. In practical terms, I kept getting RST 598 reports.

There was an elaborate 12 volt switcher in QEX magazine a few years ago that solved the jitter noise problem. I was delighted to see that I wasn't the only one who noticed "jitter noise." The problem is real, but after studying the complicated Rube Goldberg solutions, my desire to build one vanished.

Charge pumps

One method to build a relatively quiet efficient supply is to build a charge pump or other unregulated switched system that boosted (or lowered) the input voltage to just above the desired voltage. Then I could use a linear voltage regulator to complete the regulation function with a minimum of waste heat generated. This is the low noise approach I used to power my super-regulated miniature VFO power supplies described in Chapter 10.

One idea for a high power charge pump would be to use a manually adjusted pulse width modulator for the AC generation. This way the output voltage could be manually set so that a linear regulator would waste as little energy as possible. This regulation margin would depend on how consistent my line voltage was and how stiff the charge pump conversion system was. For example, starting with 120 volts AC, the charge pump might lower the voltage to say, 15 volts DC. Then a linear regulator could reduce the 15 volts DC down to 12 to 14 volts.

A LINE-POWERED 200 WATT 12 VOLT POWER SUPPLY

A 60 Hz transformer based, linear regulated, RF noise-free design



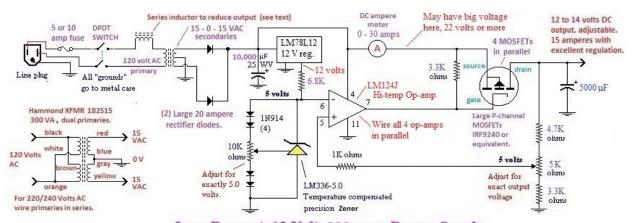
I eventually built this supply as a substitute for my golf cart batteries and can run the whole station on it. Rather than build a charge pump to reduce the line voltage down to a low voltage, I used a 60 Hz transformer. One difficult part of this design is finding (and affording) the large transformer needed to drive the 200 watt version of the little 15 watt transformer shown earlier. The transformer I selected was a Hammond type 182S15. It is rated at 300 Volt-Amps, 120 Volts AC input with double primary windings and two 15 volt AC secondary windings. There are two 120 Volt primary windings on this transformer so I wired the two windings in parallel. They could also be wired in series for use with 240 volts AC.

This transformer happens to be a toroid design. It comes with a rubber pad to mount on a chassis. Without the pad it tends to buzz audibly during high current operation. The downside of this 60 Hz transformer design is simply that a transformer able to handle that much power is a big, heavy, expensive beast.

What are Volt-Amps?

A transformer of a given size is capable of handling a certain amount of power, in other words, *watts*. My big transformer is rated at 300 *volt-amps*. This means that, if I had a purely

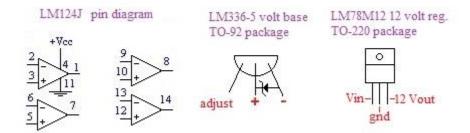
resistive load, the transformer could handle 300 watts. As you know, volts times amperes = watts. However, out in the real world of AC power, AC loads like inductors and capacitors draw currents that are out of phase - not synchronized - with the voltage. For example, if the transformer were wired to a large capacitor, the capacitor might draw 300 volt-amps without a single watt being dissipated in the capacitor! Even though no power is being dissipated in the capacitor, the transformer would be working at full capacity pushing and pulling current in and out of the capacitor. To be conservative, it is a good idea to select a transformer rated for more volt-amps than the watts you need. Quite often the load on a transformer will have some reactive component. That means the load has capacitance or inductance as well as the resistive load that needs the watts. In this case, I wanted 200 watts, so I selected a 300 volt-amp transformer.



Low Dropout 12 Volt 200 watt Power Supply

with Precision Regulator

As you can see, this is just a larger version of the QRP supply presented earlier. It doesn't have to be built exactly as shown. With the exception of the transformer and the op-amp, my supply was built from recycled and spare parts - you know, the stuff your wife calls "junk."

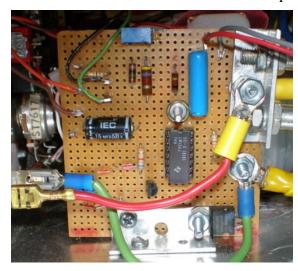


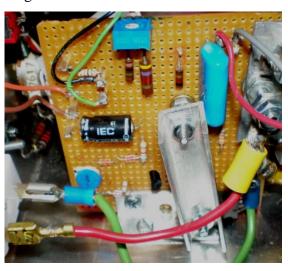
My local AC line voltage is 125 volts instead of 120. This partly explains why the unregulated DC voltage from the transformer and rectifiers was 22 volts DC and not the 15 volts DC I was expecting. The schematic above is the third revision of this supply design. I originally used my usual LM324 op-amp. The LM324 is rated for 32 volts, so I thought 22 volts wouldn't hurt it. Then one day it stopped regulating. But when I took it apart, it suddenly worked again. After several months of intermittent behavior, the regulation failed completely. I built the original design quickly and it immediately worked perfectly ... for about 9 months. I measured the temperature of the LM324 in this circuit and found it was running at about 80° C. Apparently the

LM324 can't handle continuous operation at 22 volts.

Using the LM324 while regulating higher volts, >> 15 volts DC

I replaced the LM324 op-amp with an expensive, high-temperature version of the same part, the LM124J. The LM324 is rated for 70° C while the LM124J has a ceramic case and is rated at 125° C. And because the transformer has *LOTS* of extra capacity, I was regulating 22 volts DC instead of the 15 volts DC I had planned to regulate.





Here are two views of the little punch-board circuit. The picture on the right shows a piece of aluminum channel bolted across the LM124J op-amp to better dissipate the heat. I put silicon grease on the chip to better couple it to the aluminum. With the heat sink you may be able to get away with using an ordinary, cheap LM324 op-amp (\$1.50) instead of the pricey, special-ordered LM124J (\$14).

Read and think about every word in the IC data sheets

One of my early mentors, John Anderson, told me I must never use an IC in a circuit until I have read all the data sheets and thought about the implications of <u>EVERY WORD</u>. We should do this no matter how lengthy the footnotes or how irrelevant they may seem. After my troubles with the overheated LM324, I read the footnotes: "Supply voltage greater than 15 volts can exceed the power dissipation. Short circuits from the output to V+ (or ground) can cause excessive heating and eventual destruction." And that explains why the op-amp failure took nine months to develop.

While I doing my due-diligence and reading <u>ALL</u> the IC data sheets, I looked more closely at the LM336-5 specifications: The LM336s are most happy when they are biased with about 1 milliampere of current. In my original design the LM336 was running on nearly twice that much because there was no guarantee of what voltage would be powering the op-amp and the LM336-5. By using an LM78M12 (or LM78L12) just to power the LM336-5, the current through the reference diode is always about one milliampere.

Single Op-Amp or put all 4 in parallel?

Another change I made was to wire all four operational amplifiers in the LM124J chip in parallel. Since the extra amplifiers weren't being used, I thought the extra drive to the 4

MOSFET gates might be helpful. The op-amps heat the most when the MOSFETs are turned full on or full off. I reasoned that using all 4 amplifiers should help distribute the heat.

My friend Danny in Belgium, ON1MWS, built a supply using the above schematic as a starting point. Danny disagrees with putting the four amplifiers in parallel. He argues that each op-amp will end up fighting the others and will dissipate extra heat. He may be right. In which case we should either use just one amplifier or put current balancing resistors, perhaps 100 ohms, in series with each output pin. Danny is also using an LM324 and apparently he didn't read the footnotes either. Hi! He has been running one lone amplifier on 40 volts DC and not the "less than 15 volts DC" recommended by the data sheets. Danny's supply runs on 220 volts AC and delivers 36 volts DC to his transmitter. He tells me the LM324 doesn't seem to heat significantly and, so far, it hasn't failed. His supply can also deliver well over 200 watts.



In order to prevent the LM324 from seeing more than 40 volts DC under any circumstance, Danny built a simple, hi-current transistor regulator/voltage limiter for the main DC line.

I tried to adapt my LM324 to 22 volts by regulating the chip supply (pin 4 above) at 12 volts and connecting the output to the higher voltage with some experimental homebrew transistor driver circuits. I managed to do this, but I lost the precision regulation. That was a major virtue of the original design, so I gave up on this approach. For reliable, precise regulation I seem to be stuck with the LM124J or similar high power/ high voltage op-amp. However, I shall have to try out using one op-amp and check out whether my LM124J heats significantly.

Double ordinary Zeners can substitute for the precision Zener

When I originally built this supply, I had run out of my favorite LM336-5 precision Zeners. Consequently, I made a precise Zener by double-regulating an ordinary 5 volt Zener diode. I happened to have a 12 volt LM78M12 regulator so I used that to supply the 5 volt Zener. The much smaller LM78L12 would have been just fine. This scheme isn't good enough for a VFO because VFO stability also requires temperature regulation. However, using two ordinary regulators, the difference in supply output voltage between no load and full load was less than two hundredths of a volt. This eliminated any possible chirp or SSB distortion problem, so I was happy.





With my CW transmitter set on 3.6 MHz this supply is able to deliver 200 watts DC at 13.3 volts and 15 amperes. 13.3 volts was where I set the adjustment pot to reach 200 watts. As you may know, Class B linear amplifiers run at about 50% efficiency. So naturally, if you want 100 watts of RF, you must deliver 200 watts of DC to the linear amplifier. A multi-turn 5K Ω voltage adjustment pot is advisable. For convenience I mounted the voltage adjust pot just under the blue output voltage meter. The 5K Ω pot is in between two resistors so that the adjustment range just covers the output voltage I wanted, 10 to 14 volts. As I boasted earlier, the change in output voltage regulation between no load and full load in voltage output was only 0.01 to 0.02 Volts. The 80 meter signal sounds fine on the air with no chirp. Success!

Regulation precision varies with transmitter load and the antenna tuner

I was surprised to discover that regulation precision changes with the load impedance on the transmitter. When operating into a 50 ohm dummy load on 80 meters, the change in voltage under load dropped 0.02 volts. However, when I loaded a 100 watt filament light bulb dummy load on 40 meters, the output voltage *ROSE* about 1/3 volt. Depending on how my 40 meter dipole antenna is tuned, it may *RISE* or *FALL* 1/4 volt. As you might expect, rising or falling voltage may produce an obvious CW chirp at the end of each CW dash. This produces either a rising or falling musical tone. Oops.

When I switched from the Fri-match antenna tuner to the old C-L-C tuner, I got less power out, but the signal didn't chirp and the precision went back to about a 0.02 volt drop. These two different tuner designs are described in Chapter 9. Apparently the regulation feedback is being fooled by the RF current pulses not being in sync with the voltage pulses drawn from the supply. I confess I don't really understand this.

Volt-amps and wasted power

I first tried this design with a smaller, (cheap) 12.6 volt transformer. The total voltage drop was intolerable. At low output current, the transformer delivered 16 volts DC to the regulator - so far so good. But at high current levels, it wouldn't regulate properly above a setting of 10 volts and 10 amperes output, 100 watts. Most of the voltage drop was in the transformer. Its internal impedance was much too high for the power supply to work as I had hoped. On the other hand, this transformer should have been adequate for a 50 watt transmitter.

My new transformer has the opposite problem - too much output under load: Under a

light load, the DC voltage input to the regulator is about 22 volts. Even after rectification at 15 amperes, the transformer was *still* able to deliver 18 volts DC to the regulator MOSFETs. This was much higher voltage than I expected and represents as much as 100 watts wasted power, depending how high or low I set the regulated output voltage. I had assumed that at the rated volt-amps, (200 watts perfectly regulated output plus 100 watts waste heat) the AC voltage delivered to the rectifiers would be about 15 VAC. *Wrong*.

A big part of my over-voltage problem is that my local line voltage can be as high as 125 volts AC, not 120 volts - a significant difference. No wonder I have too much voltage. Before starting a project like this, measure your local voltage and find out what you are working with. For me, the same toroid transformer core wound for 12.6 volts, might have been a better choice. On the other hand, you may need the extra voltage where you live.

The good news is that my new transformer produces enough extra voltage to operate during a significant brown out, a line-voltage under 100 VAC. Also, I have been able to operate at 240 watts with just 12 volts DC output, not 13 or more volts as described above. To operate under both conditions without losing the near perfect regulation, I added a switch to short out the input series, voltage-reducer inductor which is described below. That's the big red switch seen above.

Heat sinks

The first defense against waste heat is to bolt on as much aluminum heat-sink mass as you can. The more metal available to hold the heat, the more slowly the four transistors will heat and hopefully they will not overheat. Anything you can do to reduce temperature rise will improve the supply and make it less likely to be damaged. Use big, thick aluminum heat sinks, preferably with fins that protrude outside the enclosure to dissipate the heat. The black and silver objects attached to the back of the unit are extra heat sinks. Also, use thick, heavy gauge wires and brawny connectors for all secondary wiring. My supply cooling and wiring are lighter than they could be. Do as I say, not as I did.

How to tame an overly exuberant transformer

I considered 3 ways to cut down on the waste heat: The most versatile way would be to use a **commercial dimmer control**, like we have on our house lights or fans. A dimmer could tune the supply to minimize waste heat proportional to the local line-voltage level. Dimmers are based on **triacs** which are a double polarity, **Silicon-Controlled Rectifier**. SCRs resemble a bipolar transistor, but they latch *ON* when triggered and stay on until the end of a sinewave half cycle. A triac can be thought of as a pair of NPN and PNP transistors merged together to make a single SCR-like device that controls both polarities of a sinewave. They have a base-like control lead that turns on the triac during each half 60 Hz sinewave cycle, controlling both polarities at once. The trigger level is set by a control potentiometer making an extremely simple pulse-width modulator system. In other words, it seems to be a 60 Hz version of the charge pump regulator I was proposing earlier.

Looking at the dimmer controls at the hardware store, I noticed that they were all labeled "includes RFI filter to prevent interference to TVs and radios." I had hoped that dimmers were like charge pumps, with no pulse width dithering and little or no RF noise. Apparently not. Zero RF noise was my main incentive for not building a switching supply.

Two more methods to reduce the transformer output voltage are series **capacitors** or **inductors** to reduce the AC voltage input or output of the transformer. Capacitors and inductors dissipate essentially no power, but they reduce AC voltage like a resistor. They could be placed on the AC input or the AC output of the transformer. Quick calculations showed me that capacitors were impractical. They must be non-polar, in other words, not electrolytic. If used in series with the secondary transformer winding, they must have a huge capacitance. If used in series with the primary, they need a high working voltage.

Inductors seemed more practical and small enough to fit in my aluminum box. I tried out a some inductors from my junk box in series with the primary: The 24 volts AC secondary from a door bell transformer produced too much attenuation. A filament transformer secondary winding produced too little attenuation. I had an old 10 watt speaker transformer that was almost perfect - like Goldilock's porridge. The 3.2 ohm output winding was a little less inductance than I wanted, but when placed in series with the transformer 120 VAC input, it reduced the DC input to the regulator to 16 volts under full load. This saved me 30 watts of waste heat at 13 volts DC output to the transmitter.

How did I know what AC current the speaker transformer could handle? A rating of "3.2 ohms" impedance at 10 watts means that the transformer winding is designed to transfer 10 watts power into a 3.2 ohm speaker. The speaker turns this power into sound. I'm using this secondary winding as a simple inductor. The rest of the transformer is open circuit. So this "inductor" is rated at 10 volt-amps. When my supply is drawing maximum volt-amps, say 250 volt-amps, that implies that the line current will be 250 watts / 120 Volts AC = 2.09 amps AC. When running the power supply at full power, I measured the voltage drop across my inductor at about 5 Volts AC. 5 volts x 2.09 amps = about 10 volt-amps. Close enough! The inductor doesn't heat significantly, so I know that it isn't saturating. Just in case, wire it so that, if it shorts to ground, the fuse will disconnect the supply from your house power system.

Low AC line voltage/ high power inductor shorting switch

Most of my operating is done using far less than 200 watts DC power. As explained earlier, the power supply operates most efficiently with the 10 volt-amp speaker transformer/inductor in series with the main power transformer secondary. However, it's possible that someday I might want to operate at high RF power output with low AC line voltage. This could happen if I were using an emergency inverter powered by an engine or batteries. For this situation, operating without the series inductor is needed to generate the full 200 watts DC. The red shorting switch simply removes the inductor from the circuit.

Reducing external voltage drop

During testing I used an external, series ammeter to confirm the current drawn. This ammeter added an additional, unregulated 0.25 volt drop between the power supply and the transmitter. As explained in Chapter 15, sudden drops in voltage at high current like this can cause a feedback that distorts speech in a sideband transmitter and may contribute to chirp in a powerful CW transmitter. Having an ammeter in series with a transmitter power supply is not such a good idea after all! However, if the same ammeter is built into the power supply and is *inside the feedback loop* as diagrammed above, the regulator transistors will compensate and the voltage regulation will be maintained.

Beware of tiny source pins on TO-204 power transistors.

I used four large MOSFETs in parallel to help dissipate the heat and to reduce the current through each transistor. All of the large, size "TO-204AA" MOSFET transistors seem to be terrific components ... electrically. Unfortunately the source pins are much too small to handle many amperes of current. The TO-204 sockets have tiny spring-loaded clips to contact the skinny pins and they always work well ... at first. Except as soon as the transistor heats up, the clips expand and the source pins become intermittent. The second day I used this big supply, half the transistors started to overheat and the other half remained cold. My solution for this supply and others that I have built in the past, is to **solder the source pins to the clips** on the intermittent transistors. This is a crude solution, but until they make the source pins of TO-204 size transistors thicker or I find a better socket, it is the only fix I know. The same tiny clips and pins on the gates work well because the control currents are tiny. The drain current is carried by two large machine screws which can easily handle large currents.

The accuracy of the regulation depends on how hot you run the supply. The longer you hold the telegraph key down, the more heat that will build up in the four MOSFETs. During ham contacts, we only transmit for a minute or two at a time, so heroic cooling measures like fans and water circulation are not needed. However, my heat sinking for the transistors is not what it could be. When the supply was running on 2 transistors, I could watch the output voltage slowly sink. At first it was perfectly stable for several seconds, then it gradually began to descend. At first it sank just a hundredth of a volt per second, then faster and faster as I held the key down. With all four transistors working the stability was much better with no change for 20 seconds or more.

There is a classic full-load, heat test for high power supplies and amplifiers: You load your transmitter into a dummy load, put a brick on your telegraph key and go out for a leisurely lunch. When you return, if your ham shack hasn't burned down and the supply or amplifier hasn't been destroyed, you have passed the test. *This supply will definitely NOT pass this test*.

The 5,000 µF output capacitor

The purpose of the big capacitor on the output is to help supply sudden of surges of current during CW at high power. I hoped it would make chirp less likely. I surveyed old data sheets and power supply schematics to see how the rest of the world used supply output capacitors. I noticed that big capacitors were normal on the outputs of switching power supplies, but linear power supplies like this one usually had small output capacitors like 0.1 or 1.0 microfarad. I'm not sure what a little capacitor is supposed to do, perhaps it's for high frequency noise reduction. In any case, my 5,000 μF electrolytic capacitor works well. It's rated at 25 working volts.

The big 10,000 μF electrolytic capacitor located on the rectifier output was what I happened to have in my junk box. The capacitance isn't critical, it just needs to be large to reduce ripple and, ideally, rated at >50 working volts. I also added an LED pilot light with a 10K ohm dropping resistor which is not shown on the diagram. It runs on the regulated output.

Digital voltmeter

The blue digital voltmeter measures the output voltage with respect to ground. (It isn't shown on the schematic.) I put a switch to turn off the digital voltmeter in case I ever hear its

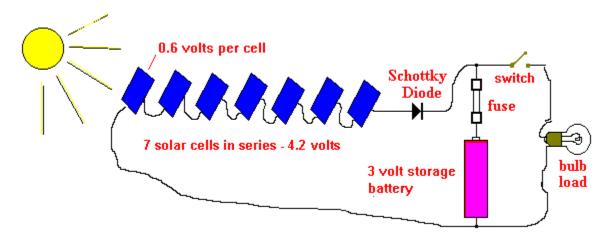
digital noise in the receiver. The digital meter turned out to be erratic when I powered it with the internal (grounded) 12 volt supply. This particular meter was apparently not designed to measure its own supply voltage. I eventually ran it with an independent (floating) "transistor-type" 9 volt battery which worked immediately without sensitive adjustment. I just turn it on when I want to adjust or monitor the output voltage. Of course I have to remember to turn it off when I'm done using the supply.

A final thought

These circuit development troubles illustrate why we should never declare a new circuit design "DONE" unless we have used it for many months. I worked for a company that developed a new model of a 200 watt, 200 KHz, RF electrosurgical generator. Under pressure from the marketing department, as soon as the first engineering prototype was working, the new model was rushed into production and sales. As I recall, it was 5 months and 47 changes to the circuit before all the glitches were discovered. Unfortunately, many of these faults were found by our customers! Once the bugs were eliminated, this unit was our best selling product for many years.

GOING SOLAR

Because my automotive trickle charger was feeble, I was charging my golf cart batteries non-stop. Back then I was using my old power-hungry vacuum tube receiver and I was having trouble keeping the battery charged for a couple hours of daily operating. However, I already owned a 12 watt, 12 volt solar panel so I installed it on the roof.



A simple solar charger circuit

Solar cells are a kind of silicon diode. They are arranged in series so that the forward voltage drop of each diode adds up to some voltage greater than the voltage of the storage battery. For example, at 0.6 volts per solar cell, we need at least 20 cells in series to raise the panel voltage higher than the 12 volt battery. Typically, an open circuited panel puts out 20 volts in bright sunshine. This extra capability insures that it will continue to charge a 12 volt battery all day and implies that there are roughly thirty 0.6 volt cells in series.

Solar cells are interesting to play with. I was surprised to discover that if you put your

hand over just one of the series cells, it turns off the whole string, something like Christmas tree lights wired in series. This means that just one wet leaf stuck on your panel could turn off the whole array.

The panel output current is proportional to the sine of the angle the sunlight makes with the panel. If your goal is to generate the maximum kilowatt-hours during the entire year, then the angle should equal your latitude. I mounted my panel at 45°, which at 40° latitude, gives me better performance during the winter. Optimizing for winter is smart because the days are short and the panel is often covered with snow. Actually 50° may be better here in Colorado. Snow slides off a steep incline and higher angles are more resistant to hail damage. On the other hand, mounting them on a tall, steep frame may make them subject to wind damage. There is no perfect angle. Most people just mount the panels flat on whatever roof they happen to have. If you wish to sacrifice some percentage of the output for beauty or mounting convenience, that's your decision.

The discharge preventing diode

It's bad form to connect a solar panel directly to a storage battery. The solar cells are forward biased diodes with respect to the battery. Therefore, whenever the sunlight quits, the panel voltage may drop below the battery voltage and a small battery current will reverse and flow through the solar panel. If there are enough extra solar cells, then the night-time voltage drop may still exceed the battery voltage. In any case, the discharge problem is typically prevented by a silicon diode in series with the panel to insure that current is never allowed to flow from the battery back into the panel. Since this check valve diode has a forward voltage drop that wastes energy, you may as well use a big Schottky diode that will only penalize you with 0.2 volts instead of 0.6 volts loss.

Another small issue is lightning protection. My panel is on the roof where, in theory, it might attract a lightning bolt. I'm not really worried, but I have a connector on the lead from the panel so I can disconnect it from my shack when I go away on trips or whenever a storm is particularly frightening. If I lived on a mountaintop or if my house were higher than the other houses in my neighborhood, I would be much more concerned.



Solar panel on the roof

I first built my panel frame out of varnished wood. The wooden boards screwed down to the roof retained water against the shingles and rapidly rotted. I replaced the boards with 2 inch aluminum angle stock which seems to be a more permanent fix. Oh, yes! The raccoons chewed up the exposed wiring behind the panel. I had to cover the wiring with a board so that the delicious vinyl insulation would no longer tempt them.

Lower power consumption helps

My solar panel charges about as much as the line-powered trickle charger, about 1 ampere. Consequently I still had to use line power to charge occasionally whenever I stayed on the air too long. A breakthrough came when I built a transistorized receiver, one of the receivers described in Chapter 13. The new receiver drew 120 mA. That is much better than 3,500 mA to power the old vacuum tube receiver. Since then, I haven't needed my line-powered charger.

12 Volt power distribution

A storage battery can deliver hundreds of amperes, so it's wise to isolate the battery from your rig and solar panel with an appropriate fuse or circuit breaker. A 30 ampere fuse should be about right. I have a master switch to isolate the battery from the ham rig when I'm not using it. A little LED pilot light tells me when it's connected and a voltmeter warns me if the battery is not fit for use. I also have charging and discharging ammeters (ampere meters) so I know the status of my supply at all times. I find the discharge meter helpful for monitoring my transmitters. You can even tune the antenna while watching the battery current. The proper antenna tuning setting coincides with a dip or minimum in the current drawn. Unfortunately, not all the "dip settings" are the optimum setting. Also, as explained above, an ampere meter can have significant voltage drop, about 0.25 volts across it at high current levels.



Battery charge monitor. The wire in front of the charge meter goes to my 12 volt desk lamp.

Maintaining clean battery contacts is critical to keeping the supply voltage constant under load. Every few months, I clean the contacts using baking powder (sodium bicarbonate) and water. I know the battery contacts need cleaning when the pilot light on my transmitter begins to flicker noticeably while I'm transmitting. I top off the batteries as needed with distilled water to keep plates in the cells from being exposed to the air. Tap water nearly always contains calcium or other ions that would contaminate the battery fluid, so distilled water is best. The grocery store usually stocks distilled water next to the regular bottled drinking water.

A gel-cell battery shouldn't have these corrosion and fluid loss problems. If you're feeling wealthy, modern "AGM," sealed, deep discharge batteries are ideal for this application. They are designed for solar systems and store roughly 50% more energy than the old golf-cart batteries of the same volume. However, if you overcharge a sealed gel-cell, the water cannot be replaced and the battery will be permanently damaged.





The 12 volt storage battery power system

The golf cart storage batteries are shown above. The transistorized inverter to the left of the batteries converts 12 volts DC to 120 volts AC for those rare times when a storm knocks out our commercial electricity. On those occasions I have simply strung an extension cord upstairs to power the TV and a few lights.

The glass and rubber device is a *hydrometer* for measuring the specific density of the battery acid. They are available in auto parts stores. They are used to check the charge status of

car batteries. The syringe-like device sucks up a sample of the acid from each battery cell. When the glass float rides high in the green zone, the battery is fully charged. Similar hydrometers are also used to check anti-freeze in a radiator to predict how low a temperature a radiator will tolerate. A friend of mine recently tried to buy a hydrometer, but the salesmen couldn't explain to him **how to read it**:

The glass float in an hydrometer is usually calibrated in terms specific gravity in relation to water. Pure water is defined as "1.0" and a fully charged lead-acid battery is about "1.3." Smaller hydrometer designs often have 3 or 4 little pith balls floating in a little glass tube. All the balls float to the top of the acid sample when the battery is fully charged. The red colored ball will float on pure water, while the green pith ball only floats on fully-charged acid. The other one or two balls float at intermediate levels of charge.

Storage battery safety

My solar panel system is small and I rarely have to add distilled water to my batteries. This tells me that my use of stored energy and the output of my small solar panel are well-matched. If I had to add water constantly it would mean that I was wasting energy and converting the water into gaseous hydrogen and oxygen.

Over-charging batteries can be dangerous. If I had a large system powering more of our household needs, the possibility of an explosion could be serious. Consequently, a large storage battery array should be located out in a well-ventilated place, perhaps a garage or, better yet, an external shed. Moreover, the state of the batteries should be continuously monitored with an electronic regulator to be sure that the batteries are not overcharged and not generating significant amounts of hydrogen. Charge control regulators are mandatory in any large system.

I read an article written by a fellow who was in charge of maintaining remote microwave relay stations. Wind turbines powered the stations. Unfortunately, the power systems were not equipped with any means to turn off the charging current to the batteries during windstorms. The results were catastrophic explosions inside the stations. Eventually, the telephone company realized the problem and put in charge-control regulators.

These days, microwave relay stations have been largely replaced with over-land fiber optic cables. One beautiful, calm summer day my buddies and I were hiking along the continental divide ridge west of Denver, Colorado. However, extreme high winds, over 100 mph (160 kmph) are common up there. We discovered an abandoned, ruined microwave relay station that fit the over-charged battery disasters described above. The little battery shack was blown open and pieces of batteries, dish antennas and wiring were scattered about. The relay station had been powered by a wind turbine. As described above, the station shack had apparently exploded. Not only that, obviously the mechanical governor on the turbine had failed to feather the turbine blades during the wind storm. The turbine alternator was hanging out of its case and the turbine blades were scattered all across the tundra. Even the steel strut tower was bent!

In summary, I get a kick out of operating like a fully solar-powered Field Day station. Because my whole station runs on 12 volts DC, in theory I'm always ready for Field Day and there's nothing to stop me from going mobile. One of my back-to-nature dreams is that, during a power failure, I can go right on operating and thumb my nose at the evil corporate power

monopoly. Twice during power failures I have galloped downstairs in the dark to make my first 100% truly independent radio contact. But before I could even tune the transmitter, the *#@%!\$ lights came back on. Oh, curse those competent fellows at Xcel Energy Company!

*Build-it-yourself 12 volt motor generator

Every year or two my friend Bob, NØRN, gets the urge to operate on Field Day, the international ham radio emergency communications exercise. Because I'm not the super, 35 words per minute CW operator he is, I'm not so enthusiastic. But I enjoy going out into the woods, setting up a tent and spending 24 hours playing Field Day with him. I do the book keeping, writing down the call letters he talks to. Bob's solution to the emergency power problem is his homebuilt gasoline-powered generator. It's a former lawnmower engine, an old automobile alternator and its matching voltage regulator. As you can see, he mounted the whole assembly on a painted wooden frame. A fan belt underneath the red-painted deck connects the engine to the alternator. The 12 to 14 volts from the alternator charges a deep discharge 12 volt marine battery with an automotive regulator. Other than the engine and alternator, it's pretty much the same as my golf-cart battery system above. It's simple and it works great.



OK, it does have one glitch - the engine is rather loud. Bob made a crude muffler out of a tin can. Also, he isolates the engine from the tent with a sound-attenuating plywood enclosure and connects it to the operating tent with a *long* cable.

LED THERE BE LIGHT

Emergency Station Lighting

As explained above, I run my whole station on solar energy stored in a 12 volt battery. An advantage of battery power is that I operate free from the power grid. This saves very little money, but it's quite romantic. Of course at night, even on batteries, I need to keep a log and throw the correct switches. Using candles or a flashlight clenched in my teeth didn't seem very sophisticated.

My first idea was to dangle a 12 volt automotive light bulb over my shack. Bob, NØRN, uses such a light in his tent on Field Day. This solution is completely practical, but it seemed old-tech and boring. It also draws about 10 watts of power. If I am going to all the trouble to build a custom 12 volt light, I figured it should at least be <u>an interesting light</u>. Modern lighting methods produce more light per watt than the old tungsten filament bulbs. Also, energy conservation is important when your station is powered by a battery charged with a small solar panel.

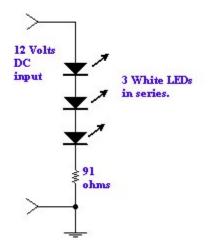


A homebrew LED and flourescent station lamp

White LEDs – a modern marvel.

I happened to notice some "white LEDs" for sale down at Radio Shack. (Part # 276-320) I thought cynically that they were probably really dim and not really white. I bought one and hooked it to a variable power supply. I slowly turned up the voltage until I obtained the rated 20 mA DC current. Hey! Not bad! The beam of white light has a slightly bluish cast, but otherwise, it throws a spot of light out to a couple feet. It's rated at 1100 mcd. That's impressive brightness when you consider its beam angle is 100°. One LED makes a perfect key chain light and many LED flashlights are now on the market.

I wrote this present little article some years ago. Since then, screw-in 12 volt light bulbs consisting of large clusters of white LEDs have become available. I now have one in the shack that draws 3 watts and delivers considerably more light than the two systems below. Unfortunately, it began to flicker annoyingly and I finally retired the new light. I took it apart and isolated the problem to a few specific LEDs, but when I disconnected or replaced them, then other LEDs began to flicker. Surely the manufacturers will fix that problem one of these years.



I'm told these white LEDs are made from sophisticated layers consisting of yellow and blue LEDs and a phosphorous that glows white. Compared to other LEDs, they have a rather high voltage drop, 3.6 volts. I figured if I put three in series plus a single dropping resistor, it could run on 12 volts. The current is limited with just one 91 ohm resistor. The resulting triple light consumes just 0.25 watt and is adequate for keeping a log and operating the station. That's amazing when you think about it. We formerly squandered hundreds of watts to illuminate entire rooms when all we really need is ½ watt to read our newspaper or book.

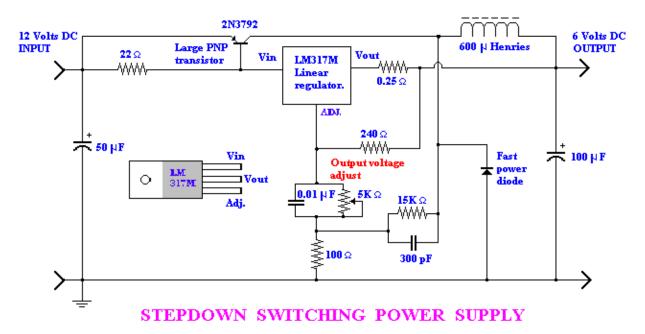
Flourescent lighting

Unfortunately, "adequate" isn't the same as "comfortably bright." So my next project was to build a 12 volt powered compact fluorescent. I fiddled for a couple hours trying to build a power oscillator capable of producing the required 800 Volts AC needed to ignite the miniature fluorescent bulb. I had several transformer and switching transistor problems that I was having trouble solving. I also fried my voltmeter because I forgot to change the range when I put it on the high voltage. There's nothing like dead test gear to make you think differently.

I remembered that I still had a 6 volt fluorescent lamp that I used to use for lighting my pup tent while camping. One day I rolled up the tent while the light was still hanging from the tent ceiling. Oops! The plastic housing was splintered and the remains of the light assembly were still in my junk box. I found the parts of the light and resoldered the broken wires. I connected it to a 6 volt power supply and it still worked fine. Next I built a shiny reflector/ lampshade out of sheet aluminum and it produced loads of light. Unfortunately, I need a 12 volt light, not a 6 volt light. I didn't have a second light to put in series with the first, so I used a big dropping resistor to run the light on 12 volts. That worked OK, but it seemed pretty crude. Besides, I was already "cheating" because I hadn't built the fluorescent high voltage supply.

Nifty "buck-type" switching power supply

I replaced the dropping resistor with a switching power supply to reduce 12 volts DC down to 6 volts. I got the design from the National Semiconductor linear IC data book. When using the switcher, the fluorescent light draws about 2.5 watts at 12 volts. The switcher is about 80% efficient. That is, it dissipates 10% of the total energy. 80% of 6 volts is about 4.8 volts, so 1.2 volts are wasted or about 10% of the total voltage. In contrast, a resistor would have dissipated 50% of my energy. I have used this little supply design for several home projects so far and found it thoroughly reliable. If you're a homebuilder, this simple, buck-switcher belongs in your bag of tricks. (<u>Buck switchers reduce voltage, boost switchers raise voltage</u>.) If you're bored with building a 12 volt light, maybe this little circuit will interest you:



(12 Volt DC to 6 Volt DC Converter)

A switching power supply made from a *linear* regulator

How can this work?

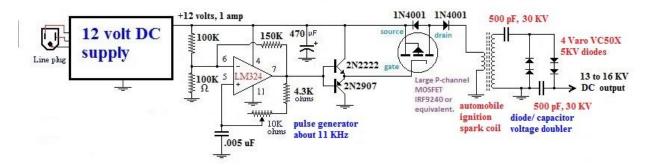
This switcher uses a LINEAR regulator to generate the pulsewidth modulation needed to implement a switching power supply. This is essentially the same linear regulator used in the suggested line-powered QRP power supply. But, when you put a scope probe on the inductor, sure enough! The linear regulator is switching full on and off in rectangular pulses. Apparently the 15K Ω resistor and 300 pF capacitor are coupling a feedback pulse from the inductor into the regulator to cause it to switch full on and full off. The pulse width varies with load and responds just like a real switcher. Aside from my amazement that linear regulators can work as switchers, I was also surprised that I hear very little switcher noise in my receiver. The RF noise it produces is apparently sufficiently isolated from the receiver that I rarely hear hash competing with the ham signals. On the rare occasions when I do hear it, I simply turn off the fluorescent.

Subjectively, the fluorescent produces roughly twice as much light as the LEDs. In other words, for ten times as much power the light seems to be twice as bright. On the other hand, it illuminates a much wider area than the LEDs, so I just run both of them simultaneously. The LEDs illuminate my log and scratch pad while the fluorescent lights up the station as a whole. I've used this light for hours at a time. It's bright enough that I'm content with it so I don't think about running across the room to turn on "the real lights." In summary, battery power and energy conservation are entertaining games. And, if we're really unlucky, someday our hobbies might even be useful in a community crisis.

A 15,000 VOLT DC POWER SUPPLY

So far as I know, this high voltage power supply has no useful purpose for amateur radio. However, like me, you might want to build one for some crazy experiment such as the resonant spark gap transmitter described in Chapter 4B. I originally built this for a wondrous air ionization idea that didn't work. Well, actually it worked perfectly, but it produced ozone along with the ions. The ozone was much too irritating to the nose and lungs. In the old days the spark gap transmitters on ships like the Titantic were so large and produced so much noise and ozone, that the radio operator could not be in the same room with his transmitter. I am presenting the supply in this chapter because it illustrates several common power supply principles:

15,000 VOLT DC POWER SUPPLY





This circuit begins with a low DC voltage source. I used the same 12 volt supply presented earlier which I originally built to power a 5 watt QRP. Because the high voltage source is an automobile ignition spark transformer, I needed 12 volts. In order to generate a different voltage level, either higher voltages or lower ones, the DC is first converted (back) into AC. The new AC pulses are usually a high frequency AC so that the transformer will not require so much iron. In this case an op-amp square wave oscillator is used to generate the square pulses. The 2N2222 and 2N2907 transistors are a push-pull complimentary transistor amplifier. The transistor amplifier squares the 11 KHz pulses and increases the current drive to the MOSFET gate. Op-amp oscillators are discussed in Chapter 9 in the article about the electronic CW keyer. The 10K ohm trim pot on the oscillator adjusts the pulse frequency for maximum output voltage.

Since I needed a very high voltage, I used an automobile spark transformer which is designed to convert 12 volt pulses into 10KV or more. By adding the diode/capacitor doubler, I was able to approximately double the output voltage.

Diode/ capacitor voltage doublers

The double diodes in the above circuit may be obscuring the function, but they are simply functioning as single diodes. I used two in each chain because they were each only rated for 5 KV. Diode voltage doublers always need 2 diodes and 2 capacitors. The circuit is driven by AC waves or pulses. The principle is that the first high voltage capacitor is charged up to the peak of the AC voltage, let's say, 8 KV. Then diodes prevent it from discharging so that, when this AC voltage goes positive again, this "8 kilovolt battery" is added to another charged "storage capacitor" at the output. Because the storage capacitor was already charged to 7 or 8 KV, the 8 KV from the first capacitor is in series with the storage capacitor. 8 KV + 7 KV = 15,000 volts. Doublers always produce less than twice the desired voltage because of the voltage drop across the diodes and because the load on the supply is constantly discharging the storage capacitor.

At the end of Chapter 10 there is another example of a voltage doubler that produces a low power 24 volts supply. That doubler works the same way as above, but is easier to understand because transistors actively "rewire" the two capacitors in series. Each capacitor has been charged to 12 volts so, 12V + 12V = about 24 volts.

Where did I get those 500 pF, 30 kilovolt capacitors? I scavenged them from the high voltage power supplies found in old fashioned TV sets. Those big old cathode ray tube displays needed a very high voltage to propel the electron stream a distance of a foot or more from the hot cathode at the back of the TV set to the big phosphorescent screen up front.

The switching transistor used is a large MOSFET of the kind discussed in Chapter 6B. Notice that there are diodes across the transistor and in series with it to protect it from transient voltage spikes from the spark coil. During each pulse, the transistor turns on and current flows through the transformer primary winding. However, when the pulse shuts off, the inductor will "try" to maintain the current flow by generating a huge voltage to force the current to continue in the same direction. This voltage might hurt the transistor so the diodes force this energy into the secondary, high voltage winding.

Notice that in elderly automobile ignitions, there is a large capacitor across the "breaker points." Breaker points are a mechanical switch which is driven by the rotating cam inside the distributor. The capacitor prevents the voltage across the open points from rising significantly. When this capacitor fails or is missing, the voltage across the secondary winding will be too low and you'll wonder why your antique car won't start.

My first attempt to build a high voltage supply began with a transformer with a smaller output voltage, 350 volts AC. I attempted to use a series of doublers to raise the voltage. I assumed I could double it successively up to 10 KV or more. I quickly discovered that after the first doubling, the multiplying effect quickly disappeared. With many stages of diodes and capacitors I never achieved higher than about 1100 volts DC.

Notice that, although you could objectively describe this design as a "switching power supply," this term usually applies to designs in which feedback regulates the output voltage. The switching power supply described in the previous article has feedback to hold the output voltage

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constant, so it is a true "switcher." In this doubler voltage supply and the one in Chapter 10, there is no feedback to hold the output constant. The actual output voltage is highly dependent on the load placed on the supply. The term I have heard for a supply like this is a "**charge pump supply**." The advantage of *NOT* regulating the voltage with feedback is that it produces very little RF noise when compared with a switcher.
