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Chapter 7

Power Sources

Our transceivers, amplifiers, accessories, computers and test equipment all require power to operate. This chapter illustrates the various techniques, components and systems used to provide power at the voltage and current levels our equipment needs. Topics range from basic transformers, rectifiers and filters to linear voltage regulation, switchmode power conversion, high voltage techniques and batteries. Material on switchmode conversion was contributed by Rudy Severns, N6LF and Chuck Mullett, KR6R. A new section on batteries was contributed by Isidor Buchmann from his book *Batteries in a Portable World*. Alan Applegate, KØBG contributed the section on selecting batteries for mobile use.

Chapter 7 — CD-ROM Content

Projects

- Four Output Bench Supply
- 12 V, 15 A Power Supply — Article and PCB Template
- 13.8 V, 5 A Power Supply — PCB Template
- 28 V High Current Power Supply — Article and PCB Template
- Dual Output Power Supply
- Micro M+ PV Charge Controller
- Revisiting the 12 V Power Supply
- Series Regulator Power Supply — Article and PCB Template
- Build an Inverting DC-DC Converter
- Adjustable Tracking Power Supply

Supplemental Articles

- Testing and Monitoring Batteries — Excerpts from *Batteries in a Portable World* by Isidor Buchmann
- Vacuum Tube and Obsolete Rectifiers

Acknowledging the changing nature of amateur power requirements, the title of this chapter has updated from the traditional *Power Supplies* to *Power Sources*. More mobile and portable operation relies on power from batteries, for example. Hybrids of ac and dc power sources are becoming more common, blurring what has traditionally been known as a "power supply." In response, the scope of this chapter now includes more of the changing power environment in the amateur station. (Generators are covered in the Portable Installations section of the chapter on **Building a Station**.)

7.1 Power Processing

Fig 7.1 illustrates the concept of a power processing unit inserted between the energy source and the electronic equipment or load. The *power processor* is often referred to as the *power supply*. That's a bit misleading in that the energy "supply" actually comes from some external source (battery, utility power and so forth), which is then converted to useful forms by the power processor. Be that as it may, in practice the terms "power supply" and "power processor" are used interchangeably.

The real world is even more arbitrary. Power processors are frequently referred to as *power converters* or simply as *converters*, and we will see other terms used later in this chapter. It is usually obvious from the context of the discussion what is meant and the

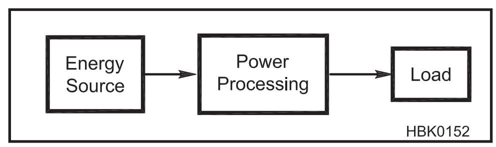


Fig 7.1 — Basic concept of power processing.

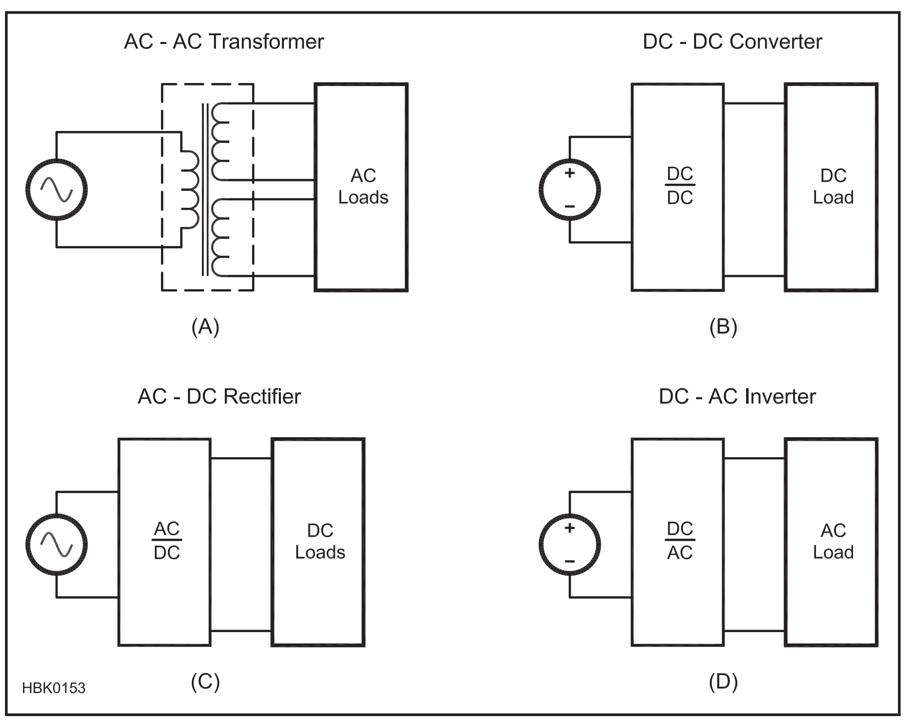


Fig 7.2 — Four power processing schemes: ac-ac, dc-dc, ac-dc and dc-ac.

glossary at the end of this chapter gives some additional information.

Power conversion schemes can take the form of: ac-to-ac (usually written ac-ac), ac-dc, dc-ac and dc-dc. Examples of these schemes are given in **Fig 7.2**. Specific names may be given to each scheme: ac-dc => rectifier, dc-dc => converter and dc-ac => inverter. These are the generally recognized terms but you will see exceptions.

Power conversion normally includes voltage and current regulation functions. For example, the voltage of a vehicle battery may vary from 14 V when being charged down to 10 V or less when discharged. A converter and regulator are required to maintain adequate voltage to mobile equipment at both over- and under-voltage conditions. Commercial utility power may vary from 90 to 270 V ac depending on where you are in the world. AC power converters are frequently required to handle that entire voltage range while still providing tightly regulated dc power.

7.2 AC-AC Power Conversion

In most US residences, three wires are brought in from the outside electrical-service mains to the house distribution panel. In this three-wire system, one wire is neutral and should be at earth ground potential. (See the **Safety** chapter for information on electrical safety.) The neutral connection to a ground rod or electrode is usually made at the distribution panel. The voltage between the other two wires is 60-Hz ac with a potential difference of approximately 240 V RMS. Half of this voltage appears between each of these wires and the neutral, as indicated in **Fig 7.3A**. In systems of this type, the 120 V household loads are divided at the breaker panel as evenly as possible between the two sides of the power mains. Heavy appliances such as electric stoves, water heaters, central air conditioners and so forth, are designed for 240 V operation and are connected across the two ungrounded wires.

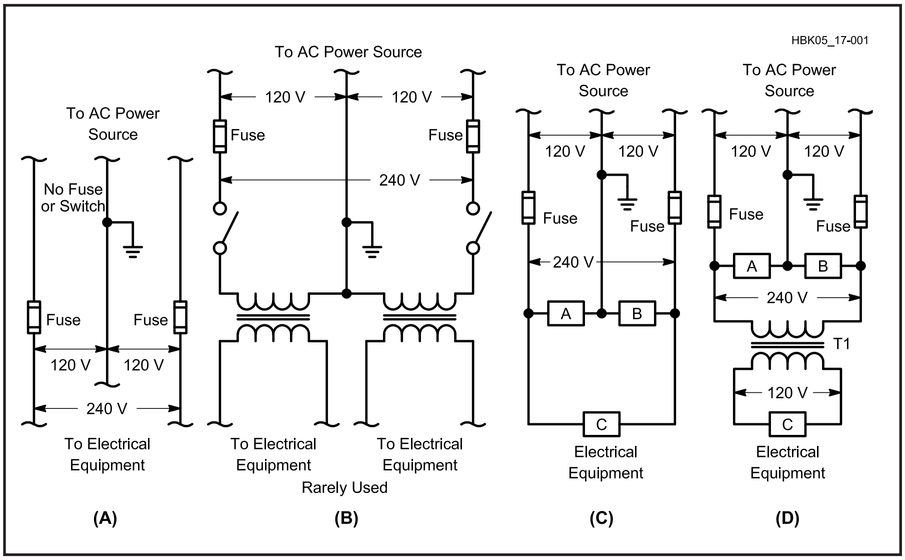


Fig 7.3 — Three-wire power-line circuits. At A, normal three-wire-line termination. No fuse should be used in the grounded (neutral) line. The ground symbol is the power company's ground, not yours! Do not connect anything other than power return wiring, including the equipment chassis, to the power neutral wire. At B, the "hot" lines each have a switch, but a switch in the neutral line would not remove voltage from either side of the line and should never be used. At C, connections for both 120 and 240 V transformers. At D, operating a 120 V plate transformer from the 240 V line to avoid light blinking. T1 is a 2:1 step-down transformer.

Both hot wires for 240 V circuits and the single hot wire for 120 V circuits should be protected by either a fuse or breaker. A fuse or breaker or any kind of switch should *never* be used in the neutral wire. Opening the neutral wire does not disconnect the equipment from an active or "hot" line, possibly creating a potential shock hazard between that line and earth ground.

Another word of caution should be given at this point. Since one side of the ac line is grounded (through the green or bare wire — the standard household wiring color code) to earth, all communications equipment should be reliably connected to the ac-line ground through a heavy ground braid or bus wire of #14 or heavier-gauge wire. This wire must be a separate conductor. You must not use the power-wiring neutral conductor for this safety ground. (A properly-wired 120 V outlet with a ground terminal uses one wire for the ac hot connection, one wire for the ac neutral connection and a third wire for the safety ground connection.) This provides a measure of safety for the operator in the event of accidental short or leakage of one side of the ac line to the chassis.

Remember that the antenna system is frequently bypassed to the chassis via an RF choke or tuned circuit, which could make the antenna electrically "live" with respect to the earth ground and create a potentially lethal shock hazard. A *ground fault circuit interrupter* (GFCI or GFI) is also desirable for safety reasons, and should be a part of the shack's electrical power wiring.

7.2.1 Fuses and Circuit Breakers

All transformer primary circuits should be fused properly and multiple secondary outputs should also be individually fused. To determine the approximate current rating of the fuse or circuit breaker on the line side of a power supply it is necessary to determine the total load power. This can be done by multiplying each current (in amperes) being drawn by the load or appliance, by the voltage at which the current is being drawn. In the case of linear regulated power supplies, this voltage has to be the voltage appearing at the output of the rectifiers before being applied to the regulator stage. Include the current drawn by bleeder resistors and voltage dividers. Also include filament power if the transformer is supplying vacuum tube filaments. The National Electrical Code (NEC) also specifies maximum fuse ratings based on the wire sizes used in the transformer and connections.

After multiplying the various voltages and currents, add the individual products. This is the total power drawn from the line by the supply. Then divide this power by the line voltage and add 10 to 30% to account for the inefficiency of the power supply itself. Use a fuse or circuit breaker with the nearest larger current rating. Remember that the charging of filter capacitors can create large surges of current when the supply is turned on. If fuse blowing or breaker tripping at turn on is a problem, use slow-blow fuses, which allow for high initial surge currents.

For low-power semiconductor circuits, use fast-blow fuses. As the name implies, such fuses open very quickly once the current exceeds the fuse rating by more than 10%.

7.3 Power Transformers

Numerous factors are considered to match a transformer to its intended use. Some of these parameters are:

1. Output voltage and current (volt-ampere rating).
2. Power source voltage and frequency.
3. Ambient temperature.
4. Duty cycle and temperature rise of the transformer at rated load.
5. Mechanical considerations like weight, shape and mounting.

7.3.1 Volt-Ampere Rating

In alternating-current equipment, the term *volt-ampere* (*VA*) is often used rather than the term watt. This is because ac components must handle reactive power as well as real power. If this is confusing, consider a capacitor connected directly across the secondary of a transformer. The capacitor appears as a reactance that permits current to flow, just as if the load were a resistor. The current is at a 90º phase angle, however. If we assume a perfect capacitor, there will be no heating of the capacitor, so no real power (watts) will be delivered by the transformer. The transformer must still be capable of supplying the voltage, and be able to handle the current required by the reactive load. The current in the transformer windings will heat the windings as a result of the I^2R losses in the winding resistances. The product of the voltage and current in the winding is referred to as "volt-amperes," since "watts" is reserved for the real, or dissipated, power in the load. The volt-ampere rating will always be equal to, or greater than, the power actually being drawn by the load.

The number of volt-amperes delivered by a transformer depends not only upon the dc load requirements, but also upon the type of dc output filter used (capacitor or choke input), and the type of rectifier used (full-wave center tap or full-wave bridge). With a capacitive-input filter, the heating effect in the secondary is higher because of the high peak-to-average current ratio. The volt-amperes handled by the transformer may be several times the power delivered to the load. The primary winding volt-amperes will be somewhat higher because of transformer losses. This point is treated in more detail in the section on ac-dc conversion. (See the **Electrical Fundamentals** chapter for more information on transformers and reactive power.)

7.3.2 Source Voltage and Frequency

A transformer operates by producing a magnetic field in its core and windings. The intensity of this field varies directly with the instantaneous voltage applied to the transformer primary winding. These variations, coupled to the secondary windings, produce the desired output voltage. Since the transformer appears to the source as an inductance in parallel with the (equivalent) load, the primary will appear as a short circuit if dc is applied to it. The unloaded inductance of the primary (also known as the *magnetizing inductance*) must be high enough so as not to draw an excess amount of input current at the design line frequency (normally 60 Hz in the US). This is achieved by providing a combination of sufficient turns on the primary and enough magnetic core material so that the core does not saturate during each half-cycle.

The voltage across a winding is directly related to the time rate of change of magnetic flux in the core. This relationship is expressed mathematically by $V = N\, d\Phi/dt$ as described in the section on Inductance in the **Electrical Fundamentals** chapter. The total flux in turn is expressed by $\Phi = A_eB$, where A_e is the cross-sectional area of the core and B is the flux density.

The maximum value for *flux density* (the magnetic field strength produced in the core) is limited to some percentage (< 80% for example) of the maximum flux density that the core material can stand without saturating, since in saturation the core becomes ineffective and causes the inductance of the primary to plummet to a very low level and input current to rise rapidly. Saturation causes high primary currents and extreme heating in the primary windings.

At a given voltage, 50 Hz ac creates more flux in an inductor or transformer core because the longer time period per half-cycle results in more flux and higher magnetizing current than the same transformer when excited by same 60-Hz voltage. For this reason, transformers and other electromagnetic equipment designed for 60-Hz systems must not be used on 50-Hz power systems unless specifically designed to handle the lower line frequency.

7.3.3 How to Evaluate an Unmarked Power Transformer

Hams who regularly visit hamfests frequently develop a junk box filled with used and unmarked transformers. Over time, transformer labels or markings on the coil wrappings may come off or be obscured. There is a good possibility that the transformer is still useable, but the problem is to determine what voltages and currents the transformer can supply. First consider the possibility that you may have an audio transformer or other impedance-matching device rather than a power transformer. If you aren't sure, don't connect it to ac power!

If the transformer has color-coded leads, you are in luck. There is a standard for transformer lead color-coding, as is given in the **Component Data and References** chapter. Where two colors are listed, the first one is the main color of the insulation; the second is the color of the stripe.

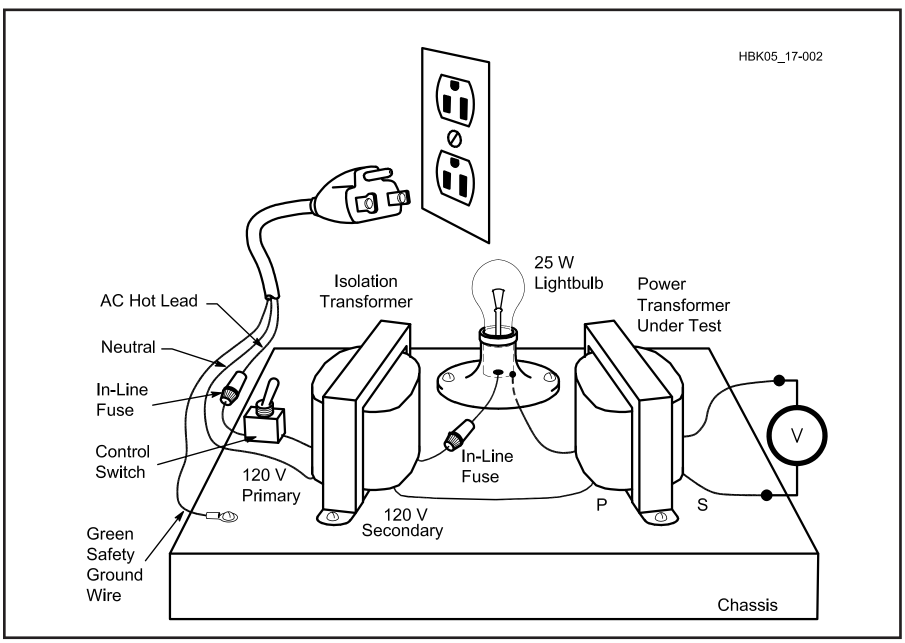


Fig 7.4 — Use a test fixture like this to test unknown transformers. Don't omit the isolation transformer, and be sure to insulate all connections before you plug into the ac mains.

Check the transformer windings with an ohmmeter to determine that there are no shorted (or open) windings. In particular, check for continuity between any winding and the core. If you find that a winding has been shorted to the core, do not use the transformer! The primary winding usually has a resistance higher than a filament winding and lower than a high-voltage winding.

Fig 7.4 shows that a convenient way to test the transformer is to rig a pair of test leads to an electrical plug with a 25 W household light bulb in series to limit current to safe (for the transformer) levels. For safety reasons use an isolation transformer and be sure to insulate all connections before you plug into the ac mains. Switch off the power while making or changing any connections. You can be electrocuted if the voltmeter leads or meter insulation are not rated for the transformer output voltage! If in doubt, connect the meter with the circuit turned off, then apply power while you are not in contact with the circuit. *Be careful! You are dealing with hazardous voltages!*

Connect the test leads to each winding separately. The filament/heater windings will cause the bulb to light to full brilliance because a filament winding has a very low impedance and almost all the input voltage will be across the series bulb. The high-voltage winding will cause the bulb to be extremely dim or to show no light at all because it will have a very high impedance, and the primary winding will probably cause a small glow. The bulb glows even with the secondary windings open-circuited because of the small magnetizing current in the transformer primary.

When the isolation transformer output is connected to what you think is the primary winding, measure the voltages at the low-voltage windings with an ac voltmeter. If you find voltages close to 6 V ac or 5 V ac, you know that you have identified the primary and the filament windings. Label the primary and low voltage windings.

Even with the light bulb, a transformer can be damaged by connecting ac mains power to a low-voltage or filament winding. In such a case the insulation could break down in a primary or high-voltage winding because of the high turns ratio stepping up the voltage well beyond the transformer ratings.

Connect the voltmeter to the high-voltage windings. Remember that the old TV transformers will typically supply as much as 800 V_{pk} or so across the winding, so make sure that your meter can withstand these potentials without damage and that you use the voltmeter safely.

Divide 6.3 (or 5) by the voltage you measured across the 6.3 V (or 5 V) winding in this test setup. This gives a multiplier that you can use to determine the actual no-load voltage rating of the high-voltage secondary. Simply multiply the ac voltage measured across the high-voltage winding by the multiplier.

The current rating of the windings can be determined by loading each winding with the primary connected directly (no bulb) to the ac line. Using power resistors, increase loading on each winding until its voltage drops by about 10% from the no-load figure. The current drawn by the resistors is the approximate winding load-current rating.

7.4 AC-DC Power Conversion

One of the most common power supply functions is the conversion of ac power to dc, or *rectification*. The output from the rectifier will be a combination of dc, which is the desired component, and ac *ripple* superimposed on the dc. This is an undesired but inescapable component. Since most loads cannot tolerate more than a small amount of ripple on the dc voltage, some form of filter is required. The result is that ac-dc power conversion is performed with a rectifier-filter combination as shown in **Fig 7.5**.

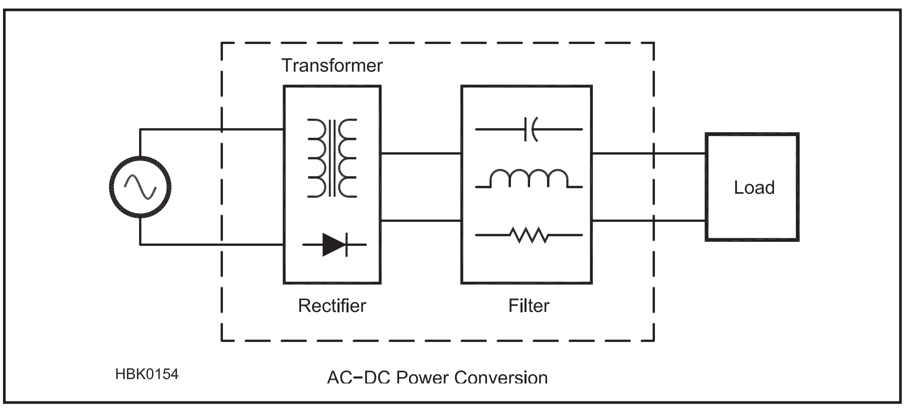


Fig 7.5 — Ac-dc power conversion with a rectifier and a filter.

As we will see in the rectifier circuit examples given in the next sections, sometimes the rectifier and filter functions will be separated into two distinct parts but very often the two will be integrated. This is particularly true for voltage and current multipliers as described in the sections on multipliers later in the chapter. Even when it appears that the rectifier and filter are separate elements, there will still be a strong interaction where the design and behavior of each part depends heavily on the other. For example the current waveforms in the rectifiers and the input source are functions of the load and filter characteristics. In turn the voltage waveform applied to the filter depends on the rectifier circuit and the input source voltages. To simplify the discussion we will treat the rectifier connections and the filters separately but always keeping in mind their interdependence.

The following rectifier-filter examples assume a conventional 60 Hz ac sine wave source, but these circuits are frequently used in switching converters at much higher frequencies and with square wave or quasi-square wave voltage and current waveforms. The component values may be different but the basic behavior will be very similar.

There are many different rectifier circuits or "connections" that may be used depending on the application. The following discussion provides an overview of some of the more common ones. The circuit diagrams use the symbol for a semiconductor diode, but the same circuits can be used with the older types of rectifiers that may be encountered in older equipment.

For each circuit we will show the voltage and current waveforms in the circuit for resistive, capacitive and inductive loads. The inductive and capacitive loads represent commonly used filters. We will be interested in the peak and average voltages as well as the RMS currents.

7.4.1 Half-Wave Rectifier

Fig 7.6 shows several examples of the half-wave rectifier circuit. It begins with a simple transformer with a resistive load (Fig 7.6A) and goes on to show how the output voltage and transformer current varies when a diode and filter elements are added.

Without the diode (Fig 7.6A) the output voltage (V_R) and current are just sine waves, and the RMS current in the transformer windings will be the same as the load (R) current.

Next, add a rectifier diode in series with the load (Fig 7.6B). During one half of the ac cycle, the rectifier conducts and there is current through the rectifier to the load. During the other half cycle, the rectifier is reverse-biased and there is no current (indicated by the broken line in Fig 7.6B) in R. The output voltage is pulsating dc, which is a combination of two components: an average dc value of $0.45\,E_{RMS}$ (the voltage read by a dc voltmeter) and line-frequency ac ripple. The transformer secondary winding current is also pulsating dc. The power delivered to R is now ½ that for Fig 7.6A but the secondary RMS winding current in Fig 7.6B is still 0.707 times what it was in Fig 7.6A. For the same winding resistance, the winding loss, in proportion to the output power, is twice what it was in Fig 7.6A. This is an intrinsic limitation of the half-wave rectifier circuit — the RMS winding current is larger in proportion to the load power. In addition, the dc component of the secondary winding current may bias the transformer core toward saturation and increased core loss.

A filter can be used to smooth out these variations and provide a higher average dc voltage from the circuit. Because the frequency of the pulses (the ripple frequency) is low (one pulse per cycle), considerable filtering is required to provide adequately smooth dc output. For this reason the circuit is usually limited to applications where the required current is small. Parts C, D and E in Fig 7.6 show some possible capacitive and inductive filters.

As shown in Fig 7.6C and D, when a capacitor is used for filtering the output dc voltage will approach

$$V_{pk} = \sqrt{2} \times E_{RMS} \tag{1}$$

and the larger we make the filter capacitance, the smaller the ripple will be.

Unfortunately, as we make the filter capacitance larger, the diode, capacitor and transformer winding currents all become high-amplitude narrow pulses which will have a very high RMS value in proportion to the power level. These current pulses are also transmitted to the input line and inject currents at harmonics of the line frequency into the power source, which may result in interference to other equipment. Narrow high-amplitude current pulses are characteristic of capacitive-input filters in all rectifier connections when driven from voltage sources.

As shown in Fig 7.6E, it is possible to use an inductive filter instead, but a second diode (D2, sometimes called a *free-wheeling diode*) should be used. Without D2 the output voltage will get smaller as we increase the size of L to get better filtering, and the output voltage will vary greatly with load. By adding D2 we are free to make L large for small output ripple but still have reasonable voltage regulation. Currents in D1 and the winding will be approximately square waves, as indicated. This will reduce the line harmonic currents injected into the source but there will still be some.

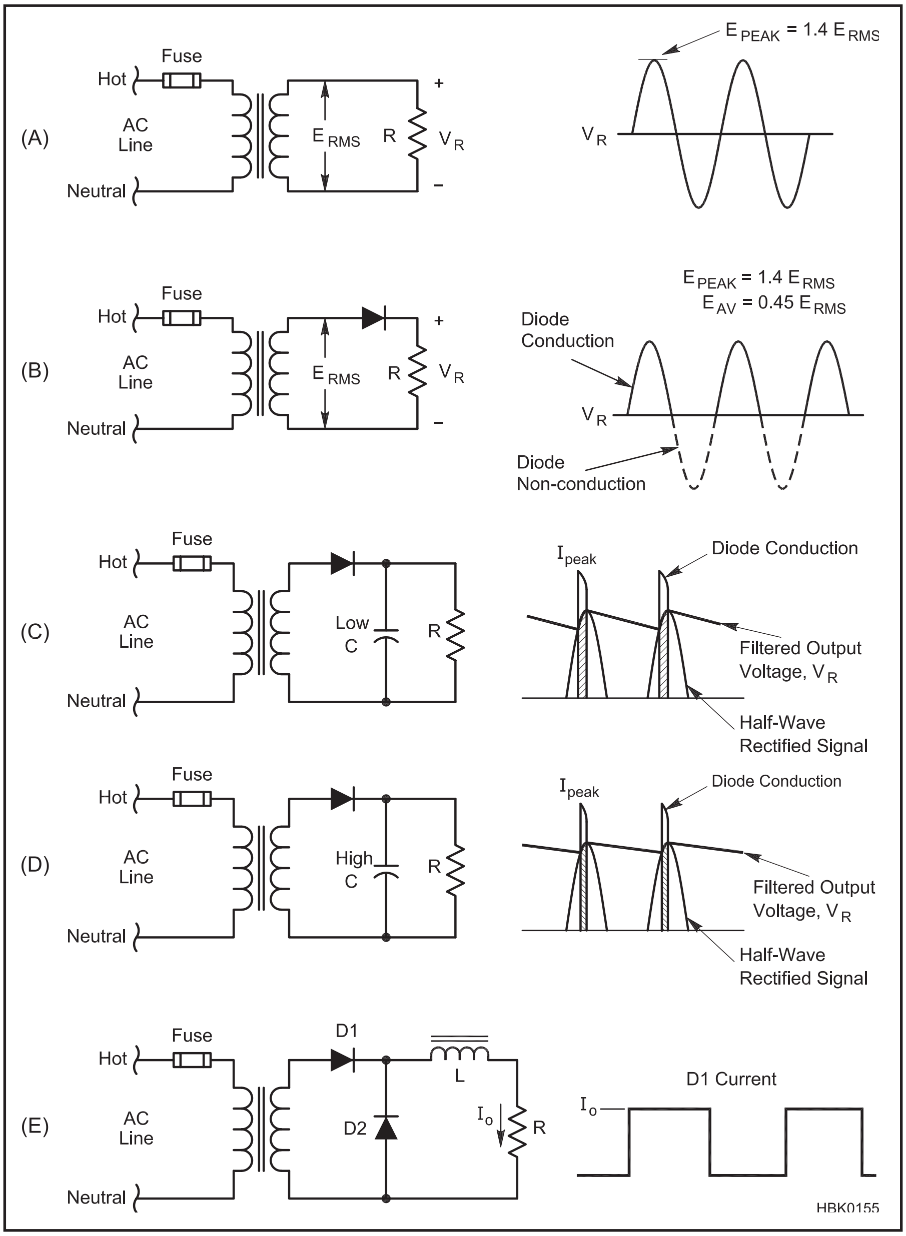


Fig 7.6 — Half-wave rectifier circuits. A illustrates the voltage waveform at the output without a rectifier. B represents the basic half-wave rectifier and the output waveform. C and D illustrate the impact of small and large filter capacitors on the output voltage and input current waveforms. E shows the effect of using an inductor filter with the half-wave rectifier. Note the addition of the shunt diode (D2) when using inductive filters with this rectifier connection.

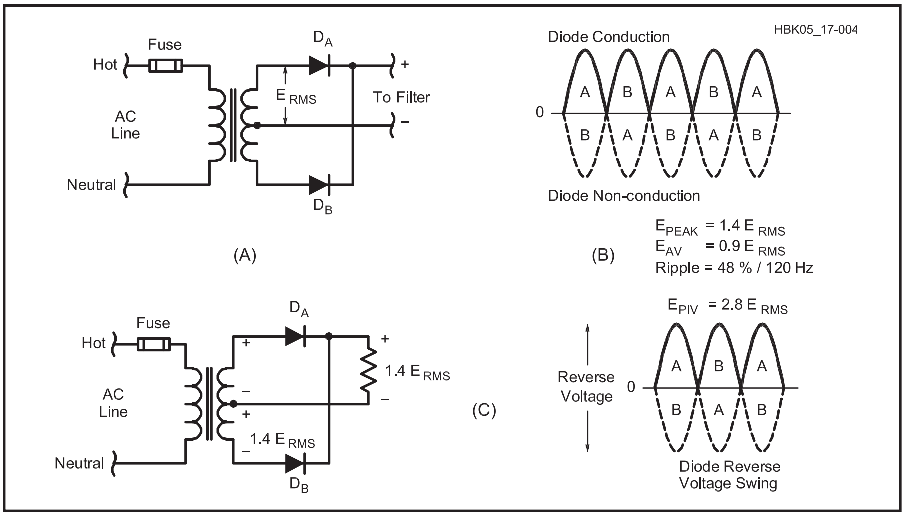


Fig 7.7 — Full-wave center-tap rectifier circuits. A illustrates the basic circuit. Diode conduction is shown at B with diodes A and B alternately conducting. The peak inverse voltage for each diode is 2.8 E_{RMS} as depicted at C.

Peak inverse voltage (*PIV*) is the maximum voltage the rectifier must withstand when it isn't conducting. This varies with the load and rectifier connection. In the half-wave rectifier, with a resistive load the PIV is the peak ac voltage (1.4 × E_{RMS}); with a capacitor filter and a load drawing little or no current, the PIV can rise to 2.8 × E_{RMS}.

7.4.2 Full-Wave Center-Tapped Rectifier

The full-wave center-tapped rectifier circuit is shown in **Fig 7.7**. It is essentially an arrangement where the outputs of two half-wave rectifiers are combined so that both halves of the ac cycle are used to deliver power to the output. A transformer with a center-tapped secondary is required.

The average output voltage of this circuit is 0.9 × E_{RMS} of half the transformer secondary (the center-tap to one side); this is the maximum that can be obtained with a suitable choke-input filter. The peak output voltage is 1.4 × E_{RMS} of half the transformer secondary; this is the maximum voltage that can be obtained from a capacitor-input filter.

As can be seen in Fig 7.7C, the PIV impressed on each diode is independent of the type of load at the output. This is because the peak inverse voltage condition occurs when diode D_A conducts and diode D_B is not conducting. The positive and negative voltage peaks occur at precisely the same time, a condition different from that in the half-wave circuit. As the cathodes of diodes D_A and D_B reach a positive peak (1.4 E_{RMS}), the anode of diode D_B is at a negative peak, also 1.4 E_{RMS}, but in the opposite direction. The total peak inverse voltage is therefore 2.8 E_{RMS}.

Fig 7.7C shows that the ripple frequency is twice that of the half-wave rectifier (two times the line frequency). Substantially less filtering is required because of the higher ripple frequency. Since the rectifiers work alternately, each handles half of the load current. The current rating of each rectifier need be only half the total current drawn from the supply.

The problem with dc bias in the transformer core associated with the half-wave connection is largely eliminated with this circuit and the RMS current in the primary winding will also be reduced.

7.4.3 Full-Wave Bridge Rectifier

Another commonly used rectifier circuit that does not require a center-tapped transformer is illustrated in **Fig 7.8**. In this arrangement, two rectifiers operate in series on each half of the cycle, one rectifier being in the lead supplying current to the load, the other being the current return lead. As shown in Figures 7.8A and B, when the top lead of the transformer secondary is positive with respect to the bottom lead, diodes D_A and D_C will conduct while diodes D_B and D_D are reverse-biased. On the next half cycle, when the top lead of the transformer is negative with respect to the bottom, diodes D_B and D_D will conduct while diodes D_A and D_C are reverse-biased.

The output voltage wave shape and ripple frequency are the same as for the full-wave center-tapped circuit. The average dc output voltage into a resistive load or choke-input filter is 0.9 times E_{RMS} delivered by the transformer secondary; with a capacitor filter and a light load, the maximum output voltage is 1.4 times the secondary E_{RMS} voltage.

Fig 7.8C shows the PIV to be 1.4 E_{RMS} for each diode which is half that of the full-wave center-tapped circuit for the same output voltage. When an alternate pair of diodes (such as D_A and D_C) is conducting, the other diodes are essentially connected in parallel

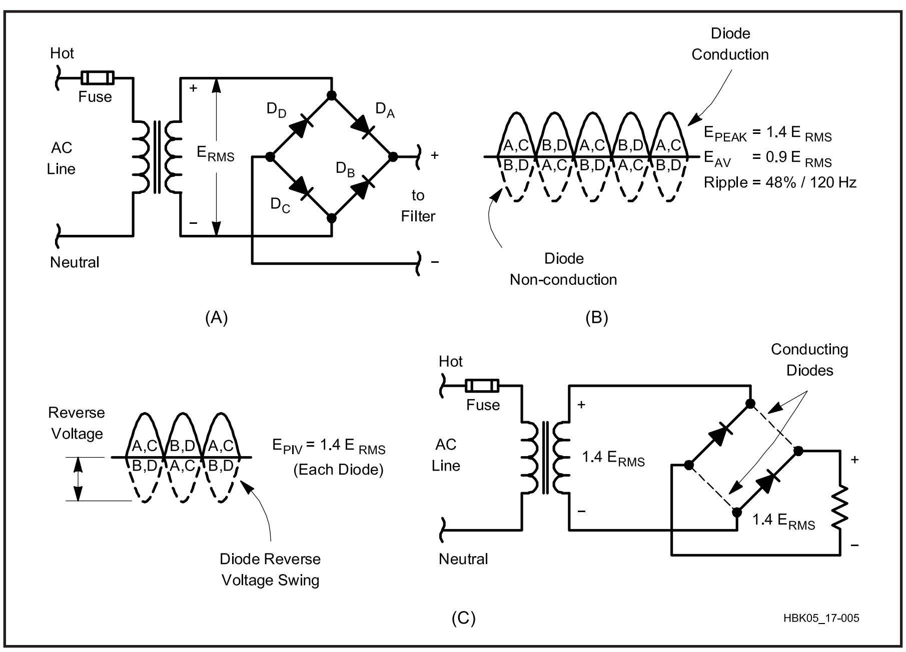


Fig 7.8 — Full-wave bridge rectifier circuits. The basic circuit is illustrated at A. Diode conduction and nonconduction times are shown at B. Diodes A and C conduct on one half of the input cycle, while diodes B and D conduct on the other. C displays the peak inverse voltage for one half cycle. Since this circuit reverse-biases two diodes essentially in parallel, 1.4 E_{RMS} is applied across each diode.

(the conducting diodes are essentially short circuits) in a reverse-biased direction. The reverse stress is then 1.4 E_{RMS}. Each pair of diodes conducts on alternate half cycles, with the full load current through each diode during its conducting half cycle. Since each diode is not conducting during the other half cycle the average diode current is one-half the total load current drawn from the supply.

Compared to the half-wave and full-wave center-tapped circuit, the full-wave bridge circuit further reduces the transformer RMS winding currents. In the case of a resistive load the winding currents are the same as when the resistive load is connected directly across the secondary. The RMS winding currents will still be higher when inductive and especially capacitive filters are used because of the pulsating nature of the diode and winding currents.

7.4.4 Comparison of Rectifier Circuits

Comparing the full-wave center-tapped and the full-wave bridge circuits, we can see that the center-tapped circuit has half the number of rectifiers as the bridge but these rectifiers have twice the PIV rating requirement of the bridge diodes. The diode current ratings are identical for the two circuits. The bridge makes better use of the transformer's secondary than the center-tapped rectifier, since the transformer's full winding supplies power during both half cycles, while each half of the center-tapped circuit's secondary provides power only during its positive half-cycle.

The full-wave center-tapped rectifier is typically used in high-current, low-voltage applications because only one diode conducts at a time. This reduces the loss associated with diode conduction. In the full-wave bridge circuit there are two diodes in series in conduction simultaneously, which leads to higher loss. The full-wave bridge circuit is typically used for higher output voltages where this is not a serious concern. The lower diode PIV and better utilization of the transformer windings makes this circuit very attractive for higher output voltages and higher powers typical of high voltage amplifier supplies.

Because of the disadvantages pointed out earlier, the half-wave circuit is rarely used in 60-Hz rectification except for bias supplies or other small loads. It does see considerable use, however, in high-frequency switchmode power supplies.

7.5 Voltage Multipliers

Other rectification circuits are sometimes useful, including *voltage multipliers*. These circuits function by the process of charging one or more capacitors in parallel on one half cycle of the ac waveform, and then connecting that capacitor or capacitors in series with the opposite polarity of the ac waveform on the alternate half cycle. In full-wave multipliers, this charging occurs during both half-cycles.

Voltage multipliers, particularly *voltage doublers*, find considerable use in high-voltage supplies. When a doubler is employed, the secondary winding of the power transformer need have only half the voltage that would be required for a bridge rectifier. This reduces voltage stress in the windings and decreases the transformer insulation requirements. This is not without cost, however, because the transformer-secondary *current* rating has to be correspondingly doubled for a given load current and charging of the capacitors leads to narrow high-RMS current waveforms in the transformer windings and the capacitors.

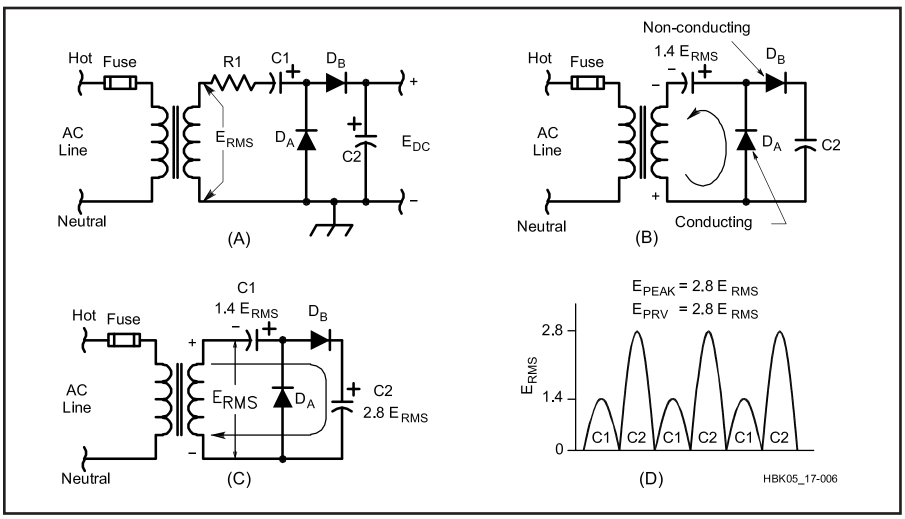


Fig 7.9 — Part A shows a half-wave voltage-doubler circuit. B displays how the first half cycle of input voltage charges C1. During the next half cycle (shown at C), capacitor C2 charges with the transformer secondary voltage plus that voltage stored in C1 from the previous half cycle. The arrows in parts B and C indicate the conventional current. D illustrates the levels to which each capacitor charges over several cycles.

7.5.1 Half-Wave Voltage Doubler

Fig 7.9 shows the circuit of a half-wave voltage doubler and illustrates the circuit operation. For clarity, assume the transformer voltage polarity at the moment the circuit is activated is that shown at Fig 7.9B. During the first negative half cycle, D_A conducts (D_B is in a nonconductive state), charging C1 to the peak rectified voltage (1.4 E_{RMS}). C1 is charged with the polarity shown in Fig 7.9B. During the positive half cycle of the secondary voltage, D_A is cut off and D_B conducts, charging capacitor C2. The amount of voltage delivered to C2 is the sum of the transformer peak secondary voltage plus the voltage stored in C1 (1.4 E_{RMS}). On the next negative half cycle, D_B is non-conducting and C2 will discharge into the load. If no load is connected across C2, the capacitors will remain charged — C1 to 1.4 E_{RMS} and C2 to 2.8 E_{RMS}. When a load is connected to the circuit output, the voltage across C2 drops during the negative half cycle and is recharged up to 2.8 E_{RMS} during the positive half cycle.

The output waveform across C2 resembles that of a half-wave rectifier circuit because C2 is pulsed once every cycle. Fig 7.9D illustrates the levels to which the two capacitors are charged throughout the cycle. In actual operation the capacitors will usually be large enough that they will discharge only partially, not all the way to zero as shown.

7.5.2 Full-Wave Voltage Doubler

Fig 7.10 shows the circuit of a full-wave voltage doubler and illustrates the circuit operation. During the positive half cycle of the transformer secondary voltage, as shown in Fig 7.10B, D_A conducts charging capacitor C1 to 1.4 E_{RMS}. D_B is not conducting at this time.

During the negative half cycle, as shown in Fig 7.10C, D_B conducts, charging capacitor C2 to 1.4 E_{RMS}, while D_A is non-conducting. The output voltage is the sum of the two capacitor voltages, which will be 2.8 E_{RMS} under no-load conditions. Fig 7.10D illustrates that each capacitor alternately receives a charge once per cycle. The effective filter capacitance is that of C1 and C2 in series, which is less than the capacitance of either C1 or C2 alone.

Resistors R1 and R2 in Fig 7.10A are used to limit the surge current through the rectifiers. Their values are based on the transformer voltage and the rectifier surge-current rating, since at the instant the power supply is turned on, the filter capacitors look like a short-circuited load. Provided the limiting resistors can withstand the surge current, their current-handling capacity is based on the maximum load current from the supply. Output voltages approaching twice the peak voltage of the transformer can be obtained with the voltage doubling circuit shown in Fig 7.10.

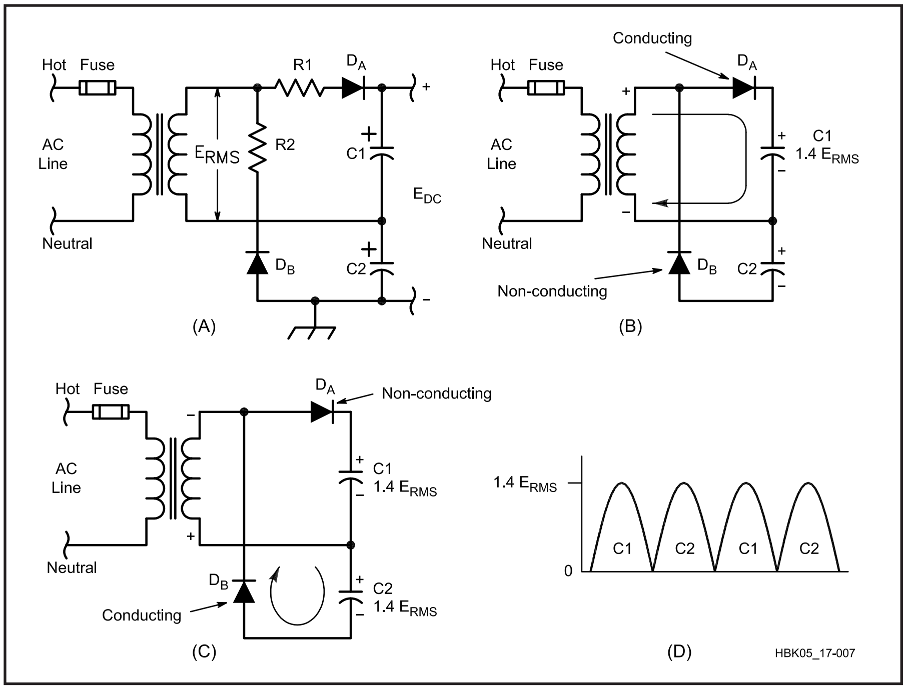


Fig 7.10 — Part A shows a full-wave voltage-doubler circuit. One-half cycle is shown at B and the next half cycle is shown at C. Each capacitor receives a charge during every input-voltage cycle. D illustrates how each capacitor is charged alternately.

Fig 7.11 shows how the voltage depends upon the ratio of the series resistance to the load resistance, and the load resistance times the filter capacitance. The peak inverse voltage across each diode is 2.8 E_{RMS}. As indicated by the curves in Fig 7.11, the output voltage regulation of this doubler connection is not very good and it is not attractive for providing high voltages at high power levels.

There are better doubler connections for higher power applications, and two possibilities are shown in **Fig 7.12**. The connection in Fig 7.12A uses two bridge rectifiers in series with capacitive coupling between the ac terminals of the bridges. At the expense of more diodes, this connection will have much better output voltage regulation at higher power levels. Even better regulation can be achieved by using the connection shown in Fig 7.12B**.** In this example, two windings on the transformer are used. It is not essential that both windings have the same voltage, but both must be capable of providing the desired output current. In addition, the insulation of the upper winding must be adequate to accommodate the additional dc bias applied to it from the lower winding.

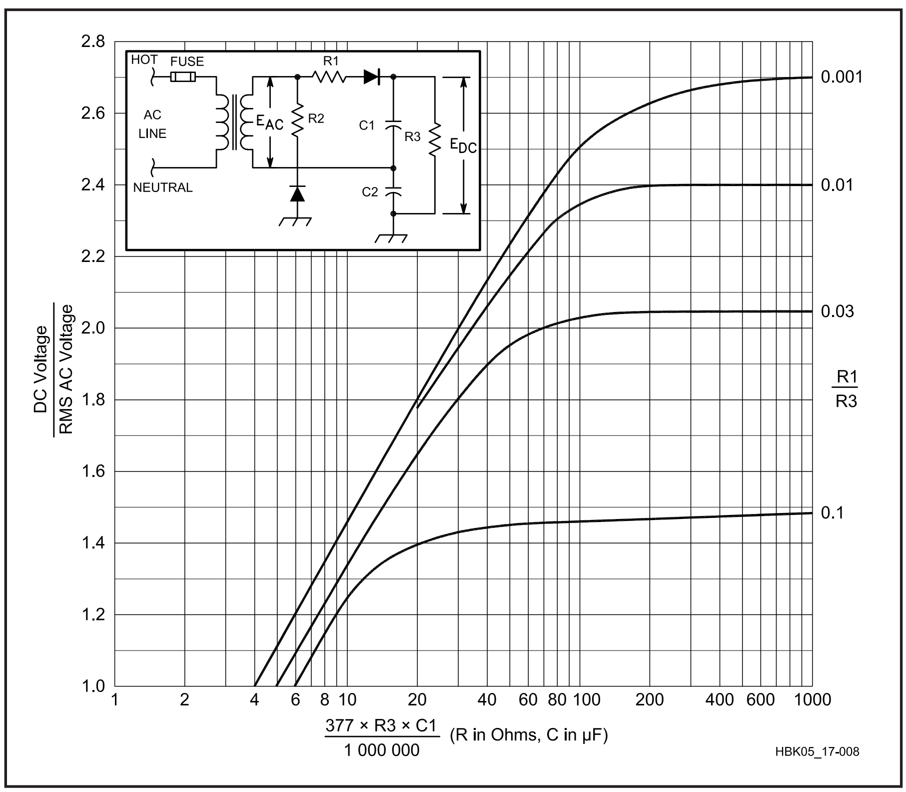
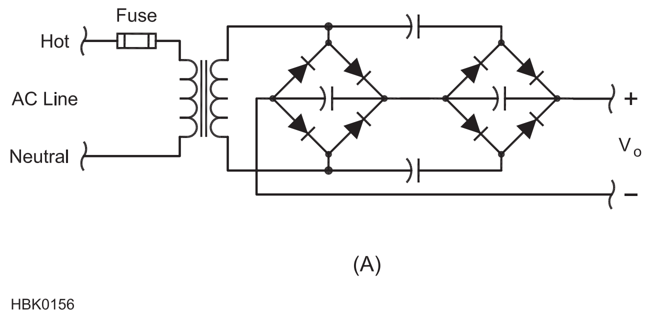


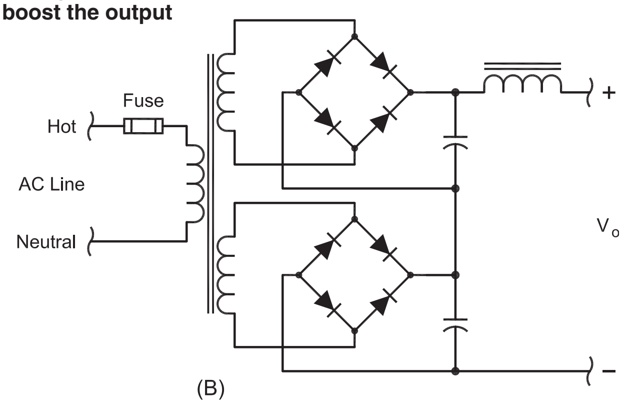
Fig 7.11 — DC output voltages from a full-wave voltage-doubler circuit as a function of the filter capacitances and load resistance. For the ratio R1 / R3 and for the R3 × C1 product, resistance is in ohms and capacitance is in microfarads. Equal resistance values for R1 and R2, and equal capacitance values for C1 and C2 are assumed. These curves are adapted from those published by Otto H. Schade in "Analysis of Rectifier Operation," ***Proceedings of the I. R. E.*****, July 1943.**

7.5.3 Voltage Tripler and Quadrupler

Fig 7.13A shows a voltage-tripling circuit. On one half of the ac cycle, C1 and C3 are charged to the source voltage through D1, D2 and D3. On the opposite half of the cycle, D2 conducts and C2 is charged to twice the source voltage, because it sees the transformer plus the charge in C1 as its source (D1 is cut off during this half cycle). At the same time, D3 conducts, and with the transformer and the

Fig 7.12 — Voltage-doubler rectifier connections for higher power levels. A is a capacitor-coupled doubler that can be extended to more sections for a higher multiplying factor. The circuit in B uses multiple transformer windings to boost the output voltage.





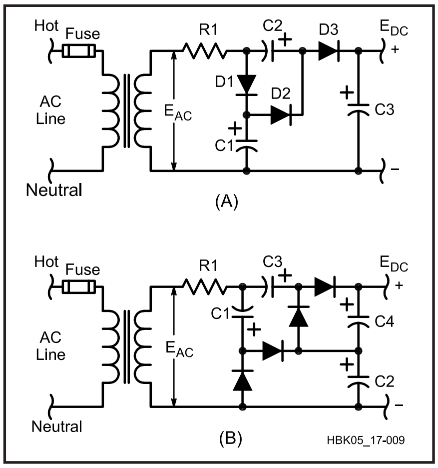


Fig 7.13 — Voltage-multiplying circuits with one side of the transformer secondary used as a common connection. A shows a voltage tripler and B shows a voltage quadrupler. Capacitances are typically 20 to 50 µF, depending on the output current demand. Capacitor dc ratings are related to E_{PEAK} (1.4 E_{RMS}):
C1 — Greater than E_{PEAK}
C2 — Greater than 2 E_{PEAK}
C3 — Greater than 3 E_{PEAK}
C4 — Greater than 2 E_{PEAK}

charge in C2 as the source, C3 is charged to three times the transformer voltage.

The voltage-quadrupling circuit of Fig 7.13B works in similar fashion. In either of the circuits of Fig 7.13, the output voltage will approach an exact multiple of the peak ac voltage when the output current drain is low and the capacitance values are large.

7.6 Current Multipliers

Just as there are voltage multiplier connections for high-voltage, low-current loads, there are current multiplier connections for low-voltage, high-current loads. An example of a current-doubler is given in **Fig 7.14A.**

To make the circuit operation easier to visualize, we can represent L1 and L2 as current sources (Fig 7.14B) which is a good approximation for steady-state operation. When terminal 1 of the secondary winding is positive with respect to terminal 2**,** diode D_A will be reverse-biased and therefore non-conducting. The current flows within the circuit are shown in Fig 7.14B. Note that all of the output current (I_o) flows through D_B but only half of I_o flows through the winding. At the cathode of D_B the current divides with half going to L2 and the other half to the transformer secondary. The output voltage will be one-half the voltage of the average winding voltage (0.45 E_{RMS}). This rectifier connection divides the voltage and multiplies the current! Because of the need for two inductors, this circuit is seldom used in line-frequency applications but it is very useful in high-frequency switchmode regulators with very low output voltages (<10 V) because it makes the secondary winding design easier and can improve circuit efficiency. At high frequencies, the inductors can be quite small.

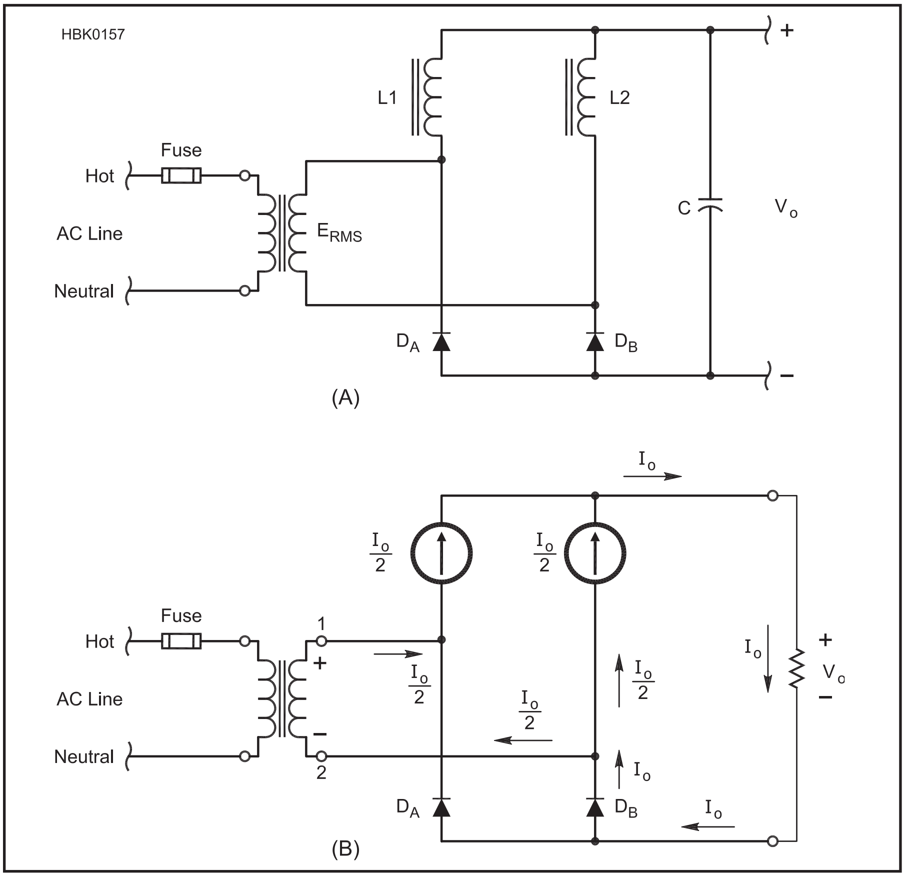


Fig 7.14 — A current doubler rectifier connection. A is the basic circuit. B illustrates current flow within the circuit.

7.7 Rectifier Types

Rectifiers have a long history beginning with mechanical rectifiers in the 1800s to today's abundant variety of semiconductor devices. While many different devices have been created for this purpose, they all have the characteristic that they block current flow in the reverse direction, withstanding substantial reverse voltage and allowing current flow in the forward direction with minimum voltage drop. The simplest rectifiers are diodes, but it is also possible to have three-terminal devices (such as a thyristor) that can be controlled to regulate the output dc in addition to providing rectification. It is also possible to use devices like MOSFETs as synchronous rectifiers with very low forward drop during conduction. This is typically done to improve efficiency for very low voltage outputs. The following is a brief description of several of the more common examples. The sections on vacuum tube and other obsolete types of rectifiers from previous editions are available as a PDF article on the CD-ROM accompanying this book.

7.7.1 Semiconductor Diodes

Rectifier diodes can be made from a number of different semiconductor materials such as germanium, silicon, silicon-carbide or gallium-arsenide, and no doubt other materials will appear in the future. The choice will depend on the application and as always cost is a factor.

Germanium diodes were the first of the solid-state semiconductor rectifiers. They have an extremely low forward voltage drop but are relatively temperature sensitive, having high reverse leakage currents at higher temperatures. They can be easily destroyed by overheating during soldering as well. Germanium diodes are no longer used as power rectifiers.

Today, silicon diodes are the primary choice for virtually all power rectifier applications. They are characterized by extremely high reverse resistance (low reverse leakage), forward drops of a volt or less and operation at junction temperatures up to 125 °C. Some multi-junction HV diodes will have forward drops of several volts, but that is still low compared to the voltage at which they are being used.

Many different types of silicon diodes are available for different applications. Silicon rectifiers fall into to two general categories: PN-junction diodes and Schottky barrier diodes (see the **Analog Basics** chapter). Schottky diodes are the usual choice for low output voltages (<20 V) where their low forward conduction drop is critical for efficiency. For higher voltages however, the high reverse leakage of Schottky diodes is not acceptable and PN-junction diodes are normally chosen.

For 50/60 Hz applications, diodes with reverse recovery times of a microsecond or even more are suitable and very economical. For switchmode converters and inverters that regularly operate at 25 kHz and higher frequencies, fast-recovery diodes are needed. These converters typically have waveform transitions of less than 1 µs within the circuit.

MOSFET power transistors often have transitions of less than 100 ns.

During the switching transitions, previously conducting diodes see a reversal of current direction. This change tends to reverse-bias those diodes, and thereby put them into an open-circuit condition. Unfortunately, as explained in the **Analog Basics** chapter, solid-state rectifiers cannot be made to cease conduction instantaneously. As a result, when the opposing diodes in a bridge rectifier or full-wave rectifier become conductive at the time the converter switches states, the diodes being turned off will actually conduct in the reverse direction for a brief time. That effectively short circuits the converter for a period of time depending on the reverse recovery characteristics of the rectifiers. This characteristic can create high current transients that stress the switching transistors and lead to increased loss and electromagnetic interference. As the switching frequency increases, more of these transitions happen each second, and more power is lost because of diode cross-conduction.

These current transients and associated losses are reduced by using *fast recovery* diodes, which are specially doped diodes designed to minimize storage time. Diodes with recovery times of 50 ns or less are available.

7.7.2 Rectifier Strings or Stacks

DIODES IN SERIES

When the PIV rating of a single diode is not sufficient for the application, similar diodes may be used in series. (Two 500 PIV diodes in series will withstand 1000 PIV and so on.) There used to be a general recommendation to place a resistor across each diode in the string to equalize the PIV drops. With modern diodes, this practice is no longer necessary.

Modern silicon rectifier diodes are constructed to have an avalanche characteristic. Simply put, this means that the diffusion process is controlled so the diode will exhibit a Zener characteristic in the reverse-biased direction before destructive breakdown of the junction can occur. This provides a measure of safety for diodes in series. A diode will go into Zener conduction before it self-destructs. If other diodes in the chain have not reached their avalanche voltages, the current through the avalanched diode will be limited to the leakage current in the other diodes. This should normally be very low. For this reason, shunting resistors are generally not needed across diodes in series rectifier strings. In fact, shunt resistors can actually create problems because they can produce a low-impedance source of damaging current to any diode that may have reached avalanche potential.

DIODES IN PARALLEL

Diodes can be placed in parallel to increase current-handling capability. Equalizing resistors should be added as shown in **Fig 7.15**. Without the resistors, one diode may take most of the current. The resistors should be selected to have a drop of several tenths of a volt at the expected peak current. A disadvantage of this form of forced current sharing will be the increase in power loss because of the added resistors.

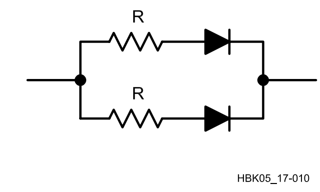


Fig 7.15 — Diodes can be connected in parallel to increase the current-handling capability of the circuit. Each diode should have a series current-equalizing resistor, with a value selected to have a drop of several tenths of a volt at the expected current.

7.7.3 Rectifier Ratings versus Operating Stress

Power supplies designed for amateur equipment use silicon rectifiers almost exclusively. These rectifiers are available in a wide range of voltage and current ratings: PIV ratings of 600 V or more and current ratings as high as 400 A are available. At 1000 PIV, the current ratings may be several amperes. It is possible to stack several units in series for higher voltages. Stacks are available commercially that will handle peak inverse voltages up to 10 kV at a load current of 1 A or more.

7.7.4 Rectifier Protection

The discussion of rectifier circuits included the peak reverse voltage seen by the rectifiers in each circuit. You will need this information to select the voltage rating of the diodes in given application. It is normal good practice to not expose the diodes to more than 75% of their rated voltage for the worst case reverse voltage. This will probably be when operating at the highest input voltage but should also take into account transients that may occur.

The important specifications of a silicon diode are:

1. PIV — the peak inverse voltage.
2. I_0 — the average dc current rating.
3. I_{REP} — the peak repetitive forward current.
4. I_{SURGE} — a non-repetitive peak half-sine wave of 8.3 ms duration (one-half cycle of 60-Hz line frequency).
5. Switching speed or reverse recovery time.
6. Power dissipation and thermal resistance.

The first two specifications appear in most catalogs. I_{REP} and I_{SURGE} are not often specified in catalogs, but they are very important. Except in some switching regulator and capacitive filter circuits, rectifier current typically flows half the time — when it does conduct, the rectifier has to pass at least twice the average direct current. With a capacitor-input filter, the rectifier conducts much less than half the time. In this case, when it does conduct, it may pass as much as 10 to 20 times the average dc current, under certain conditions.

CURRENT INRUSH

When the supply is first turned on, the filter capacitors are discharged and act like a dead short. The result can be a very heavy current surge through the diode for at least one half-cycle and sometimes more. This current transient is called I_{SURGE}. The maximum surge current rating for a diode is usually specified for a duration of one-half cycle (at 60 Hz), or about 8.3 ms. Some form of surge protection is usually necessary to protect the diodes until the filter capacitors are nearly charged, unless the diodes used have a very high surge-current rating (several hundred amperes). If a manufacturer's data sheet is not available, an educated guess about a diode's capability can be made by using these rules of thumb for silicon diodes commonly used in Amateur Radio power supplies:

Rule 1. The maximum I_{REP} rating can be assumed to be approximately four times the maximum I_0 rating, where I_0 is the average dc current rating.

Rule 2. The maximum I_{SURGE} rating can be assumed to be approximately 12 times the maximum I_0 rating. This figure should provide a reasonable safety factor. Silicon rectifiers with 750 mA dc ratings, for example, seldom have 1-cycle surge ratings of less than 15 A; some are rated up to 35 A or more. From this you can see that the rectifier should be selected on the basis of I_{SURGE} and not on I_0 ratings.

Although you can sometimes rely on the resistance of the transformer windings to provide surge-current limiting, this is seldom adequate in high-voltage power supplies. Series resistors are often installed between the secondary and the rectifier strings or in the transformer's primary circuit, but these can be a deterrent to good voltage regulation.

One way to have good surge current limiting at turn-on without affecting voltage regulation during normal operation is to have a resistor in series with the input, along with a relay across the resistor that shorts it out after 50 ms or so. This kind of arrangement is particularly important in HV supplies.

VOLTAGE TRANSIENTS

Vacuum-tube rectifiers had little problem with voltage transients on the incoming power lines. The possibility of an internal arc was of little consequence, since the heat produced was of very short duration and had little effect on the massive plate and cathode structures.

Unfortunately, such is not the case with silicon diodes. Because of their low forward voltage drop, silicon diodes create very little heat with high forward current and therefore have tiny junction areas. However, conduction in the reverse direction beyond the normal reverse recovery time (reverse avalanching) can cause junction temperatures to rise extremely rapidly with the resulting destruction of the semiconductor junction.

To protect semiconductor rectifiers from voltage transients, special surge-absorption devices are available for connection across the incoming ac bus or transformer secondary. These devices operate in a fashion similar to a Zener diode; they conduct heavily when a specific voltage level is reached. Unlike Zener diodes, however, they have the ability to absorb very high transient energy levels without damage. With the clamping level set well above the normal operating voltage range for the rectifiers, these devices normally appear as open circuits and have no effect on the power-supply circuits. When a voltage transient occurs, however, these protection devices clamp the transient and thereby prevent destruction of the rectifiers.

Transient protectors are available in three basic varieties:

1. *Silicon Zener diodes* — large junction Zeners specifically made for this purpose and available as single junction for dc (unipolar) and back-to-back junctions for ac (bipolar). These silicon protectors are available under the trade name of TransZorb from General Semiconductor Corporation and are also made by other manufacturers. They have the best transient-suppressing characteristics of the three varieties mentioned here, but are expensive and have the least energy absorbing capability per dollar of the group.

2. *Varistors* — made of a composition metal-oxide material that breaks down at a certain voltage. Metal-oxide varistors, also known as MOVs, are cheap and easily obtained, but have a higher internal resistance, which allows a greater increase in clamped voltage than the Zener variety. Varistors can also degrade with successive transients within their rated power handling limits (this is not usually a problem in the ham shack where transients are few and replacement of the varistor is easily accomplished).

Varistors usually become short-circuited when they fail. Large energy dissipation can result in device explosion. Therefore, it is a good idea to include a fuse that limits the short-circuit current through the varistor, and to protect people and circuitry from debris.

3. *Gas tube* — similar in construction to the familiar neon bulb, but designed to limit conducting voltage rise under high transient currents. Gas tubes can usually withstand the highest transient energy levels of the group. Gas tubes suffer from an ionization time problem, however. A high voltage across the tube will not immediately cause conduction. The time required for the gas to ionize and clamp the transient is inversely proportional to the level of applied voltage in excess of the device ionization voltage. As a result, the gas tube will let a little of the transient through to the equipment before it activates.

In installations where reliable equipment operation is critical, the local power is poor and transients are a major problem, the usual practice is to use a combination of protectors. Such systems consist of a varistor or Zener protector, combined with a gas-tube device. Often there is an indicator light to warn when a surge has blown out the varistor. Operationally, the solid-state device clamps the surge immediately, with the beefy gas tube firing shortly thereafter to take most of the surge from the solid-state device.

HEAT

The junction of a diode is quite small, so it must operate at a high current density. The heat-handling capability is, therefore, quite small. Normally, this is not a prime consideration in high-voltage, low-current supplies. Use of high-current rectifiers at or near their maximum ratings (usually 2 A or larger, stud-mount rectifiers) requires some form of heat sinking. Frequently, mounting the rectifier on the main chassis — directly or with thin thermal insulating washers — will suffice.

When a rectifier is directly mounted on the heatsink it is good practice to use a thin layer of thermal grease between the diode and the heat sink to assure good heat conduction. Most modern insulating thermal washers do not require the use of grease, but the older mica and other washers may benefit from a *very thin layer* of grease. Thermal grease and heat conducting insulating washers and pads are standard products available from mail-order component sellers.

Large, high-current rectifiers often require special heat sinks to maintain a safe operating temperature. Forced-air cooling from a fan is sometimes used as a further aid. Safe case temperatures are usually given in the manufacturer's data sheets and should be observed if the maximum capabilities of the diode are to be realized. See the thermal design section in the chapter on **Electrical Fundamentals** for more information.

7.8 Power Filtering

Most loads will not tolerate the ripple (an ac component) of the pulsating dc from the rectifiers. Filters are required between the rectifier and the load to reduce the ripple to a low level. As pointed out earlier, some capacitances or inductances may be inherent in the rectifier connection, reducing the ripple amplitude. In most cases, however, additional filtering is required. The design of the filter depends to a large extent on the dc voltage output, the desired voltage regulation of the power supply and the maximum load current. Power-supply filters are low-pass devices using series inductors and/or shunt capacitors.

7.8.1 Load Resistance

In discussing the performance of power-supply filters, it is sometimes convenient to characterize the load connected to the output as a resistance. This *load resistance* is equal to the output voltage divided by the total load current, including the current drawn by the bleeder resistor.

7.8.2 Voltage Regulation

In an unregulated supply, the output voltage usually decreases as more current is drawn. This happens not only because of increased voltage drops in the transformer and filter chokes, but also because the output voltage at light loads tends to soar to the peak value of the transformer voltage as a result of charging the first capacitor. Proper filter design can reduce this effect. The change in output voltage with load is called the *voltage regulation* and is expressed as a percentage.

$$\text{Percent Regulation} = \frac{(E1 - E2)}{E2} \times 100\% \tag{2}$$

where

E1 = the no-load voltage
E2 = the full-load voltage.

A steady load, such as that represented

by a receiver, speech amplifier or unkeyed stages of a transmitter, does not require good (low) regulation as long as the proper voltage is obtained under load conditions. The filter capacitors must have a voltage rating safe for the highest value to which the voltage will rise when the external load is removed.

Typically the output voltage will display a larger change with long-duration changes in load resistance than with short transient changes. The reason for this is that transient load currents are supplied from energy stored in the output capacitance. The regulation with long-term changes is often called the *static regulation*, to distinguish it from the *dynamic regulation* (transient load changes). A load that varies at a syllabic or keyed rate, as represented by some audio and RF amplifiers, usually requires good dynamic regulation (<15%) if distortion products are to be held to a low level. The dynamic regulation of a power supply can be improved by increasing the output capacitance.

When essentially constant voltage is required, regardless of current variation (for stabilizing an oscillator, for example), special voltage regulating circuits described later in this chapter are used.

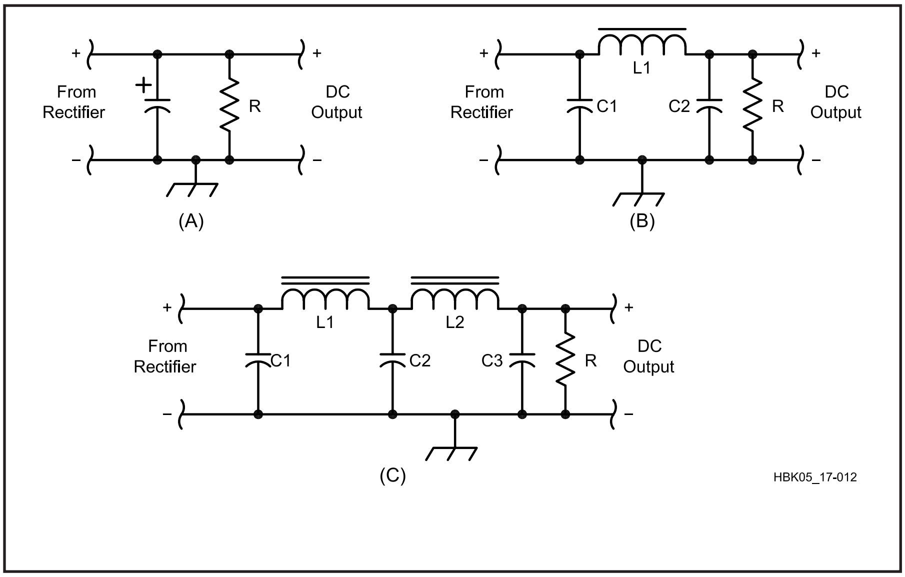


Fig 7.16 — Capacitor-input filter circuits. At A is a simple capacitor filter. B and C are single- and double-section filters, respectively.

7.8.3 Bleeder Resistors

A *bleeder resistor* is a resistance (R) connected across the output terminals of the power supply as shown in **Fig 7.16A**. Its functions are to discharge the filter capacitors as a safety measure when the power is turned off and to improve voltage regulation by providing a minimum load resistance. When voltage regulation is not of importance, the resistance may be as high as 100 Ω per volt of output voltage. The resistance value to be used for voltage-regulating purposes is discussed in later sections. From the consideration of safety, the power rating of bleeder resistors should be as conservative as possible — having a burned-out bleeder resistor is dangerous!

7.8.4 Ripple Frequency and Voltage

The ripple at the output of the rectifier is an alternating current superimposed on a steady direct current. From this viewpoint, the filter may be considered to consist of: 1) shunt capacitors that short circuit the ac component while not interfering with the flow of the dc component; and/or 2) series chokes that readily pass dc but will impede the ac component.

The effectiveness of the filter can be expressed in terms of percent ripple, which is the ratio of the RMS value of the ripple to the dc value in terms of percentage.

$$\text{Percent Ripple (RMS)} = \frac{E1}{E2} \times 100\% \quad (3)$$

where

E1 = the RMS value of ripple voltage

E2 = the steady dc voltage.

Any frequency multiplier or amplifier supply in a CW transmitter should have less than 5% ripple. A linear amplifier can tolerate about 3% ripple on the plate voltage. Bias supplies for linear amplifiers should have less than 1% ripple. VFOs, speech amplifiers and receivers may require no greater than 0.01% ripple.

Ripple frequency refers to the frequency of the pulsations in the rectifier output waveform — the number of pulsations per second. The ripple frequency of half-wave rectifiers is the same as the line-supply frequency — 60 Hz with a 60-Hz supply. Since the output pulses are doubled with a full-wave rectifier, the ripple frequency is doubled — to 120 Hz with a 60-Hz supply.

The amount of filtering (values of inductance and capacitance) required to give adequate smoothing depends on the ripple frequency. More filtering is required as the ripple frequency is reduced. This is why the filters used for line-frequency rectification are much larger than those used in switchmode converters where the ripple frequency is often in the hundreds of kHz.

7.8.5 Capacitor-Input Filters

Typical capacitor-input filter systems are shown in Fig 7.16. The ripple can be reduced by making C1 larger, but that can lead to very large capacitances and high inrush currents at turn-on. Better ripple reduction will be obtained when moderate values for C1 are employed and LC sections are added as shown in Fig 7.16B and C.

INPUT VERSUS OUTPUT VOLTAGE

The average output voltage of a capacitor-input filter is generally poorly regulated with load-current variations. As shown earlier (Fig 7.6) the rectifier diodes conduct for only a small portion of the ac cycle to charge the filter capacitor to the peak value of the ac waveform. When the instantaneous voltage of the ac passes its peak, the diode ceases to conduct. This forces the capacitor to support the load current until the ac voltage on the opposing diode in the bridge or full wave rectifier is high enough to pick up the load and recharge the capacitor. For this reason, the peak diode currents are usually quite high.

Since the cyclic peak voltage of the capacitor-filter output is determined by the peak of the input ac waveform, the minimum voltage and, therefore, the ripple amplitude, is determined by the amount of voltage discharge, or "droop," occurring in the capacitor while it is discharging and supporting the load. Obviously, the higher the load current, the proportionately greater the discharge, and therefore the lower the average output.

There is an easy way to approximate the peak-to-peak ripple for a certain capacitor and load by assuming a constant load current. We can calculate the droop in the capacitor by using the relationship:

$$C \times E = I \times t \quad (4)$$

where

C = the capacitance in microfarads

E = the voltage droop, or peak-to-peak ripple voltage
I = the load current in milliamperes
t = the length of time in ms per cycle during which the rectifiers are not conducting, during which the filter capacitor must support the load current. For 60-Hz, full-wave rectifiers, t is about 7.5 ms.

As an example, let's assume that we need to determine the peak-to-peak ripple voltage at the dc output of a full-wave rectifier/ filter combination that produces 13.8 V dc and supplies a transceiver drawing 2.0 A. The filter capacitor in the power supply is 5000 µF. Using the above relationship:

$$C \times E = I \times t \quad (5)$$

$$5000\ \mu F \times E = 2000\ mA \times 7.5\ ms$$

$$E = \frac{2000\ mA \times 7.5\ ms}{5000\ \mu F} = 3\ V\ P\text{-}P$$

Obviously, this is too much ripple. A capacitor value of about 20,000 µF would be better suited for this application. If a linear regulator is used after this rectifier/filter combination, then it is possible to trade off higher ripple voltage against high power dissipation in the regulator. A properly designed linear regulator can reduce the ripple amplitude to a very small value.

7.8.6 Choke-Input Filters

Choke-input filters provide the benefits of greatly improved output voltage stability over varying loads and low peak-current surges in the rectifiers. On the negative side, the output voltage will be lower than that for a capacitor-input filter.

In line-frequency power supplies, choke-input filters are less popular than they once were. This change came about in part because of the high surge current capability of silicon rectifiers, but more importantly because size, weight and cost are reduced when large filter chokes are eliminated. However, choke input filters are frequently used in high-frequency switchmode converters where the chokes will be much smaller.

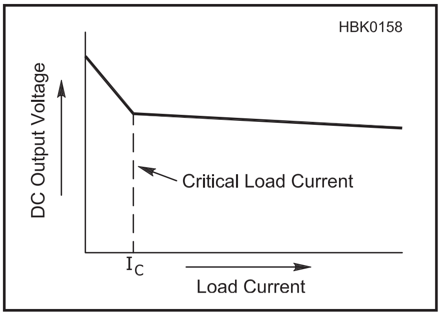


Fig 7.17 — Inductive filter output voltage regulation as a function of load current. The transition from capacitive peak charging to inductive averaging occurs at the critical load current, I_C.

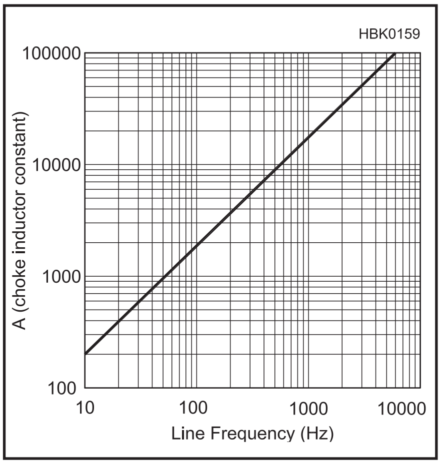


Fig 7.18 — The choke inductor constant, A, is used to solve equation 6.

As long as the inductance of the choke is large enough to maintain a continuous current over the complete cycle of the input ac waveform, the filter output voltage will be the average value of the rectified output. The average dc value of a full-wave rectified sine wave is 0.637 times its peak voltage. Since the RMS value is 0.707 times the peak, the output of the choke input filter will be (0.637 / 0.707), or 0.9 times the RMS ac voltage.

As shown in **Fig 7.17**, there is a minimum or "critical" load current below which the choke does not provide the necessary filtering. For light loads, there may not be enough energy stored in the choke during the input waveform crest to allow continuous current over the full cycle. When this happens, the filter output voltage will rise as the filter assumes more and more of the characteristics of a capacitor-input filter. One purpose of the bleeder resistor is to keep the minimum load current above the critical value.

The value for the critical (or minimum) inductance for a given maximum value of load resistance in a single phase, full-wave rectifier with a sine wave source voltage can be approximated from:

$$L_c = R/A \quad (6)$$

where
R = the maximum load resistance
A = a constant obtained from Fig 7.18, derived from the frequency of the input current (see Reference 1).

Low values for minimum load current (high minimum load R) can lead to large values for L_C which may not be practical. Standard filter inductors typically have a relatively constant value for L as the dc current is varied but it is possible to use a swinging choke instead. This is an inductor which has a high inductance at low currents and much lower inductance at high currents. Using a swinging choke will usually result in a much smaller filter choke and/or better output regulation.

7.9 Power Supply Regulation

The output of a rectifier/filter system may be usable for some electronic equipment, but for today's transceivers and accessories, further measures may be necessary to provide power sufficiently clean and stable for their needs. Voltage regulators are often used to provide this additional level of conditioning.

Rectifier/filter circuits by themselves are unable to protect the equipment from the problems associated with input-power-line fluctuations, load-current variations and residual ripple voltages. Regulators can eliminate these problems, but not without costs in circuit complexity and power-conversion efficiency.

7.9.1 Zener Diodes

A Zener diode (developed by Dr Clarence Zener) can be used to maintain the voltage applied to a circuit at a practically constant value, regardless of the voltage regulation of the power supply or variations in load current. The typical circuit is shown in **Fig 7.19**. Note that the cathode side of the diode is connected to the positive side of the supply.

Zener diodes are available in a wide variety of voltages and power ratings. The voltages range from less than 2 V to a few hundred volts, while the power ratings (power the diode can dissipate) run from less than 0.25 W to 50 W. The ability of the Zener diode to stabilize a voltage depends on the diode's conducting impedance. This can be as low as 1 Ω or less in a low-voltage, high-power diode or as high as 1000 Ω in a high-voltage, low-power diode.

The circuit in Fig 7.19 is a *shunt* regulator in that it "shunts" current through a controlling device (the Zener diode) to maintain a constant output voltage. To design a Zener shunt regulator, you must know the minimum and maximum input voltage (E_{DC}); the

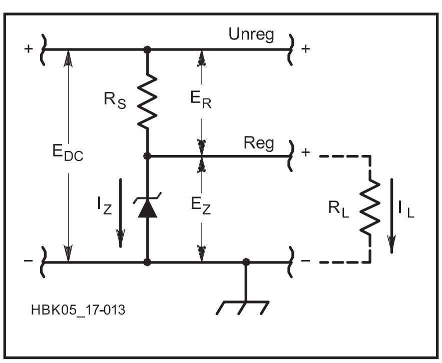


Fig 7.19 — Zener-diode voltage regulation. The voltage from a negative supply may be regulated by reversing the power-supply connections and the diode polarity.

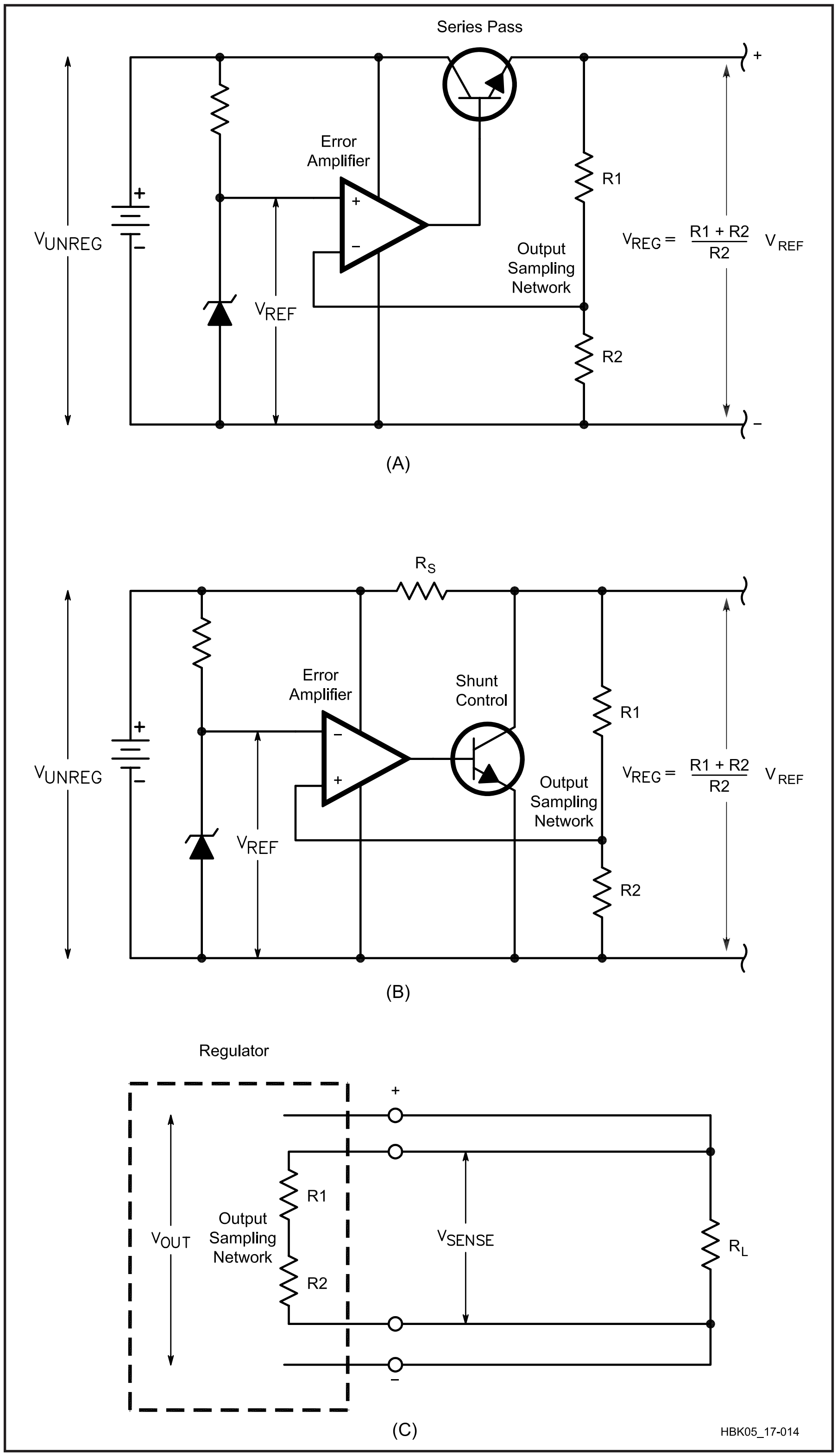


Fig 7.20 — Linear electronic voltage regulator circuits. In these diagrams, batteries represent the unregulated input-voltage source. A transformer, rectifier and filter would serve this function in most applications. Part A shows a series regulator and Part B shows a shunt regulator. Part C shows how remote sensing overcomes poor load regulation caused by the IR drop in the connecting wires by bringing them inside the feedback loop. The use of extra connections to sense voltage is called a "four wire Kelvin connection."

output voltage, which is equal to the Zener diode voltage (E_Z); and the minimum and maximum load current (I_L) through R_L. If the input voltage is variable, you must specify the maximum and minimum values for E_{DC}. As a rule of thumb, the current through the Zener should be 10% of the maximum load current for good regulation and must be greater than the $I_{Z(min)}$ at which the Zener diode maintains its constant voltage drop. Once these quantities are known the series resistance, R_S, can be determined:

$$R_S = \frac{E_{DC(min)} - E_Z}{1.1\, I_{L(max)}} \qquad (7)$$

The power dissipation of the Zener diode, P_D, is

$$P_{DZ} = \left[\frac{E_{DC(max)} - E_Z}{R_S} - I_{L(min)} \right] E_Z \qquad (8)$$

and of the series resistor, R_S,

$$P_{DR} = \frac{\left(E_{DC(max)} - E_Z\right)^2}{R_S} \qquad (9)$$

It is good practice to provide a five times rated power dissipation safety margin for both the series resistor and the Zener diode. This avoids heating in the Zener and the resulting drift in voltage. High-power Zener diodes (10 W dissipation or more) will require heat-sinking as discussed in the section on Managing Heat in the **Electrical Fundamentals** chapter.

7.9.2 Linear Regulators

Linear regulators come in two varieties, *series* and *shunt*, as shown in **Fig 7.20**. The shunt regulator is simply an electronic (also called "active") version of the Zener diode. For the most part, the active shunt regulator (Fig 7.20B) is rarely used since the series regulator is a superior choice for most applications.

The series regulator (Fig 7.20A) consists of a stable voltage reference, which is usually established by a Zener diode, a transistor in series between the power source and the load (called a *series pass transistor*), and an error amplifier. In critical applications a temperature-compensated reference diode would be used instead of the Zener diode.

The output voltage is sampled by the error amplifier, which compares the output (usually scaled down by a voltage divider) to the reference. If the scaled-down output voltage becomes higher than the reference voltage, the error amplifier reduces the drive current to the pass transistor, thereby allowing the output voltage to drop slightly. Conversely, if the load pulls the output voltage below the desired value, the amplifier drives the pass transistor into increased conduction.

The "stiffness" or tightness of regulation of a linear regulator depends on the gain of the error amplifier and the ratio of the output scaling resistors. In any regulator, the output is cleanest and regulation stiffest at the point where the sampling network or error amplifier is connected. If heavy load current is drawn through long leads, the voltage drop can degrade the regulation at the load. To combat this effect, the feedback connection to the error amplifier can be made directly to the load. This technique, called *remote sensing*, or a *four wire Kelvin connection*, moves the point of best regulation to the load by bringing the connecting loads inside the feedback loop. This is shown in Fig 7.20C.

INPUT VERSUS OUTPUT VOLTAGE

In a series regulator, the pass-transistor power dissipation is directly proportional to the load current and input/output voltage differential. The series pass element can be located in either leg of the supply. Either NPN or PNP devices can be used, depending on the ground polarity of the unregulated input.

The differential between the input and output voltages is a design tradeoff. If the input voltage from the rectifiers and filter is only slightly higher than the required output voltage, there will be minimal voltage drop across the series pass transistor. A small drop results in minimal thermal dissipation and high power-supply efficiency. The supply will have less capability to provide regulated power in the event of power line brownout and other reduced line voltage conditions, however. Conversely, a higher input voltage will provide operation over a wider range of input voltage, but at the expense of increased heat dissipation.

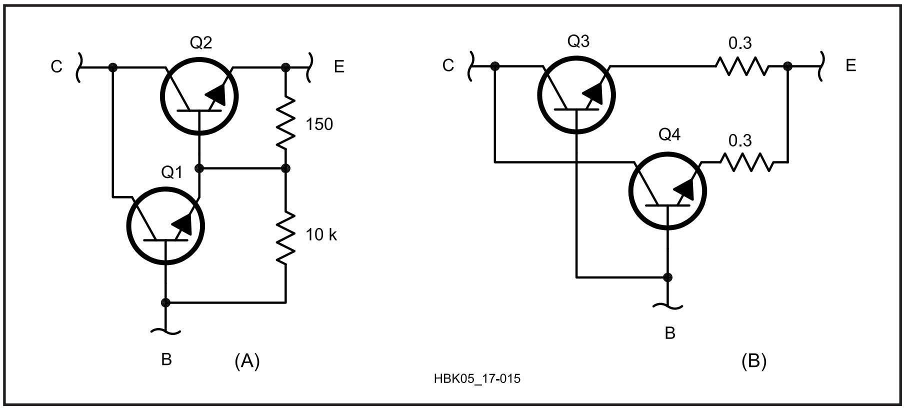


Fig 7.21 — At A, a Darlington-connected transistor pair for use as the pass element in a series-regulating circuit. At B, the method of connecting two or more transistors in parallel for high-current output. Resistances are in ohms. The circuit at A may be used for load currents from 100 mA to 5 A, and the one at B may be used for currents from 6 A to 10 A.

Q1 — NPN transistor, MJE340 or equivalent

Q2-Q4 — Power transistor such as 2N3055 or 2N3772

7.9.3 Linear Regulator Pass Transistors

DARLINGTON PAIRS

A simple Zener-diode reference or IC op-amp error amplifier may not be able to source enough current to a pass transistor that must conduct heavy load current. The Darlington configuration of **Fig 7.21A** multiplies the pass-transistor beta, thereby extending the control range of the error amplifier. If the Darlington arrangement is implemented with discrete transistors, resistors across the base-emitter junctions may be necessary to prevent collector-to-base leakage currents in Q1 from being amplified and turning on the transistor pair. These resistors are contained in the envelope of a monolithic Darlington device.

When a single pass transistor is not available to handle the current required from a regulator, the current-handling capability may be increased by connecting two or more pass transistors in parallel. The circuit of Fig 7.21B shows the method of connecting these pass transistors. The resistances in the emitter leads of each transistor are necessary to equalize the currents.

TRANSISTOR RATINGS

When bipolar (NPN, PNP) power transistors are used in applications in which they are called upon to handle power on a continuous basis, rather than switching, there are four parameters that must be examined to see if any maximum limits are being exceeded. Operation of the transistor outside these limits can easily result in device failure, and these parameters must be considered during the design process.

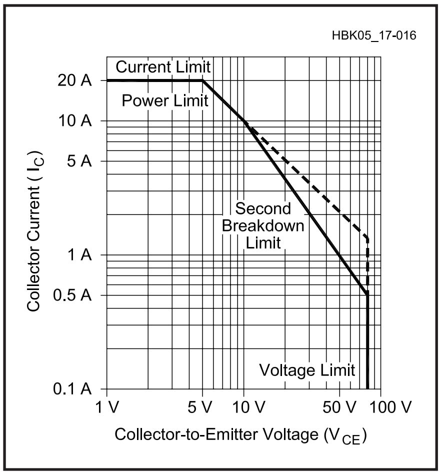


Fig 7.22 — Typical graph of the safe operating area (SOAR) of a transistor. See text for details. Safe operating conditions for specific devices may be quite different from those shown here.

The four limits are maximum collector current (I_C), maximum collector-emitter voltage (V_{CEO}), maximum power and *second breakdown* (I_{SB}). All four of these parameters are graphically shown on the transistor's data sheet on what is known as a *safe operating area (SOA)* graph. (see **Fig 7.22**) The first three of these limits are usually also listed prominently with the other device information, but it is often the fourth parameter — secondary breakdown — that is responsible for the "sudden death" of the power transistor after an extended operating period.

The maximum current limit of the transistor ($I_{C\ MAX}$) is usually the current limit for fusing of the bond wire connected to the emitter, rather than anything pertaining to the transistor chip itself. When this limit is exceeded, the bond wire can melt and open circuit the emitter. On the operating curve, this limit is shown as a horizontal line extending out from the Y-axis and ending at the voltage point where the constant power limit begins.

The maximum collector-emitter voltage limit of the transistor ($V_{CE\ MAX}$) is the point at which the transistor junctions can no longer withstand the voltage between collector and emitter.

With increasing collector-emitter voltage drop at maximum collector current, a point is reached where the power in the transistor will cause the junction temperature to rise to a level where the device leakage current rapidly increases and begins to dominate. In this region, the product of the voltage drop and the current would be constant and represent the maximum power (P_t) rating for the transistor; that is, as the voltage drop continues to increase, the collector current must decrease to maintain the power dissipation at a constant value.

With most transistors rated for higher voltages, a point is reached on the constant power portion of the curve whereby, with further increased voltage drop, the maximum power rating is *not* constant, but decreases as the collector to emitter voltage increases. This decrease in power handling capability continues until the maximum voltage limit is reached.

This special region is known as the *forward bias second breakdown* (FBSB) area. Reduction in the transistor's power handling capability is caused by localized heating in certain small areas of the transistor junction ("hot spots"), rather than a uniform distribution of power dissipation over the entire surface of the device.

The region of operating conditions contained within these curves is called the safe operating area, or SOA. If the transistor is always operated within these limits, it should provide reliable and continuous service for a long time.

MOSFET TRANSISTORS

The bipolar junction transistor (BJT) is rapidly being replaced by the MOSFET in new power supply designs because MOSFETs are easier to drive. The N-channel MOSFET (equivalent to the NPN bipolar) is more popular than the P-channel for pass transistor applications.

There are some considerations that should be observed when using a MOSFET as a linear regulator series pass transistor. Several volts of gate drive are needed to start conduction of the device, as opposed to less than 1 V for the BJT. MOSFETs are inherently very-high-frequency devices and will readily oscillate with stray-circuit capacitances. To prevent oscillation in the transistor and surrounding circuits, it is common practice to insert a small resistor of about 100 Ω directly in series with the gate of the series-pass transistor to reduce the gate circuit Q.

OVERCURRENT PROTECTION

Damage to a pass transistor can occur when the load current exceeds the safe amount. **Fig 7.23A** illustrates a simple current-limiter circuit that will protect Q1. All of the load current is routed through R1. A voltage difference will exist across R1; the value will depend on the exact load current at a given time. When the load current exceeds a predetermined safe value, the voltage drop across R1 will forward-bias Q2 and cause it to conduct. Because Q2 is a silicon transistor, the voltage drop across R1 must exceed 0.6 V to

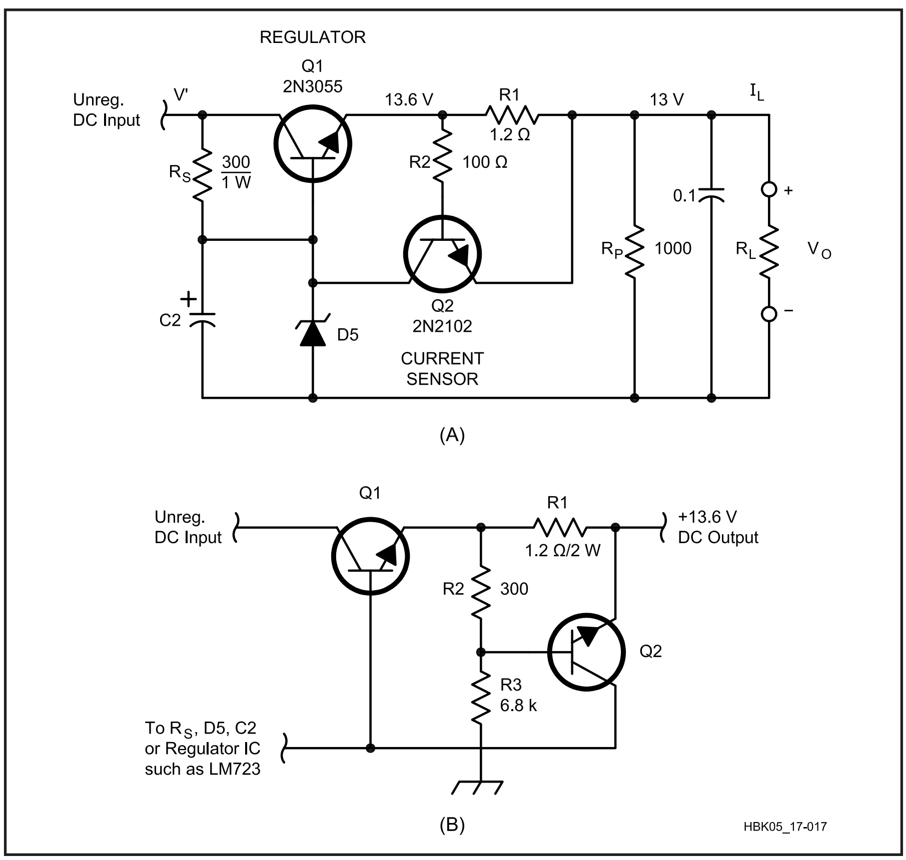


Fig 7.23 — Overload protection for a regulated supply can be implemented by addition of a current-overload-protective circuit, as shown at A. At B, the circuit has been modified to employ current-foldback limiting.

turn Q2 on. This being the case, R1 is chosen for a value that provides a drop of 0.6 V when the maximum safe load current is drawn. In this instance, the drop will be 0.6 V when I_L reaches 0.5 A. R2 protects the base-emitter junction of Q2 from current transients, or from destruction in the event Q1 fails under short-circuit conditions.

When Q2 turns on, some of the current through R_S flows through Q2, thereby depriving Q1 of some of its base current. This action, depending upon the amount of Q1 base current at a precise moment, cuts off Q1 conduction to some degree, thus limiting the current through it.

FOLDBACK CURRENT LIMITING

Under short-circuit conditions, a constant-current type current limiter must still withstand the full source voltage and limited short-circuit current simultaneously, which can impose a very high power dissipation or second breakdown stress on the series pass transistor. For example, a 12 V regulator with current limiting set for 10 A and having a source of 16 V will have a dissipation of 40 W [(16 V – 12 V) × 10 A] at the point of current limiting (knee). But its dissipation will rise to 160 W under short-circuit conditions (16 V × 10 A).

A modification of the limiter circuit can cause the regulated output current to decrease with decreasing load resistance beyond the over-current knee. With the output shorted, the output current is only a fraction of the knee current value, which protects the series-pass transistor from excessive dissipation and possible failure. Using the previous example of the 12 V, 10 A regulator, if the short-circuit current is designed to be 3 A (the knee is still 10 A), the transistor dissipation with a short circuit will be only 16 V × 3 A = 48 W.

Fig 7.23B shows how the current-limiter example given in the previous section would be modified to incorporate foldback limiting. The divider string formed by R2 and R3 provides a negative bias to the base of Q2, which prevents Q2 from turning on until this bias is overcome by the drop in R1 caused by load current. Since this hold-off bias decreases as the output voltage drops, Q2 becomes more sensitive to current through R1 with decreasing output voltage. See **Fig 7.24**.

The circuit is designed by first calculating the value of R1 for short-circuit current. For example, if 0.5 A is chosen, the value for R1 is simply 0.6 V / 0.5 A = 1.2 Ω (with the output shorted, the amount of hold-off bias supplied by R2 and R3 is very small and can be neglected). The knee current is then chosen. For this example, the selected value will be 1.0 A. The divider string is then proportioned to provide a base voltage at the knee that is just sufficient to turn on Q2 (a value of 13.6 V for 13.0 V output). With 1.0 A flowing through R1, the voltage across the divider will be 14.2 V. The voltage dropped by R2 must then be 14.2 V –13.6 V, or 0.6 V. Choosing a divider current of 2 mA, the value of R2 is then 0.6 V / 0.002 A = 300 Ω. R3 is calculated to be 13.6 V / 0.002 A = 6800 Ω.

7.9.4 Three-Terminal Voltage Regulators

The modern trend in regulators is toward the use of three-terminal devices commonly referred to as *three-terminal regulators*. Inside each regulator is a voltage reference, a high-gain error amplifier, temperature-compensated voltage sensing resistors and a pass element. Many currently available units have thermal shut-down, overvoltage protection and current foldback, making them virtually destruction-proof. It is easy to see why regulators of this sort are so popular when you consider the low price and the number of individual components they can replace.

Three-terminal regulators have connections for unregulated dc input, regulated dc output and ground, and they are available in a wide range of voltage and current ratings. Fixed-voltage regulators are available with output ratings in most common values between 5 and 28 V. Other families include devices that can be adjusted from 1.25 to 50 V.

The regulators are available in several different package styles, depending on current ratings. Low-current (100 mA) devices frequently use the plastic TO-92 and DIP-style cases. TO-220 packages are popular in the 1.5 A range, and TO-3 cases house the larger 3 A and 5 A devices. They are available in surface mount packages too.

Three-terminal regulators are available as positive or negative types. In most cases, a positive regulator is used to regulate a positive voltage and a negative regulator a negative voltage. Depending on the system ground requirements, however, each regulator type may be used to regulate the "opposite" voltage.

Fig 7.25A and B illustrate how the regulators are used in the conventional mode. Several regulators can be used with a common-input supply to deliver several voltages with a common ground. Negative regulators may be used in the same manner. If no other common supplies operate from the input supply to the regulator, the circuits of Fig 7.25C and D may be used to regulate positive voltages with a negative regulator and vice versa. In these configurations the input supply is floated; neither side of the input is tied to the system ground.

Manufacturers have adopted a system of

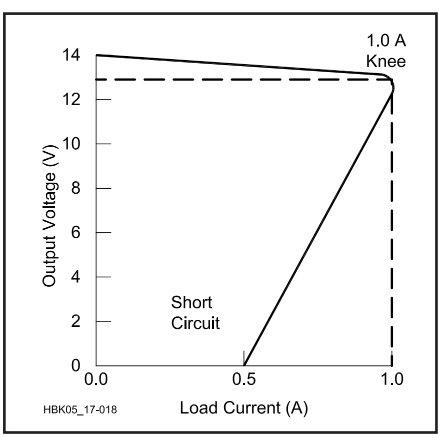


Fig 7.24 — The 1 A regulator shown in Fig 7.23B will fold back to 0.5 A under short-circuit conditions. See text.

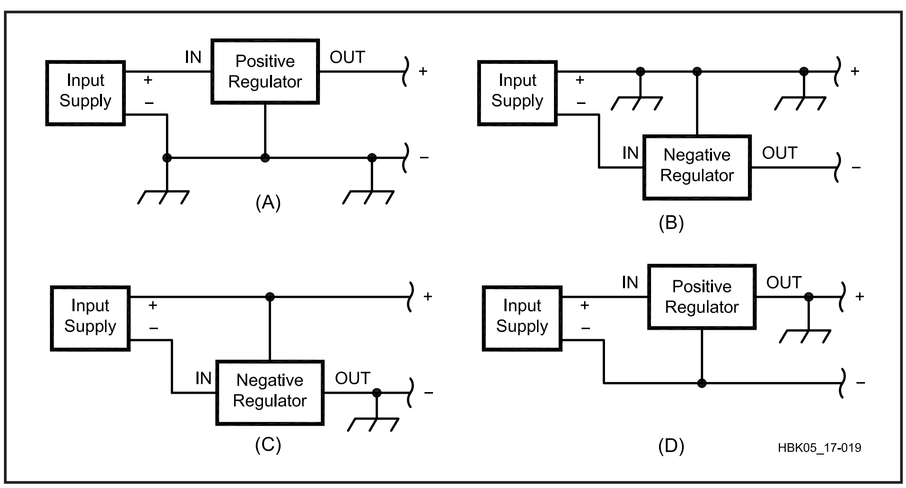


Fig 7.25 — Parts A and B illustrate the conventional manner in which three-terminal regulators are used. Parts C and D show how one polarity regulator can be used to regulate the opposite-polarity voltage.

family numbers to classify three-terminal regulators in terms of supply polarity, output current and regulated voltage. For example, 7805 describes a positive 5 V, 1.5 A regulator and 7905 a negative 5 V, 1.5 A unit. Depending on the manufacturer, the full part number might have a prefix such as LM, UA or MC, along with various suffixes (for example, LM7805CT or MC7805CTG). There are many such families with widely varied ratings available from manufacturers. More information may be found in the **Component Data and References** chapter.

SPECIFYING A REGULATOR

When choosing a three-terminal regulator for a given application, the most important specifications to consider are device output voltage, output current, minimum and maximum input-to-output differential voltages, line regulation, load regulation and power dissipation. Output voltage and current requirements are determined by the load with which the supply will ultimately be used.

Input-to-output differential voltage is one of the most important three-terminal regulator specifications to consider when designing a supply. The differential value (the difference between the voltage applied to the input terminal and the voltage on the output terminal) must be within a specified range. The minimum differential value, usually about 2.5 V, is called the *dropout voltage*. If the differential value is less than the dropout voltage, no regulation will take place. Special *low dropout regulators* with lower minimum differential values are available as well. At the other end of the scale, maximum input-output differential voltage is generally about 40 V. If this differential value is exceeded, device failure may occur.

Increases in either output current or differential voltage produce proportional increases in device power consumption. By employing current foldback, as described above, some manufacturers ensure that maximum dissipation will never be exceeded in normal operation. **Fig 7.26** shows the relationship between output current, input-output differential and current limiting for a three-terminal regulator nominally rated for 1.5 A output current. Maximum output current is available with differential voltages ranging from about 2.5 V (dropout voltage) to 12 V. Above 12 V, the output current decreases, limiting the device dissipation to a safe value. If the output terminals are accidentally short circuited, the input-output differential will rise, causing current foldback, and thus preventing the power-supply components from being over stressed. This protective feature makes three-terminal regulators particularly attractive in simple power supplies.

When designing a power supply around

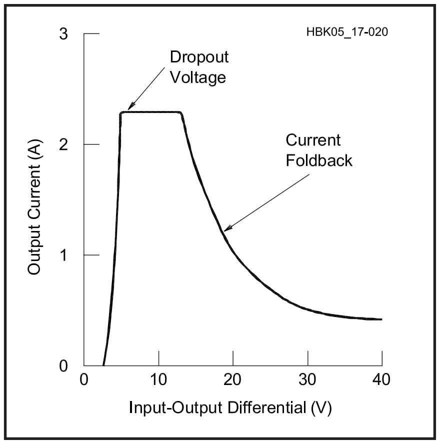


Fig 7.26 — Effects of input-output differential voltage on three-terminal regulator current.

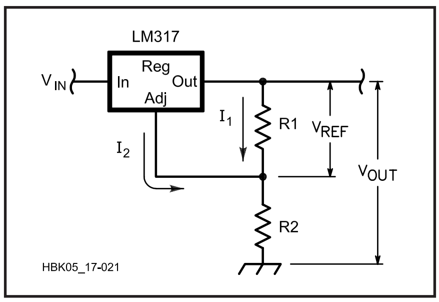


Fig 7.27 — By varying the ratio of R2 to R1 in this simple LM317 schematic diagram, a wide range of output voltages is possible. See text for details.

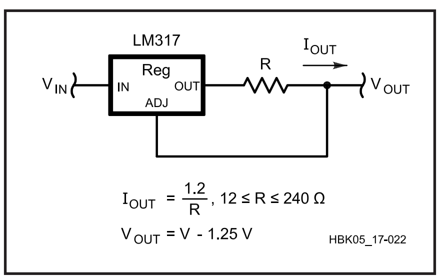


Fig 7.28 — The basic LM317 voltage regulator is converted into a constant-current source by adding only one resistor.

a particular three-terminal regulator, input-output voltage characteristics of the regulator should play a major role in selecting the transformer-secondary and filter-capacitor component values. The unregulated voltage applied to the input of the three-terminal device should be higher than the dropout voltage, yet low enough that the regulator does not go into current limiting caused by an excessive differential voltage. If, for example, the regulated output voltage of the device shown in Fig 7.26 were 12 V, then unregulated input voltages of between 14.5 and 24 V would be acceptable if maximum output current is desired.

In use, all but the lowest-current regulators generally require an adequate external heat sink because they may be called on to dissipate a fair amount of power. Also, because the regulator chip contains a high-gain error amplifier, bypassing of the input and output leads is essential for stable operation.

Most manufacturers recommend bypassing the input and output directly at the leads where they protrude through the heat sink. Solid tantalum capacitors are usually recommended because of their good high-frequency capabilities.

External capacitors used with IC regulators may discharge through the IC junctions under certain circuit conditions, and high-current discharges can harm ICs. Look at the regulator data sheet to see whether protection diodes are needed, what diodes to use and how to place them in any particular application.

Adjustable Regulators

In addition to fixed-output-voltage ICs, high-current, adjustable voltage regulators are available. These ICs require little more than an external potentiometer for an adjustable output range from 5 to 24 V at up to 5 A. The unit price on these items is only a few dollars, making them ideal for test-bench power supplies. A very popular low current, adjustable output voltage three terminal regulator, the LM317, is shown in **Fig 7.27**. It develops a steady 1.25 V reference, V_{REF}, between the output and adjustment terminals. By installing R1 between these terminals, a constant current, I1, is developed, governed by the equation:

$$I1 = \frac{V_{REF}}{R1} \qquad (10)$$

Both I1 and a 100 µA error current, I2, flow through R2, resulting in output voltage V_O. V_O can be calculated using the equation:

$$V_O = V_{REF}\left(1 + \frac{R2}{R1}\right) + I2 \times R2 \qquad (11)$$

Any voltage between 1.2 and 37 V may be obtained with a 40 V input by changing the ratio of R2 to R1. At lower output voltages, however, the available current will be limited by the power dissipation of the regulator.

Fig 7.28 shows one of many flexible applications for the LM317. By adding only one resistor with the regulator, the voltage regulator can be changed into a constant-current source capable of charging NiCd batteries, for example. Design equations are given in the figure. The same precautions should be taken with adjustable regulators as with the fixed-voltage units. Proper heat sinking and lead bypassing are essential for proper circuit operation.

INCREASING REGULATOR OUTPUT CURRENT

When the maximum output current from an IC voltage regulator is insufficient to operate the load, discrete power transistors may be connected to increase the current capability. **Fig 7.29** shows two methods for boosting the output current of a positive regulator, although the same techniques can be applied to negative regulators.

In A, an NPN transistor is connected as an emitter follower, multiplying the output current capacity by the transistor beta. The shortcoming of this approach is that the base-emitter junction is not inside the feedback loop. The result is that the output voltage is reduced by the base-emitter drop, and the load regulation is degraded by variations in this drop.

The circuit at B has a PNP transistor "wrapped around" the regulator. The regulator draws current through the base-emitter junction, causing the transistor to conduct. R1 provides bias voltage for turning on Q1 so that U1 doesn't see the excess current. For example, a 6 Ω resistor will limit the current U1 sees to 100 mA. The IC output voltage is unchanged by the transistor because the collector is connected directly to the IC output (sense point). Any increase in output voltage is detected by the IC regulator, which shuts off its internal-pass transistor, and this stops the boost-transistor base current.

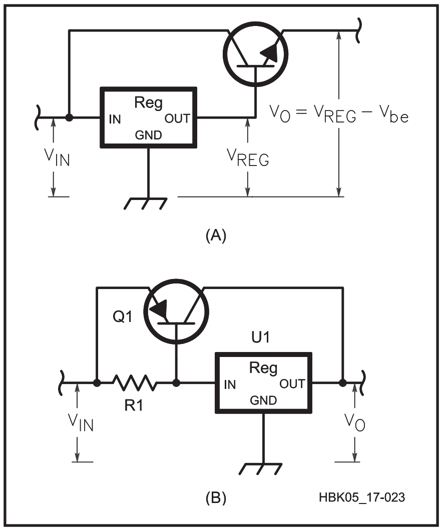


Fig 7.29 — Two methods for boosting the output-current capacity of an IC voltage regulator. Part A shows an NPN emitter follower and B shows a PNP "wrap-around" configuration. Operation of these circuits is explained in the text.

7.10 "Crowbar" Protective Circuits

Electronic components *do* fail from time to time. In a regulated power supply, the only component standing between an elevated dc source voltage and your transceiver is one transistor, or a group of transistors wired in parallel. If the transistor, or one of the transistors in the group, happens to short internally, your equipment could suffer lots of damage.

To safeguard the load equipment against possible overvoltage, some power-supply manufacturers include a circuit known as a *crowbar*. This circuit usually consists of a silicon-controlled rectifier (SCR) or thyristor connected directly across the output of the power supply, with an over-voltage-sensing trigger circuit tied to its gate. The SCR is large enough to take the full short-circuit output current of the supply, as if a crowbar were placed across the output terminals, thus the name.

In the event the output voltage exceeds the trigger set point, the SCR will fire, and the output is short circuited. The resulting high current in the power supply (shorted output in series with a series pass transistor failed short) will blow the power supply's line fuses. This is a protection for the supply as well as an indicator that something has malfunctioned internally. For these reasons, never replace blown fuses with ones that have a higher current rating.

An example of a crowbar overvoltage protection circuit can be found as a project at the end of this chapter. It provides basic design equations that can be adapted to a wide range of power supply applications.

7.11 DC-DC Switchmode Power Conversion

Very often the power source is dc, such as a battery or solar cell, or the output of an unregulated rectifier connected to an ac source. In most applications high conversion efficiency is desired, both to conserve energy from the source and to reduce heat dissipation in the converter. When high efficiency is needed, some form of switching circuit will be employed for dc-dc power conversion. Besides being more efficient, switching circuits are usually much smaller and lighter than conventional 60 Hz, transformer-rectifier circuits because they operate at much higher frequencies — from 25 to 400 kHz or even higher. Switching circuits go by many names; *switching regulators* and *switchmode converters* are just two of the more common names.

The possibility of achieving high conversion efficiency stems directly from the use of switches for the power conversion process, along with low-loss inductive and capacitive elements. An active switch is a device that is either ON or OFF and the state of the switch (ON or OFF) can be controlled with an external signal. The loss in the switch is always the product of the voltage across the switch and the current flowing through it ($P = E \times I$).

In the ON (conducting) state the voltage drop across the switch is small, and in the OFF state the current through the switch is small. In both cases the losses can be small relative to the power level of the converter. During transitions between ON and OFF states, however, there will simultaneously be both substantial voltage across the switch and significant current flowing through it. This results in power dissipation in the switch, called *switching loss*. This loss is minimized by making the switching transitions as short as possible. In this way even though the instantaneous power dissipation may be high, the average loss is low because of the small duty cycle of the transitions. Of course the more frequently the switch operates (higher switching frequency), the higher the average loss will be and this eventually limits the maximum operating frequency. A limitation on the lower end of the switching frequency range is that it needs to be above audible frequencies (>25 kHz).

This is quite different from the linear regulators discussed earlier in which there is always some voltage drop across the pass transistor (which is acting as a controlled variable resistor) while current is flowing through it. As a result the efficiency of a linear regulator can be very low, often 65% or less. Switchmode converters on the other hand will typically have efficiencies in the range of 85 to 95%.

Switchmode circuits can also generate radio-frequency interference (RFI) through VHF because of switching frequency harmonics and ringing induced by the rapid rise and fall times of voltage and current. In attempting to minimize the ON-OFF transition time, significant amounts of RF energy can be generated. To prevent RFI to sensitive receivers, careful bypassing, shielding and filtering of both input and output circuits is required. (RFI from switchmode or "switching" supplies is also discussed in the chapter on **RF Interference**.)

There are literally hundreds of different switchmode circuits or "topologies" (see Reference 2) but we will only look at a few of those most commonly used by amateurs. Fortunately, the characteristics of the simpler circuits are to a large extent replicated in more complex circuits so that an understanding of the basic circuits provides an entry point to many other circuits.

The following discussion is only an introduction to the basics of switchmode converters. To really get a handle on designing these circuits the reader will have to do some additional reading. Fortunately a very large amount of useful information is freely available on-line. Many useful application notes are available from semiconductor manufacturers, and additional information can be found on the websites of filter capacitor and ferrite core manufacturers (see References 3 and 4). There are also numerous books on the subject, often available in libraries and used book stores.

Switchmode circuits can and have been implemented with many different kinds of switches, from mechanical vibrators to vacuum and gas tubes to semiconductors. Today however, semiconductors are the universal choice. For converters in the power range typical of amateur applications (a few watts through 2-3 kW) the most common choices of semiconductor switches would be either bipolar junction transistors (BJTs) or power MOSFETs. BJTs have a long history of use in switchmode applications, but to employ BJTs in a reliable and trouble-free circuit requires a relatively sophisticated understanding of them. While the MOSFET must also be used carefully, it is generally easier for a newcomer. The following circuit diagrams will show MOSFETs or generic switch symbols for the switches but keep in mind that all of the circuits can be implemented with other types of switches.

7.11.1 The Buck Converter

A schematic for a *buck converter* is shown in **Fig 7.30A**. This circuit is called a "buck" converter because the output voltage is always less than or equal to the input voltage. Power is supplied from the dc source (V_S) through

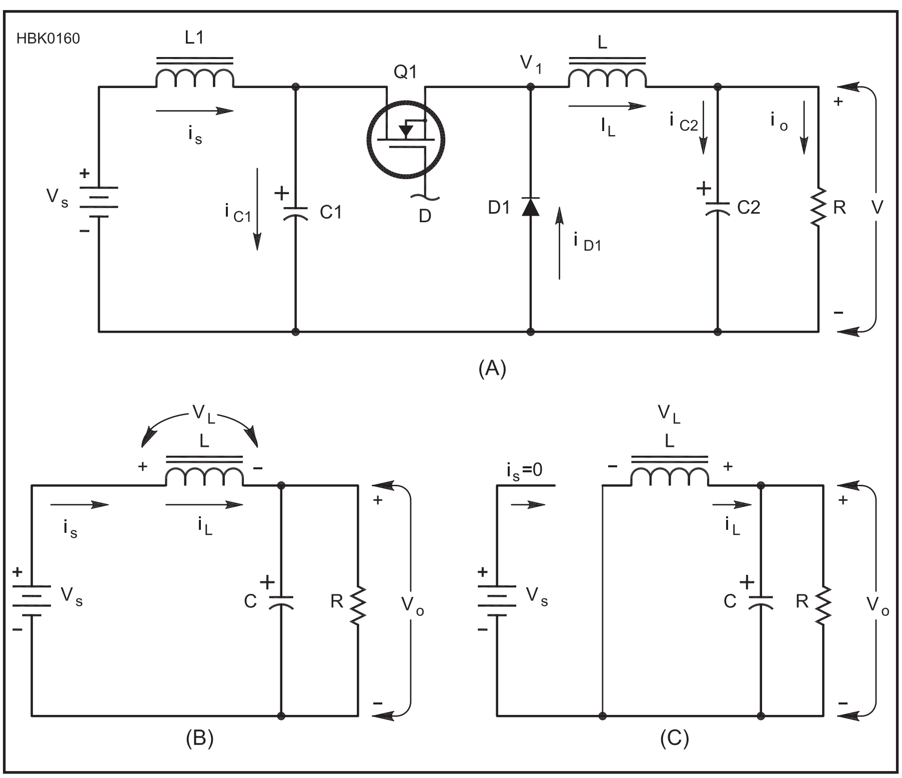


Fig 7.30 — Typical buck converter.

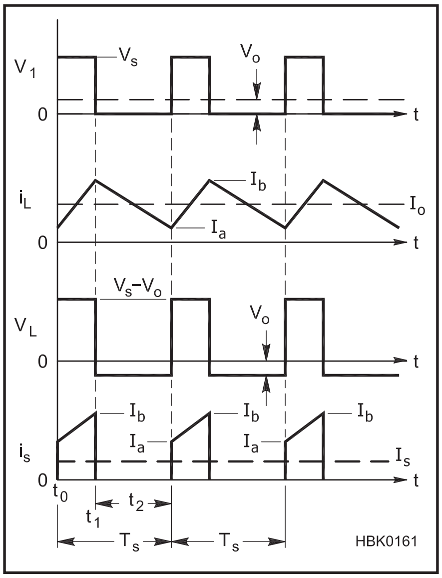


Fig 7.31 — Waveforms in a buck converter.

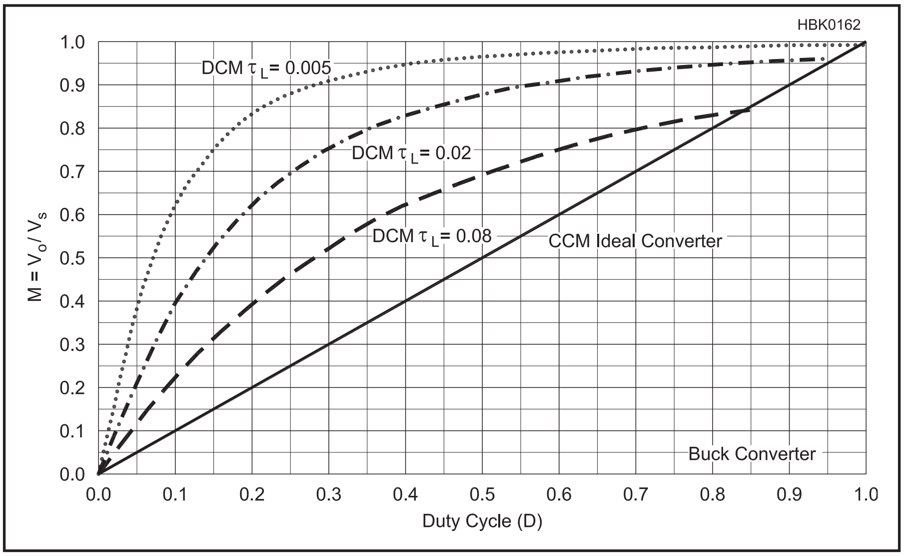


Fig 7.32 — Change in output voltage to input voltage ratio (M=VO/VS) as a function of switch duty cycle (D).

the input filter (L1, C1) to the drain of the switch (Q1). The load (R) is connected across the output filter (L, C2).

The equivalent circuit when Q1 is ON is shown in Fig 7.30B (where the input filter components are assumed to be part of V_S). V_S is connected to one end of the output inductor (L) and, because $V_O < V_S$, current flows from the source to the output delivering energy from the source to the output and also storing energy in L. At some point Q1 is turned OFF and the current flowing in L commutates (switches) to D1, as shown in Fig 7.30C. (The current in an inductor cannot change instantaneously, so when Q1 turns OFF, the collapsing magnetic field in L pulls current through shunt diode D1, called a *free-wheeling diode*.) The energy in L is now being discharged into the output. This cycle is repeated at the switching frequency (f_s). The ratio of the switch ON-time to the total switching period ($T_s = t_{on} + t_{off} = 1/f_s$) is called the *duty cycle (D)*.

Typical voltage and current waveforms for a buck converter are shown in **Fig 7.31** where V_1 is the voltage at the junction of Q1, D1 and L (see Fig 7.30A).

The interval 0-t_1 corresponds to the ON time of Q1 and $T_s - t_1$ corresponds to the OFF time ($T_s = t_1 + t_2$). From the waveforms it can be seen that the current in the inductor rises while Q1 is ON and falls while Q1 is OFF. The energy in the inductor is proportional to $LI^2/2$.

The input current (I_s) is pulsating at the switching frequency. This pulsation in the input current is the reason for the input filter (L1 and C1). We need to keep this high frequency noise (the ac component of the pulsation) out of the source. All switchmode converters require some form of filter on the input to keep switching noise out of the source. Some form of filter is also required on the output to keep the switching noise out of the load. In Fig 7.30, L and C2 form the output filter. For applications requiring low ripple it would not be unusual to see an additional stage of L-C filtering added to the output.

The voltage waveform (V_1) at the input to the output filter (L and C2) is pulse-width modulated (PWM) and V_O (the dotted line in the waveform for V_1 in Fig 7.31A) is the time average of V_1. V_O is controlled or regulated by adjusting the duty cycle of Q1 in response to input voltage or output load changes. If we increase D we increase V_O up to the point where D = 1 (the switch is ON all the time) and $V_O \approx V_S$. If we never turn Q1 on (D = 0) then $V_O = 0$. Normal operation will be somewhere between these extremes.

The inductor current waveform in Fig 7.31 does not go to zero while Q1 is OFF. In other words, not all of the energy stored in L is discharged into the output by the end of each switching cycle. This is a common mode of operation for heavier loads. It is referred to as the *continuous conduction mode* or CCM, where the conduction referred to is the current in L. There is another possibility: during the time Q1 is off all of the energy in L may be discharged and for some period of time the inductor current is zero until Q1 is turned ON again. This is referred to as the *discontinuous conduction mode* or DCM. A typical converter will operate in CCM for heavy loads but as the load is reduced, at some point the circuit operation will change to DCM. CCM is often referred to as the "heavy load" condition and DCM as the "light load" condition.

This distinction turns out to be very important because the behavior of the circuit, for both small signal and large signal, is radically different between the two modes. **Fig 7.32** shows the relationship between the duty cycle (D) of Q1 and the ratio of the output voltage to the input voltage ($M = V_O/V_S$) as a function of τ_L in Fig 7.32:

$$\tau_L = \left(\frac{L}{R}\right) f_S \qquad (12)$$

τ_L is just a convenient way to make Fig 7.32 more general by tying together the variables L, R and f_s. Smaller values for τ_L correspond to lighter loads (larger values for R). As can been seen in Fig 7.32, for very light loads the higher values for D have little effect on the output/input voltage ratio. This is basically charging of the output capacitor (C2) to the peak value of $V_1 \approx V_S$.

For CCM operation, M is a linear function of D. As we vary the load, V_O will remain relatively constant. But when we go into DCM, the relation between D and M is no longer linear and in addition is heavily dependent on the load: V_O will vary as the load is changed unless the duty cycle is varied to compensate. This kind of behavior is typical of all switching regulators, even those not directly related to the buck converter. In fact, we have seen this behavior already in the section on choke input filters in Fig 7.17 where the output voltage is close to the peak input voltage for light loads and decreases as the load increases until a point is reached (I_C) where V_O stabilizes.

In a buck converter the value for the critical inductance (L_C) can be found from:

$$L_c = R\left(\frac{1-M}{2 f_S}\right) \qquad (13)$$

This looks just like equation 6 (in the earlier section on choke-input filters) with

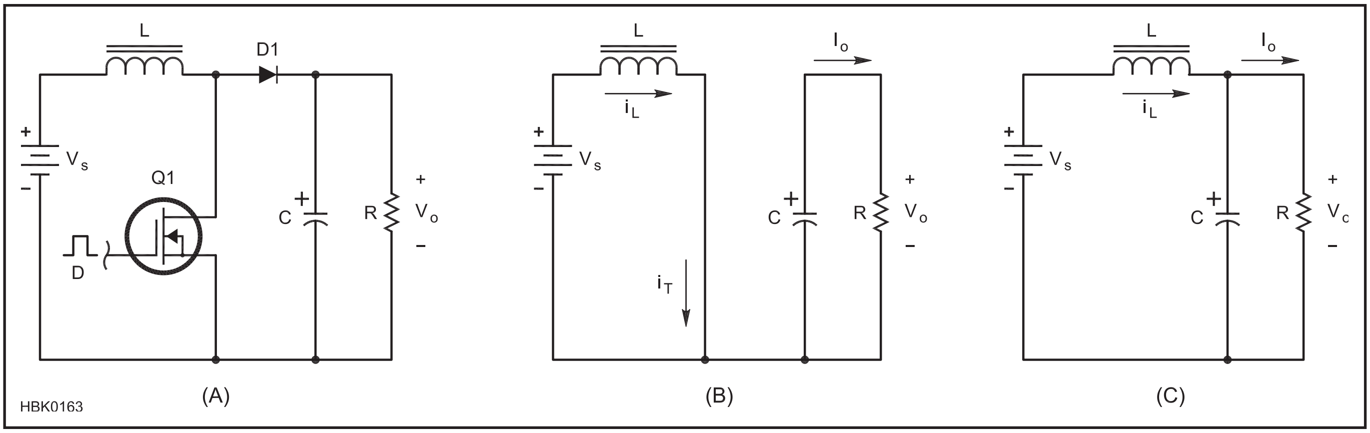


Fig 7.33 — Typical boost converter.

A = 2fs / (1 – M)! The two phenomena are the same: peak charging versus averaging of V1.

7.11.2 The Boost Converter

A *boost converter* circuit is shown in **Fig 7.33A**. This circuit is called a "boost" converter because the output voltage is always greater than or equal to the input voltage.

When Q1 is ON (Fig 7.33B), L is connected in parallel with the source (V_S) and energy is stored in it. During this time interval load energy is supplied from C. When Q1 turns OFF (Fig 7.33C), L is connected via D1 to the output and the energy in L, plus additional energy from the source, is discharged into the output. The value for L, V_S and length of time it is charged determines the energy stored in L. Again we have the possibilities that either some (CCM) or all (DCM) the energy in L is discharged during the OFF-time of Q1. The variation in the ratio of the output-to-input voltage (M) with duty cycle is shown in **Fig 7.34**.

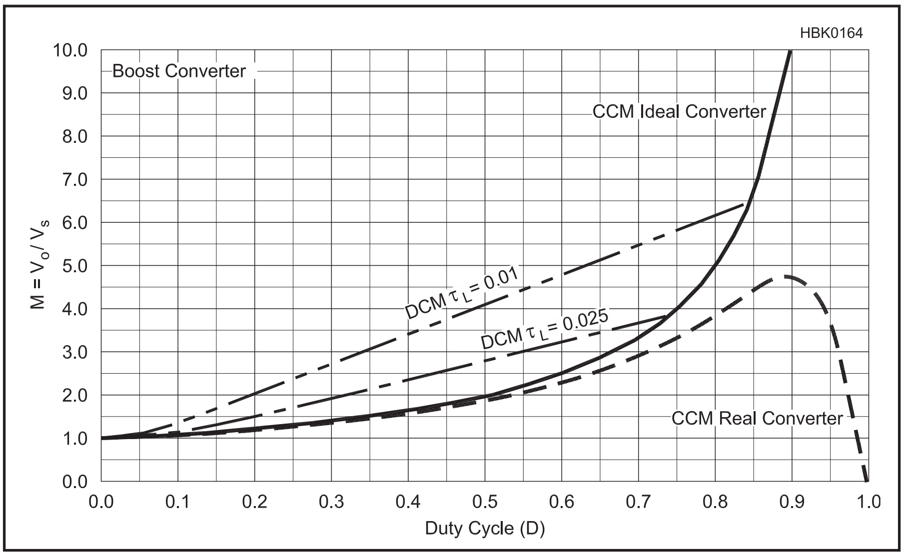


Fig 7.34 — DC control characteristic for a boost converter. M = V_O/V_S, D = duty cycle of Q1 and $\tau_L = f_s$ (L/R).

As we saw in the buck converter, the conduction mode of L is important. In an ideal converter operating in CCM, the output voltage is substantially independent of load and $M \approx 1 / (1 – D)$. In realistic boost converters there is an important limit on the CCM value for M. In an ideal boost converter you could make the boost ratio (M) as large as you wish but in real converters the parasitic resistances associated with the components will limit the maximum value of M as indicated by the dashed line for CCM operation. The exact shape of this part of the control function will depend on the ratio of the parasitic resistance within the converter to the load resistance (see Reference 2).

There is also another very important practical effect of this limitation on the peak value for M. When the duty cycle is increased beyond the point of maximum M (this occurs at D = 0.9 in Fig 7.34), the sign of the slope of the control function changes so that the control loop will change from negative feedback to positive feedback. This can cause the converter to latch up under some load conditions if the control circuit allows D to exceed the value at maximum M. In boost converters the design of the control circuit must limit the maximum value for D so that latch-up is not possible although this may be difficult for overload conditions.

As in the case of the buck converter, in DCM the control function for M is very different from what it is in CCM and is strongly dependent on the load R. One advantage of the DCM operation is that the limitation on the maximum value for M because of parasitic circuit resistances is not nearly so pronounced. By operating in DCM it is possible to have M > 5.

An important limitation of the boost converter is that with Q1 turned OFF, you have no control over V_O. V_O will simply equal V_S. In addition, when V_S is turned on there will be an inrush current through D1, into C which cannot be controlled by Q1. In the case of the buck converter, if Q1 is kept OFF when V_S is turned on, there will be no inrush current charging the output filter capacitor (C2). In the buck converter C2 can be charged slowly by ramping up the duty cycle of Q1 during turn-on but this is not possible in the boost converter.

7.11.3 Buck-Boost and Flyback Converters

Fig 7.35 shows an example of a *buck-boost converter*. The name "buck-boost" comes from the fact that the magnitude of the output voltage can be either greater or less than the input voltage.

When S1 is ON, V_S is applied across L and energy is stored in it. During the ON time of Q1, D1 is reverse-biased and non-conducting. The output voltage (V_O) across the load (R) is supported solely from the energy

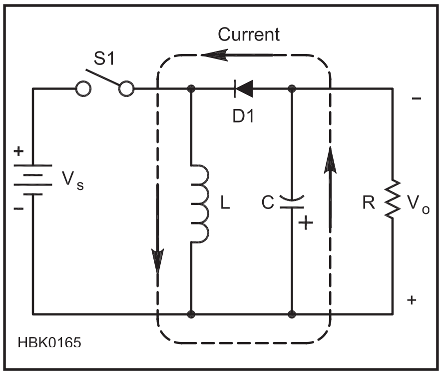


Fig 7.35 — An example of a buck-boost converter.

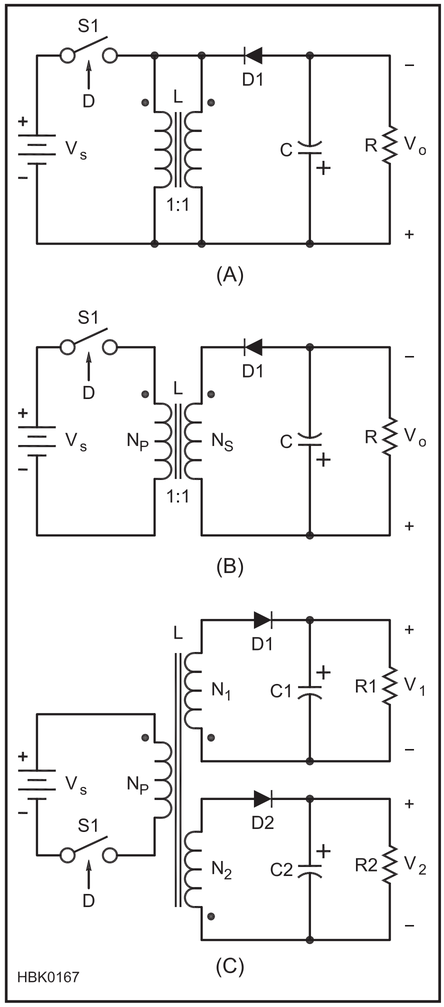


Fig 7.37 — The relationship between buck-boost and flyback converters.

stored in C. When S1 is OFF, the energy in L is discharged into C through D1. Note that the polarity of V_O is inverted from V_S: *positive V_S means negative V_O*. The relationship between V_O and V_S as a function of duty cycle is shown in **Fig 7.36**.

This graph closely resembles that for the boost converter (Fig 7.34) with one important exception: |M| begins at zero. This allows the magnitude of the output voltage to be either below or above the source voltage, hence the name "buck-boost."

FLYBACK CONVERTERS

Simple buck-boost converters are occasionally used, but much more often it is the transformer-coupled version of this converter, referred to as a *flyback converter*, that is employed. The relationship between the flyback and buck-boost converters is illustrated in **Fig 7.37**. In Fig 7.37A we have a standard buck-boost converter, the only change from Fig 7.35 being two parallel and equal windings on the inductor. In Fig 7.37B we remove the links at the top and bottom of the two parallel windings, converting the inductor into a transformer with primary and secondary windings. The only change is that when S1 is ON, current flows in the primary of the transformer and when S1 is OFF, the current flows in the secondary winding delivering the stored energy to the output. At this point the circuit operation is the same except that we have introduced primary-to-secondary galvanic isolation.

We are now free to change the turns ratio from 1:1 to anything we wish. We can also change the polarity of the output voltages and/or add more windings with other voltages and additional loads as shown in Fig 7.37C, a typical example of a flyback converter. These are most often used in the power range of a few watts to perhaps 200 W. For higher power levels other circuits are generally more useful.

The advantages of the flyback converter lie in its simplicity. It requires only one power switch and one diode on each of the output windings. The inductor is also the isolation transformer so you have only one magnetic component. The disadvantage of this circuit is that both in the input and output current waveforms are pulsating. The result is that more filtering is required and the filter capacitors are exposed to high RMS currents relative to the power level.

7.11.4 The Forward Converter

The buck converter has many useful properties but it lacks input-to-output galvanic isolation, the ability to produce output voltages higher than the input voltage, and/or multiple isolated output voltages for multiple loads. We can overcome these drawbacks by inserting a transformer between the switch (S1) and the shunt diode (D1). To make this simple idea work however, we also have to add a diode in series with the output of the transformer (D2), and a third winding (N_R) with another diode (D3) to the transformer. This is done to provide a means for resetting the core (returning the magnetic flux to zero) by the end of each switching cycle. The result is the *forward converter* shown in **Fig 7.38**.

The circuit in A is the one just described. The variation in B uses two switches (S1 and S2, which switch ON and OFF *simultaneously*) instead of one but eliminates the need for a reset winding on the transformer. For the circuit in A and a given input voltage, the voltage across the switch (in the OFF state) will be equal to V_S plus the reset voltage during the OFF-time. Typically the peak switch voltage will be about $2V_S$. In the circuit shown in B the switch voltage is limited to V_S which is

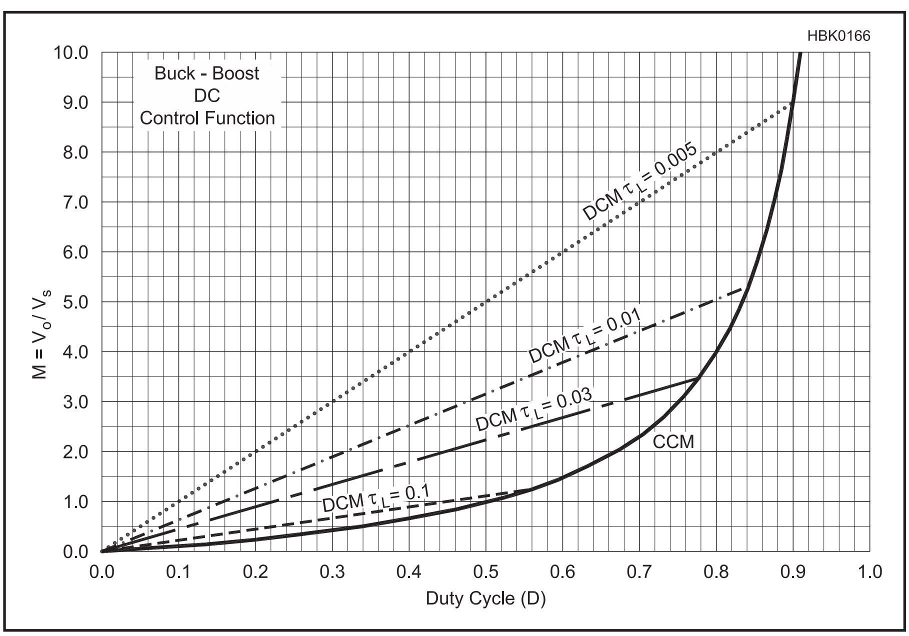


Fig 7.36 — DC control function for an ideal buck-boost converter. $M = V_O/V_S$, D = duty cycle of Q1 and $\tau_L = f_s (L/R)$.

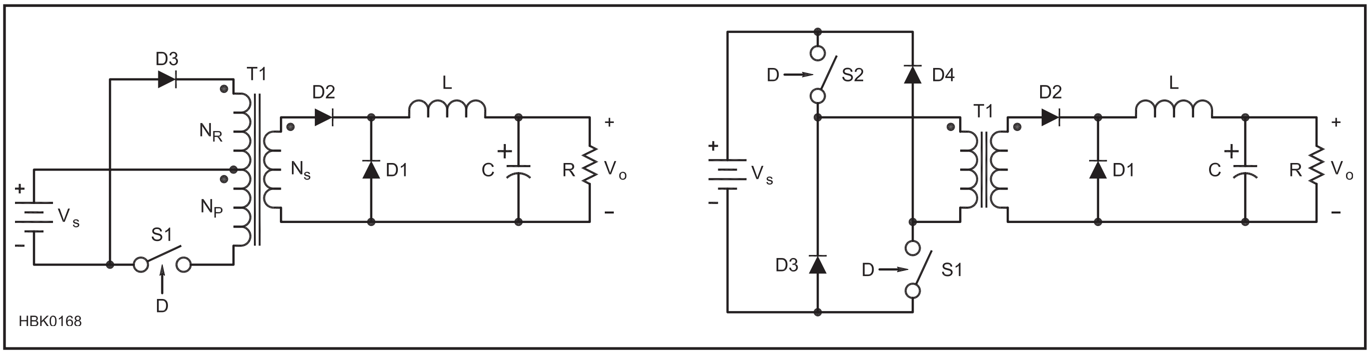
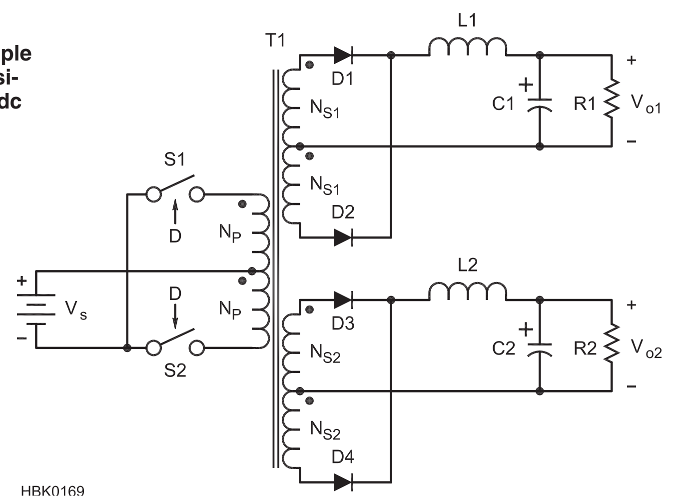


Fig 7.38 — Example of a forward converter.

Fig 7.39 — Example of a parallel quasi-square wave dc-dc converter.



very helpful at higher line voltages. These circuits behave just like a buck converter except you can now have multiple isolated outputs with arbitrary voltages and polarities. These circuits are typically used in converters with power levels of 100 to 500 W.

7.11.5 Parallel, Half and Full-Bridge Converters

As the power level increases it becomes advantageous to use more switches in a somewhat more complex circuit. For applications where the input voltage is low (<100V) and the current high, the push-pull *quasi-square wave* circuit shown in **Fig 7.39** is often used.

S1 and S2 are switched on alternately with duty cycles <0.5. The output voltages are controlled by the duty cycle, D. The peak switch currents are equal to the input current but the peak switch voltages will be $2V_S$.

This circuit is still just a buck converter, but with an isolation transformer added that allows multiple outputs with different voltages above or below the input voltage. It would be very common to have a 5 V, high-current output and ±12 V, lower-current outputs, for example. This converter is typically used for operation from vehicular power with loads up to several hundred watts.

Operating directly from rectified ac utility power usually means that V_S will be 200 V or more. For these applications, **Fig 7.40** shows how the switches are configured in either a half- (Fig 7.40A) or full-bridge (Fig 7.40B) circuit.

In A, S1 and S2 switch alternately and are pulse-width modulated (PWM) to control the output. CA and CB are large capacitors that form a voltage divider with $V_S/2$ across each capacitor. The peak switch voltages will be equal to V_S but the switch currents will be $2I_S$. The peak voltage across the primary winding will be $V_S/2$. This circuit would typically be used for off-line applications with output powers of 500 W or so.

In B, S1 and S4 switch simultaneously alternating with S2 and S3 which also switch simultaneously. The output is controlled by PWM. The peak switch voltage will be equal to V_S and the peak switch current close to I_S (the peak value is a little higher due to ripple on the inductor current which is reflected back into the primary winding). The full-bridge circuit is typically used for power levels of 500 W to several kW. C_S is present in the full-bridge circuit to prevent core saturation due to any asymmetry in the primary PWM voltage waveforms.

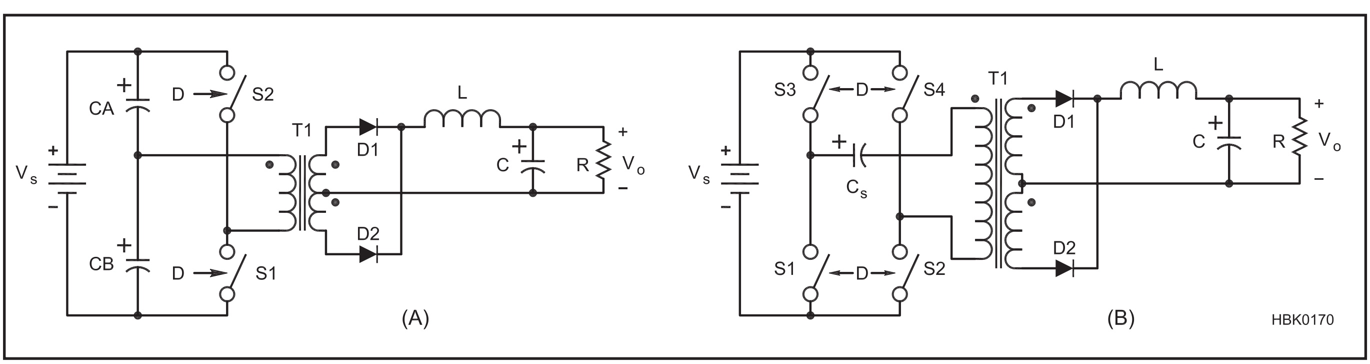


Fig 7.40 — Examples of half and full-bridge quasi-square wave dc-dc converters.

7.11.6 Building Switchmode Power Supplies

Selecting a switching circuit or topology is just the first step in building a practical switch-mode power supply. In the actual circuit you will have to sample the output voltage, provide a voltage reference against which to compare the output, include a modulator that will convert the error voltages to a variable-duty cycle signal and finally provide correct drive to the power switches. Fortunately, all of these functions can be provided with readily available integrated circuits and a few external components. These ICs typically come with extensive applications information.

Particularly for low power applications (<100 W) there are ICs that provide all the

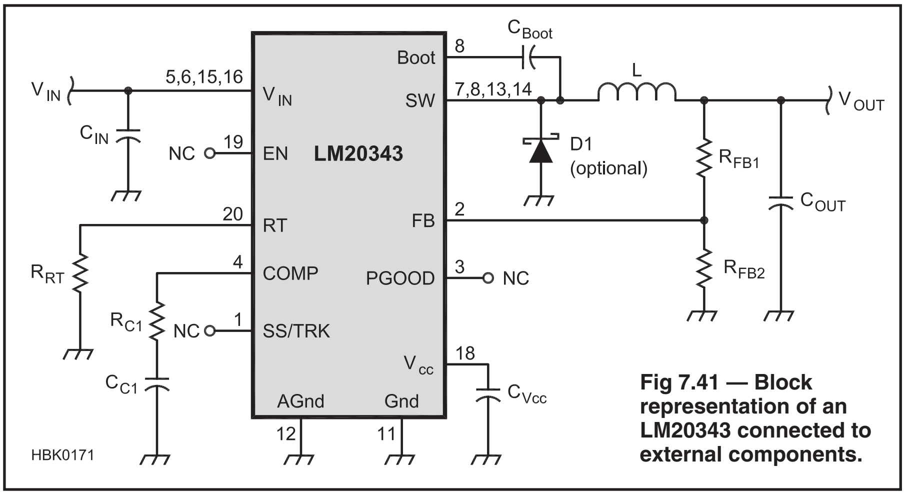


Fig 7.41 — Block representation of an LM20343 connected to external components.

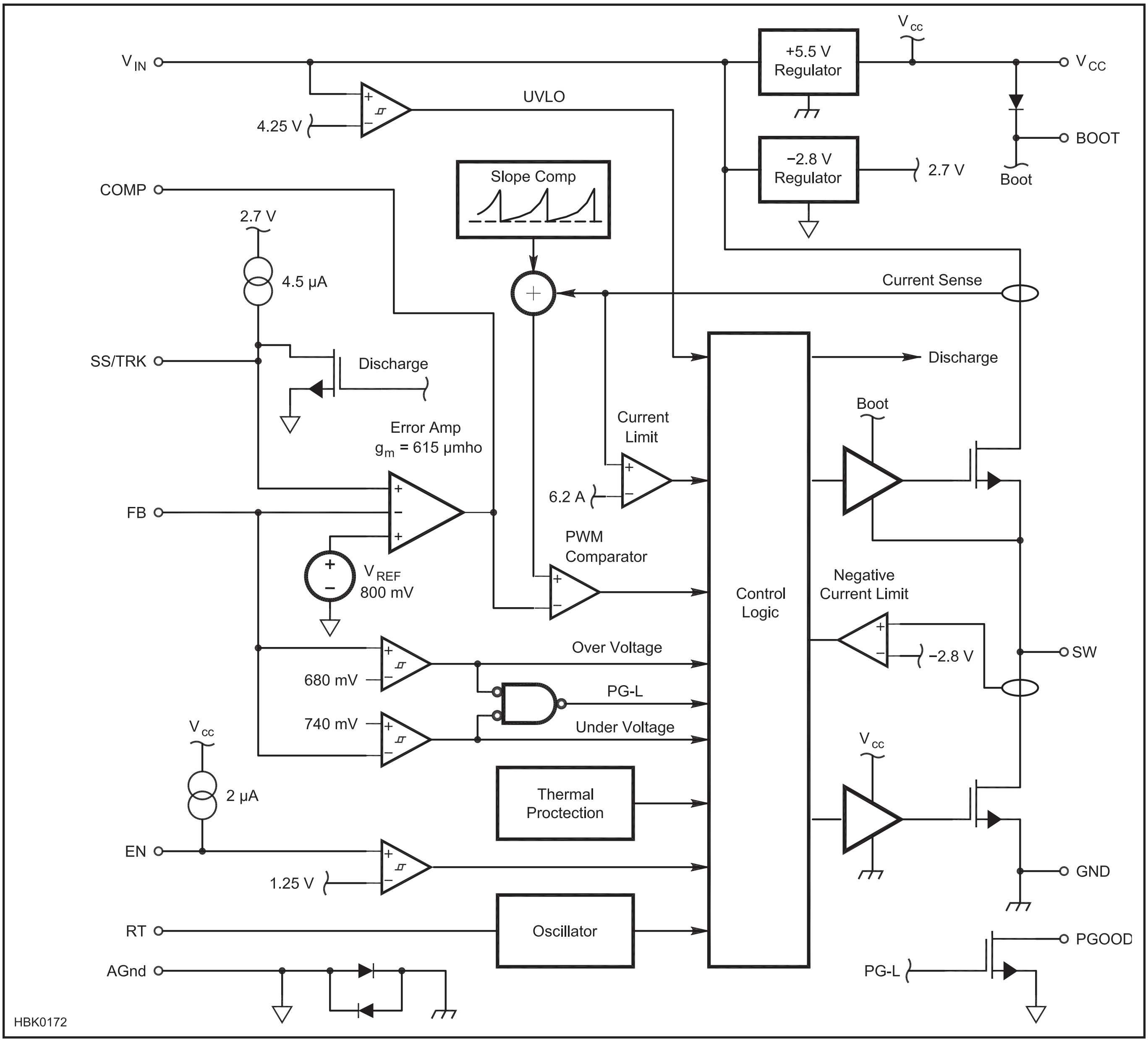


Fig 7.42 — Internal block diagram for the LM20343.

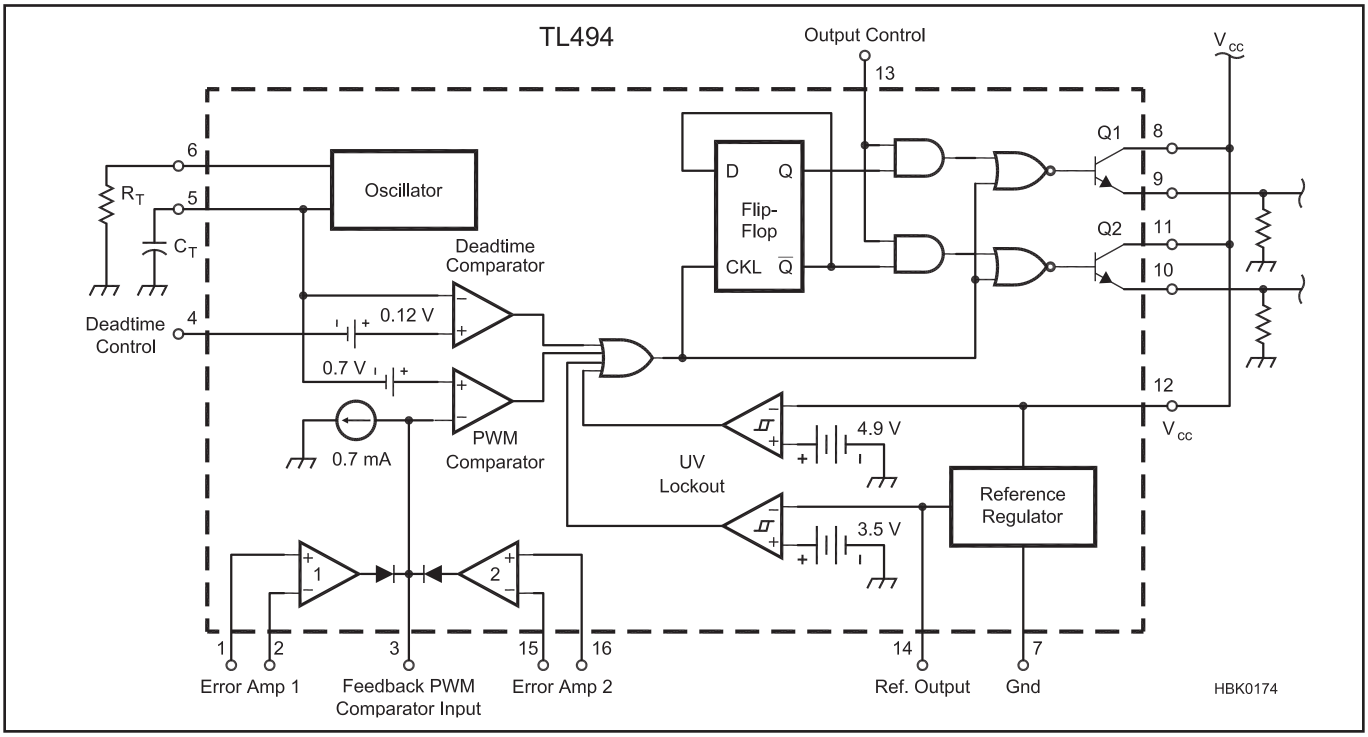


Fig 7.43 — Internal block diagram representation for the TL494.

control functions *and* the power switch. In some cases a power diode is also included. **Fig 7.41** gives an example of one of these ICs. Similar ICs are made by many different manufacturers.

The IC provides most of the components for a buck converter but some external components are still needed: filter capacitors (C_{IN}, C_{OUT}, C_{VCC}), the output inductor (L), output voltage sensing (R_{FB1} and R_{FB2}) and components to set the switching frequency (R_{C1} and C_{C1}). The shunt diode (D1) is marked as optional because there is an internal switch that can perform this function for lower powers.

Fig 7.42 and **Fig 7.43** show the internal block-diagram of typical voltage regulator control ICs. (See the manufacturer data sheets for application information and reference designs.) In addition to the control functions there are also some protective functions such as input under- and overvoltage protection, over-temperature (thermal) protection, overcurrent limiting and slow-starting (slowly ramping up D) to limit inrush current at turn-on. ICs similar to this one are available for boost, buck-boost and flyback converters, as well as many other topologies. There are also ICs available that implement more complex control schemes such as current mode control and feed-forward compensation.

7.11.7 Switchmode Control Loop Issues

We do not have the space in this book to explain all the control issues associated with switchmode converters, but it is important to recognize that designing stable, high performance control loops for switchmode converters is a much more complex task than it would be for a series pass-regulator or an audio amplifier. All we can do here is to alert the reader to some of the issues and suggest consulting Reference 2 with detailed explanations and examples. In addition, there are numerous books and applications notes on switchmode converter design that go into the necessary detail.

The complexities arise from the inherent behavior of switchmode circuits. This behavior is often non-intuitive and sometimes even bizarre. As we've seen already, the dc behavior differs dramatically between CCM and DCM modes of operation. This difference is even more pronounced in the small-signal control-to-output characteristics. It is very common to see poles and zeros in the control system's response (see the **Analog Basics** chapter) that move with input voltage, duty cycle and/or load. Fixed double-poles can change to moving single-poles. Moving right-half-plane zeros (this is a zero with decreasing phase-shift instead of increasing phase-shift with frequency) are inherent in CCM operation of boost and buck-boost circuits and their derivatives. There can also be large signal instabilities such as oscillations at sub-harmonics of the switching frequency and occasionally chaotic response to large load current or line voltage changes.

This is not intended to discourage readers from working with switchmode converters, but to simply alert them in advance to some of the difficulties. Once a basic understanding is achieved, the design of switchmode converters can be very interesting and rewarding.

Switchmode Converter Design Aids

Today, there are hundreds of ICs on the market, from dozens of manufacturers, aimed at controlling the power conversion process. These devices have grown from their simplest forms when introduced over 20 years ago to include a long list of ancillary functions aimed at reducing the supporting circuitry and enhancing the quality and efficiency of the power conversion process. As a result, the task of designing these ICs into the final power conversion circuit has actually become more complex. To the circuit designer who is below the expert level, the task can seem daunting, indeed.

In answer to this problem, many IC manufacturers provide computer-aided design tools that greatly simplify the task of using their products. These tools take several forms, from the most rudimentary cookbook-style guides, to full-fledged circuit simulation tools like *SPICE*. The purpose of these tools is to help the designer pick appropriate resistors, capacitors and magnetic components for the design, and also to estimate the stresses on the power-handling components.

These design tools fall generally into two types: equation-based design tools and iterative circuit simulators. The differences are that the equation-based tools simply automate the basic design equations of the circuit, providing recommended choices for the components and then solving equations to compute the voltage, current and power stresses on the components. In some cases, thermal analysis is also included.

The simulators, on the other hand, use detailed mathematical models for the components and provide both dc and ac simulation of the circuits. This allows the user to see the dynamic behavior of the circuit. The simulation includes details during the switching intervals and shows rise times, parasitic effects caused by component capacitance, internal resistance and other characteristics.

In modern power converter design, the magnetic components — transformers, power inductors and filter inductors — can be a challenge to the designer not versed in magnetic design. As a result, the vendors of these parts usually furnish design tools created specifically to the design of these components and/or the proper choice of off-the-shelf versions.

The reader is encouraged to explore design aids available from the websites of manufacturers (**Table 7.A1**). The following is far from complete, but should give the reader valuable insight into the vast array of available tools. Remember also that manufacturers of passive components such as capacitors, resistors, heat sinks and thermal hardware may also have helpful and informative design aids on their websites. — *Chuck Mullett, KR6R*

Table 7.A1
Switchmode Converter Design Aids

Vendor	*Main Web Site*	*Design Tools*
Fairchild Semiconductor	**www.fairchildsemi.com**	From the home page, select “Design Center”
Infineon	**www.infineon.com**	From the home page Search window, select “Website” and “Search Technical Documents”, then select “Power Management IC’s” from the pull-down menu. From the subsequent list, select “Application Notes”
International Rectifier	**www.irf.com/indexsw.html**	**www.irf.com/design-center/mypower/**
Intersil	**www.intersil.com**	**www.intersil.com/design/**
National Semiconductor	**www.national.com/analog**	**www.national.com/analog/power/simple_switcher**
ON Semiconductor	**www.onsemi.com**	**onsemi.com/PowerSolutions/supportDoc.do?type=tools**
Texas Instruments	**www.power.ti.com**	From the Power Management page, click “Tools and Software”
Linear Technology Corp	**www.linear.com**	Search for “LTSpice” in the home page window to access the simulation tools page.

7.12 High-Voltage Techniques

The construction of high-voltage supplies requires special considerations in addition to the normal design and construction practices used for lower-voltage supplies. In general, the builder needs to remember that physical spacing between leads, connections, parts and the chassis must be sufficient to prevent arcing. Also, the series connection of components such as capacitor and resistor strings needs to be done with consideration for the distribution of voltage stresses across the components. High-voltages can constitute a safety hazard and great care must be taken to limit physical access to components and wiring while high potentials are present.

7.12.1 High-Voltage Capacitors

For reasons of economy and availability, electrolytic capacitors are frequently used for output filter capacitors. Because these capacitors have relatively low voltage ratings (<600 V), in HV applications it will usually be necessary to connect them in series strings to form an equivalent capacitor with the capability to withstand the higher applied voltage. Electrolytic capacitors have relatively high leakage currents (low leakage resistance) especially at higher temperatures.

To keep the voltages across the capacitors in the series string relatively constant, equal-value bypassing resistors are connected across each capacitor. These *equalizing resistors* should have a value low enough to equalize differences in capacitor leakage resistance between the capacitors, while high enough not to dissipate excessive power. Also, capacitor bodies need to be insulated from the chassis and from each other by mounting them on insulating panels, thereby preventing arcing to the chassis or other capacitors in the string. The insulated mounting for the capacitors is often plastic or other insulating material in board form. A typical example from a commercial amplifier that implements some the guidelines given in this section is shown in **Fig 7.44**.

Equalizing resistors are needed because of differences in dc leakage current between different capacitors in the series string. The data sheet for an electrolytic capacitor will usually give the dc leakage current at 20 °C in the form of an equation. For example:

$$I_{leakage} = 3\sqrt{CV} \qquad (14)$$

where
 C = the value in µF
 V = the working voltage
 $I_{leakage}$ = leakage current in µA.

Keep in mind that the leakage current will increase as the capacitor temperature rises above 20 °C. A value of 3 to 4 times the 20 °C value would not be unusual because of normal heating.

We can use an approximation which includes allowance for heating to determine the maximum value of the divider resistors:

$$R \le \frac{V_r - V_m}{I_{leakage}} \qquad (15)$$

where
 V_r = the voltage rating of the capacitor
 V_m = the voltage across the capacitor during normal operation.

A typical 3000 V power supply might use eight 330 µF, 450 V capacitors in series. In that case, V_r = 450 V, V_m = 375 V and $I_{leakage}$ = 1.06 mA. This would make R = 68 kΩ (standard value) or a total of 544 kΩ for the resistor string. With 3000 V across the resistor string, the total power dissipation would be 16.5 W or about 2.06 W per resistor. To be conservative you should use resistors rated for at least 4 W each.

The equalizing resistors may dissipate significant power and become quite warm. It is important that these resistors do not heat the capacitors they are associated with, as this will increase the capacitor leakage current. You also have to be careful that the heat from the resistors is not trapped under the plastic support panels. The best practice is to place the resistors above the capacitors and their mounting structure allowing the heat to rise unobstructed as shown in Fig 7.44.

OIL-FILLED CAPACITORS

For high voltages, oil-filled paper-dielectric capacitors are superior to electrolytics because they have lower internal impedance at high frequencies, higher leakage resistance and are available with much higher working voltages. These capacitors are available with values of several microfarads and have working voltage ratings of thousands of volts. On the other hand, they can be expensive, heavy and bulky.

Oil-filled capacitors are frequently offered for sale at flea markets at attractive prices. One caution: It is best to avoid older oil-filled capacitors because they may contain polychlorinated biphenyls (PCBs), a known cancer-causing agent. Newer capacitors have eliminated PCBs and have a notice on the case to that effect. Older oil-filled capacitors should be examined carefully for any

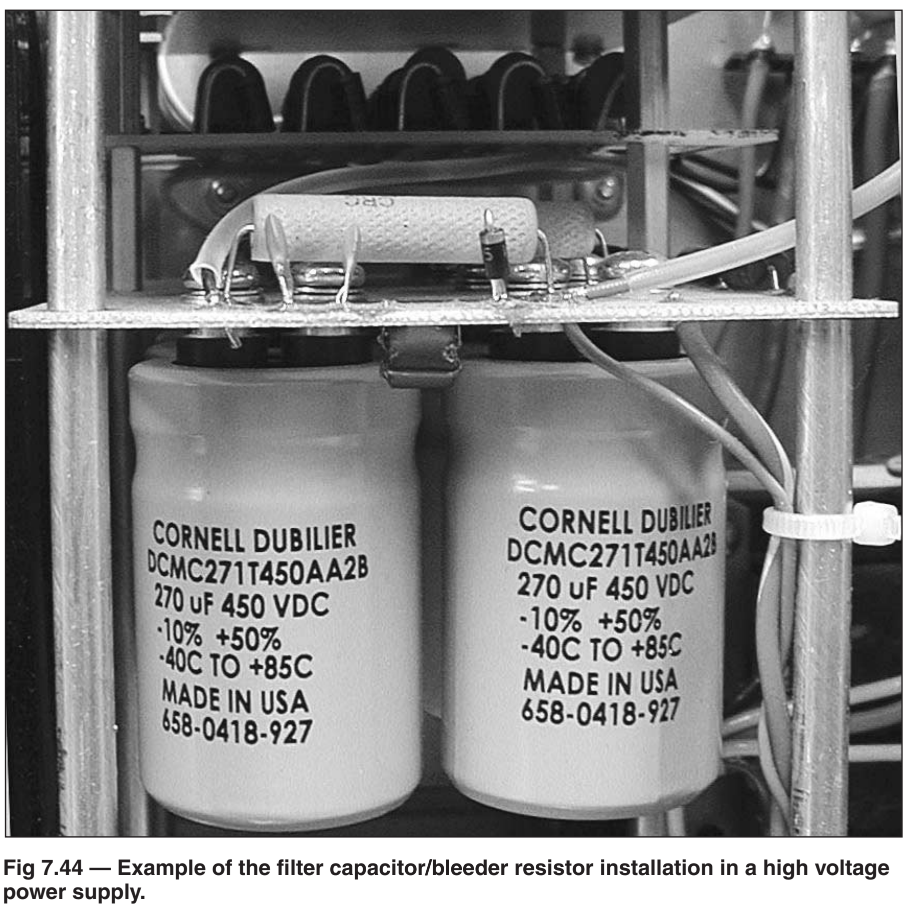


Fig 7.44 — Example of the filter capacitor/bleeder resistor installation in a high voltage power supply.

signs of leakage. Contact with leaking oil should be avoided, with careful washing of the hands after handling. Do not dispose of any oil-filled capacitors with household trash, particularly older units. Contact your local recycling agency for information about how to dispose of them properly.

7.12.2 High-Voltage Bleeder Resistors

Bleeder resistors across the output are used to discharge the stored energy in the filter capacitors when the power supply is turned off and should be given careful consideration. These resistors provide protection against shock when the power supply is turned off and dangerous wiring is exposed. A general rule is that the bleeder should be designed to reduce the output voltage to 30 V or less within 30 seconds of turning off the power supply.

Take care to ensure that the maximum voltage rating of the resistor is not exceeded. In a typical divider string, the resistor values are high enough that the voltage across the resistor is not dissipation limited. The voltage limit is typically related to the insulation intrinsic to the resistor. Resistor maximum voltage ratings are usually given in the manufacturer's data sheet and can be found online. Two major resistor manufacturers are Ohmite Electronics (**www.ohmite.com)** and Stackpole Electronics (**www.seielect.com**).

A 2 W carbon composition resistor will have a maximum voltage rating of 500 V. As a rough estimate, larger wire-wound power resistors are typically rated at 500 V_{RMS} per inch of length — but check with the manufacturer to be sure.

The bleeder will consist of several resistors in series. Typically wire-wound power resistors are used for this application. One additional recommendation is that two separate (redundant) bleeder strings be used, to provide safety in the event one of the strings fails. When electrolytic capacitors are used, the equalizing resistors can also serve as the bleeder resistor but they should be redundant. Again, give careful attention to keeping the heat from the resistors away from the capacitors as shown in Fig 7.44.

In the example given above for calculating the equalizing resistor value, eight 330 μF capacitors in series created the equivalent of a 41 μF capacitor with a 3000 V rating. The total resistance across the capacitors was 8×63 kΩ = 504 kΩ. This gives us a time constant (R × C) of about $R \times C \approx 21$ seconds. To discharge the capacitors to 30 V from 3000 V would take about four time constants (about 84 seconds) which is well over a minute. To get the discharge time down to 30 seconds would require reducing the equalizing resistors to 25 kΩ each. The bleeder power dissipation would then be:

$$P = \frac{V^2}{R} = \frac{3000^2}{200,000} = 45 \text{ W} \qquad (16)$$

For a 2 or 3 kV power supply, this is a reasonable value but it is still a significant amount of power and you need to make sure the resulting heat is properly managed.

7.12.3 High-Voltage Metering Techniques

Special considerations should be observed for metering of high-voltage supplies, such as the plate supplies for linear amplifiers. This is to provide safety to both personnel and to the meters themselves.

To monitor the current, it is customary to place the ammeter in the supply return (ground) line. This ensures that both meter terminals are close to ground potential. Placing the meter in the positive output line creates a hazard because the voltage on each meter terminal would be near the full high-voltage potential. Also, there is the strong possibility that an arc could occur between the wiring and coils inside the meter and the chassis of the amplifier or power supply itself. This hazardous potential cannot exist with the meter in the negative leg.

Another good safety practice is to place a low-voltage Zener diode across the terminals of the ammeter. This will bypass the meter in the event of an internal open circuit in the meter. A 1 W Zener diode will suffice since the current in the metering circuit is low.

The chapter on **RF Power Amplifiers** contains examples of how to perform current and voltage metering in high voltage supplies and amplifiers. In the past, amplifier articles have shown the meters mounted on plastic boards with stand-off insulators behind a plastic window in the amplifier or power supply front panel. While this can work it is not considered good practice today. It is usually possible to arrange the metering so that the meters are close to ground potential and may be safely mounted on the front panel of either the amplifier or the power supply.

For metering of high voltage, the builder should remember that resistors to be used in multiplier strings will often have voltage-breakdown ratings well below the total voltage being sampled. Usually, several identical series resistors will be used to reduce voltage stress across individual resistors. A basic rule of thumb is that these resistors should be limited to a maximum of 200 V, unless rated otherwise. For example, in a 2000 V power supply, the voltmeter multiplier should have a string of 10 resistors connected in series to distribute the voltage equally. The comments on resistor voltage rating in the sections on capacitor equalization and bleeder resistors apply to this case, as well.

7.12.4 High-Voltage Transformers and Inductors

Usable transformers and filter inductors can often be found at amateur flea markets but frequently these are very old units, often dating from WWII. The hermetically-sealed military components are likely to still be good, especially if they have not been used. Open-frame units, with insulation that has been directly exposed to the atmosphere and moisture for long periods of time, should be considered suspect. These units can be checked by running what is called a "hipot test" (high potential test). This involves a low current, variable output voltage power supply with a high-value resistor in series with the output. Unfortunately this equipment is seldom available to amateurs. Some motor repair shops will have an insulation tester called a "Megger" and may be willing to perform an insulation test on a transformer or inductor for you. This is not a completely definitive test but will certainly detect any gross problems with the insulation.

An alternative would be to perform the transformer tests discussed earlier with a variable autotransformer on the ac input. Slowly increase the input voltage until full line voltage is reached and let the transformer run for an hour or two while watching to see if there are any signs of failure. Doing this test in a dark room makes it easier to see any visible corona discharge, another sign of insulation problems. Because the transformer terminals will be at full voltage great care should be taken to avoid contact with the HV terminals. Some form of transparent insulating shield for the test setup is necessary.

7.12.5 Construction Techniques for High-Voltage Supplies

Layout and component arrangement in HV supplies requires some additional care beyond those for lower voltage projects. The photographs in the **RF Power Amplifiers** chapter are a good start, but there are some points which may not be obvious from the pictures.

SHARP EDGES

Sharp points, board edges and/or hardware with ragged edges can lead to localized intensification of the electric field's strength, resulting in a possible breakdown. One common offender is the component leads on the soldered side of a printed-circuit board. These are usually soldered and then cut off leaving a small but often very sharp point. The best way to handle this is to cut the lead as close to the board as practical and form a small solder ball or mound around the cutoff lead end. An example of these suggestions is given in **Fig 7.45**. The protruding component wire

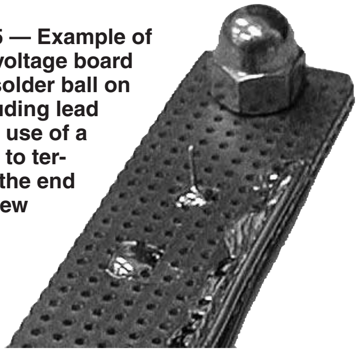


Fig 7.45 — Example of a high voltage board with a solder ball on a protruding lead and the use of a cap nut to terminate the end of a screw thread.

near the top would have a high field gradient. Below that we see a wire cut short with a rounded mound of solder covering the end of the wire.

The ends of bolts with sharp threads often protrude beyond the associated nut. One way to eliminate this is to use the dome-style nuts (cap nuts) that capture the end of the bolt or screw, forming a nicely rounded surface. An example of a cap nut is shown in Fig 7.45.

Sheet metal screws, with their needle-sharp ends, should be avoided if possible. Sheet metal screws used to close metal housings at high potential should have the screw tips inside the enclosure, which would be normal in most cases. You must also be careful of the tips of sheet metal screws that protrude on the inside of an outer enclosure. If these are in proximity to circuits at high potential, they can also lead to arcing. Keeping sheet metal screw tips well away from high voltage circuitry is the best defense.

Small pieces of sheet metal that may be part of a structure at high potential should have their edges rounded off with a file. Copper traces near the edges of circuit boards do not benefit from rounding, however. In fact, filing may make the edge sharper, ragged and more prone to breakdown. In critical areas, a small solid round wire can be soldered to the edges of a copper trace to form a rounded edge as illustrated at the right side of Fig 7.45.

INSULATORS

Some portions of the circuit may be mounted on insulators or plastic sheets. A new, clean insulator should easily withstand 10 kV per inch without creepage or breakdown across the insulating surface, but over time that surface will accumulate dirt and dust. Reducing the high-voltage stress across insulators to 5 kV per inch would be more conservative.

In theory the spacing between two smooth surfaces across an air gap can be much smaller, perhaps 20 to 30 kV per inch or even higher. But given the uncertainties of layout and voltage gradients around hardware, wiring, components and board edges, sticking with 5 kV per inch is good idea even for air gaps. This separation will seldom cause construction layout problems unless you are trying to build a very compact unit.

FUSES

Sometimes a fuse will be placed in series with a high voltage output to provide protection in case of load arcing. These fuses pose special problems. When a fuse blows, the fuse element will at least melt and perhaps even vaporize. There may be an interval when most, if not all, the output voltage appears across the fuse but the fuse has not stopped conducting. That is, there can be a sustained arc in the fuse.

Fuses have voltage ratings that are the maximum voltages across the fuse for which the arc can be expected to quench quickly. The standard 0.25 × 1.25 inch fuses used in the input ac line are typically rated for 250 V. While no doubt these ratings are conservative, this type of fuse cannot be expected to reliably clear an arc with 2 to 3 kV across the fuse and should not be used in series with a high-voltage output.

Your first choice for HV fuses should be the recommended part specified by the power supply manufacturer. If those are unavailable or you are building the supply yourself, fuses for microwave oven transformer secondary use are often suitable. Do not substitute lower-voltage fuses or fuse holders not rated for HV service. When working on a HV power supply with the fuse visible and uncovered, be sure to wear safety glasses as the fuse may explode during a high-current overload, scattering shards of glass or ceramic at high speed.

7.12.6 High-Voltage Safety Considerations

The voltages present in HV power supplies are potentially lethal. Every effort must be made to restrict physical access to any high potentials. A number of steps can be taken:

1) Build the power supply within a closed box, preferably a metal one.

2) Install interlocks on removable panels used for access to the interior. An interlock is usually a normally-open microswitch in series with the input power line. The microswitch is

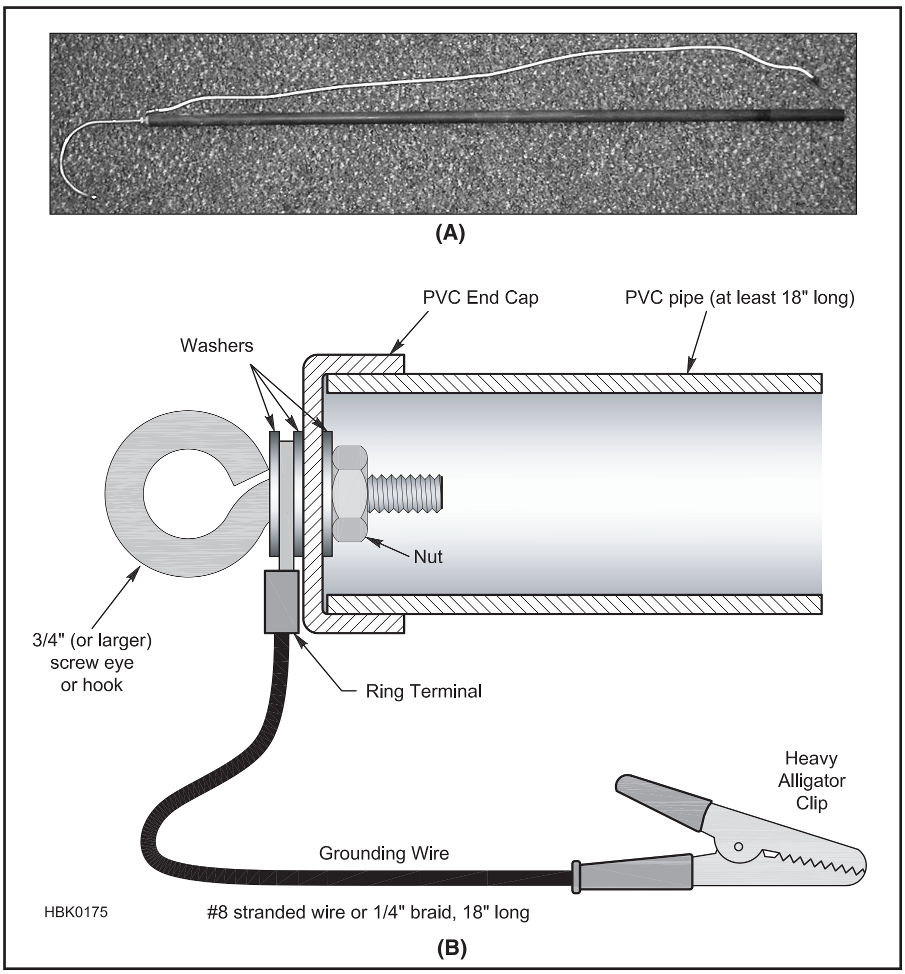


Fig 7.46 — Example of a grounding stick or hook to discharge capacitor energy safely. The end of the wire is connected to ground and the hook is touched to the capacitor terminals to discharge them. A diagram showing how to construct a grounding stick is shown at B.

positioned so that it can be closed only when the overlying panel has been secured in place. When the panel is removed the switch moves to the open position, removing power from the supply.

3) As noted previously, the use of a bleeder resistor to rapidly discharge the capacitors is mandatory.

4) To further protect the operator when accessing the inside of a high-voltage power supply, a grounding hook like that shown in **Fig 7.46A** should be used to positively discharge each capacitor by touching the hook to each capacitor terminal. The hook is connected to the chassis via the wire shown and held by the insulated handle. It is normal practice to leave the hook in place across the capacitors while the supply is being worked on, just in case primary power is inadvertently applied. When the work is finished, remove the hook and replace the covers on the power supply.

Fig 7.46B shows how to construct a grounding stick of your own. A large screw eye or hook is substituted for the hook. It is important that the grounding wire be left *outside* the handle so that any hazardous voltages or currents will not be present near your hand or body.

7.13 Batteries

A battery is a group of individual *cells*, usually series-connected to give some desired multiple of the *cell voltage*. The cell voltage is usually in the range of 1 to 4 V. Each chemical system used in the cell gives a particular nominal voltage that will vary with temperature and state of charge. This must be taken into account to make up a particular battery voltage. For example, four 1.5 V carbon-zinc cells make a 6 V battery and six 2 V lead-acid cells make a 12 V battery. **Table 7.1** lists the dimensions of commonly used batteries.

The following sections on battery types and usage consist primarily of excerpts from *Batteries in a Portable World* by Isidor Buchmann, CEO of Cadex Electronics (**www.cadex.com**), a leading manufacturer of battery charging and related equipment. The ARRL appreciates having been given permission to use this material. The book discusses the issues summarized here (and many others) in detail. The reader is directed to the original text for more complete information. This summary is intended to present and compare the various options commonly used by amateurs. Additional information and an extensive battery glossary is provided online at **www.batteryuniversity.com**.

Batteries are divided into two categories: *primary* (non-rechargeable) and *secondary* (rechargeable). Secondary batteries are expected to account for more than 80% of global battery use by 2015. The most common types of battery chemistry are lithium, lead and nickel-based systems.

Batteries store energy well and for a considerable length of time. Primary batteries hold more energy than secondary, and their *self-discharge* is lower. Alkaline cells are good for 10 years with minimal losses. Lead, nickel and lithium-based batteries need periodic recharges to compensate for lost power. **Fig 7.47** illustrates the energy and power densities of lead acid, nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and the lithium-ion family (Li-ion).

Rather than giving batteries unique names by type, they are broadly distinguished by the following characteristics:

Battery Safety

In addition to the precautions given for each type of battery, the following precautions apply to all battery types. Always follow the manufacturer's advice! Extensive application information can found on manufacturer's websites.

Hydrogen gas escaping from storage batteries can be explosive. Keep flames or any kind of burning material away, including cigarettes, cigars, pipes and so on. Use and charge batteries in well-ventilated areas to prevent hydrogen gas from building up.

No battery should be subjected to unnecessary heat, vibration or physical shock. The battery should be kept clean. Frequent inspection for leaks is a good idea. Electrolyte that has leaked or sprayed from the battery should be cleaned from all surfaces. The electrolyte is chemically active and electrically conductive, and may ruin electrical equipment. Acid may be neutralized with sodium bicarbonate (baking soda), and alkalis (found in NiCd batteries) may be neutralized with a weak acid such as vinegar. Both neutralizers will dissolve in water and should be quickly washed off. Do not let any of the neutralizer enter the battery.

Keep a record of the battery use, and include the last output voltage and, for lead-acid storage batteries, the hydrometer reading. This allows prediction of useful charge remaining, and the recharging or procuring of extra batteries, thus minimizing failure of battery power during an excursion or emergency.

Batteries can contain a number of hazardous materials such as lead, cadmium, mercury or acid, and some thought is needed for their disposal at the end of useful life. Municipal and county waste disposal sites and recycling centers will usually accept lead acid batteries because they can readily be recycled. Other types of batteries are typically not recycled and should be treated as hazardous waste. Most disposal sites and recycling centers will have occasional special programs for accepting household hazardous waste. Hardware and electronic stores may have battery recycling programs, as well. Take advantage of them.

Table 7.1
Dimensions of Common Standard Cells

Size	*Dimensions*	*Notes*
D	34 × 61 mm	
C	25.5 × 50 mm	
A	17 × 50 mm	Only available for NiCd; also available in half-length size
AA	14.5 × 50 mm	
AAA	10.5 × 44.5 mm	
AAAA	8.3 × 42.5 mm	Typical size of cell making up 9 V batteries
N	12 × 32 mm	
9 V	48.5 × 26.5 × 17.5 mm	Contains six AAAA cells in series, snap terminals
18650	18 × 65 mm	Commonly used in lithium-ion battery packs
Lantern	115 × 68.2 × 68.2	Spring terminals
CR2016	20 × 1.6 mm	Coin cell
CR2025	20 × 2.5 mm	Coin cell
CR2032	20 × 3.2 mm	Coin cell

Information courtesy of Cadex and from **http://en.wikipedia.org/wiki/List_of_battery_sizes**

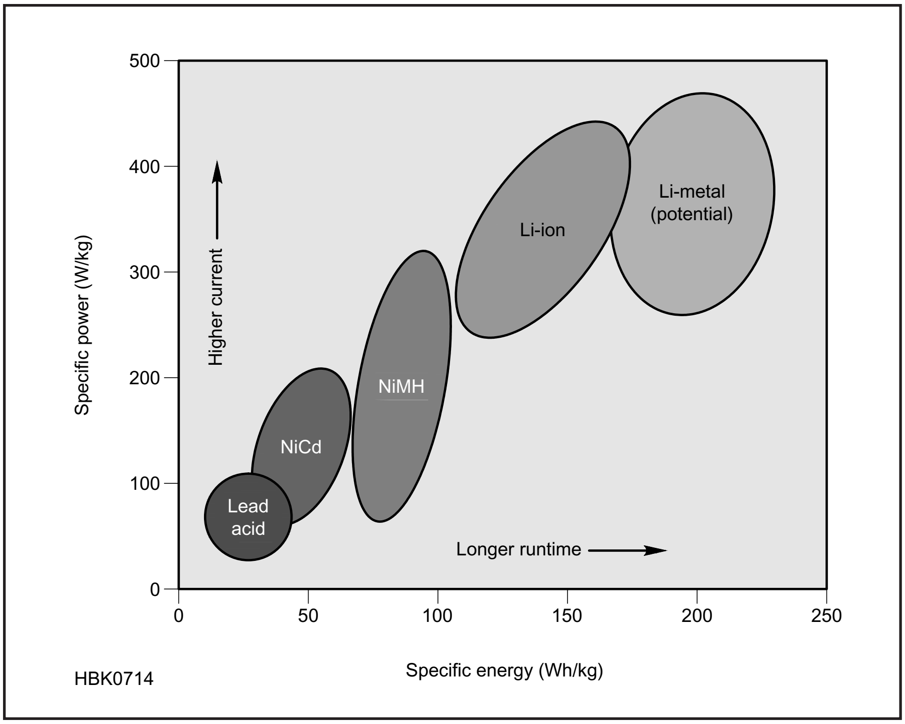


Fig 7.47 — Specific energy and specific power of rechargeable batteries. (Courtesy of Cadex)

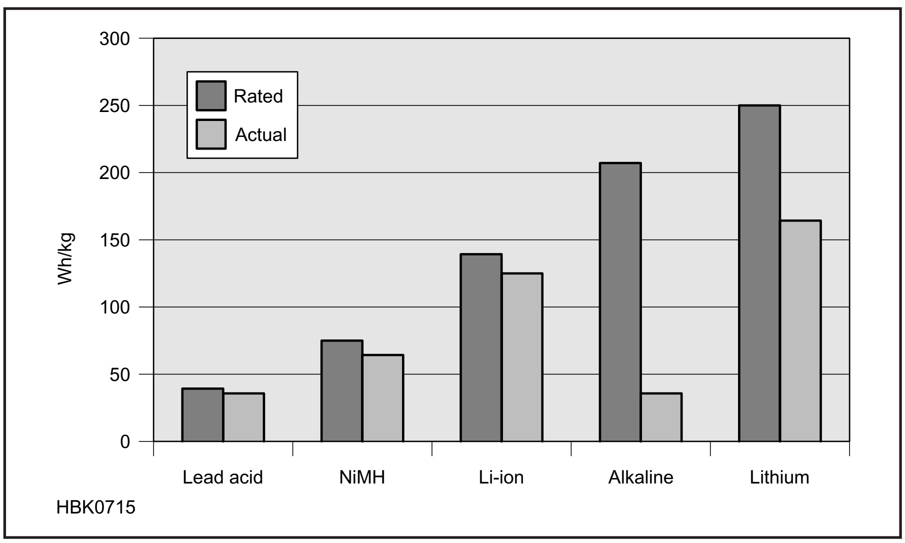


Fig 7.48 — Energy comparison of different battery types at a load of 1 C. (Courtesy of Cadex)

Table 7.2
Alkaline Specifications of Standard Batteries at Low Load

Battery Type	*Nominal Voltage (V)*	*Rated Capacity (mAh)*	*Voltage Cutoff (V)*	*Rated Load (Ω)*	*Discharge C-rate*
9 V	9	570	4.8	620	0.025
AAA	1.5	1150	0.8	75	0.017
AA	1.5	2870	0.8	75	0.007
C	1.5	7800	0.8	39	0.005
D	1.5	17,000	0.8	39	0.0022

(Table courtesy of Cadex)

Chemistry — the families of chemicals used to make the battery. The most common chemistries are lead, nickel and lithium.

Voltage — the nominal open circuit voltage (OCV), which varies with chemistry and the number of cells connected in series.

Size — standard sizes of batteries or cells, such as AAA, AA, C and D.

Capacity (C) — the specific energy in ampere-hours (Ah).

Cold Cranking Amps (CCA) — a starter battery's ability to supply high load current at –18° C (0° F) as specified by the vehicle standard SAE J357.

Specific energy — battery capacity in watt-hours per kilogram (Wh/kg)

Specific power — indicates the loading capability or the amount of current the battery can provide in watts/kilogram (W/kg)

C-rate — charge and discharge rate specified in units of C (capacity). At 1 C, the battery charges or discharges at a current numerically equal to its Ah rating. For example, a 2000 mAh battery discharging at 1 C is supplying a current of 2 A. At 0.5 C, the current would be 1 A, and so forth.

Load — whatever draws energy from the battery. Internal battery resistance and depleting the battery's state of charge cause the voltage to drop.

Primary batteries have one of the highest energy densities. One of the most common primary batteries is the *alkaline-manganese*, or alkaline battery. The *carbon-zinc* or *Leclanché battery* is less expensive but holds less energy than the alkaline battery. Although secondary batteries have improved, a regular household alkaline cell provides 50% more energy than lithium-ion.

Primary batteries tend to have high internal resistance, which limits the discharge to light loads. This reduces the battery's specific power, even though its specific energy may be quite high. Non-rechargeable lithium metal and alkaline batteries are commonly used in low power applications such as clocks, meter LCDs, keyers and so forth.

Manufacturers of primary batteries specify specific energy at a small fraction of C and the batteries are allowed to discharge to a very low voltage of 0.8 volts per cell. **Fig 7.48** compares primary and secondary batteries discharged at a rate of 1 C. The primary (alkaline and lithium) batteries are unable to deliver their rated specific energy at heavy loads. **Table 7.2** gives typical specifications for alkaline batteries at light loads, such as operating a handheld radio during receive.

If recharging is available, using primary batteries can be expensive — about thirty-fold higher than for secondary batteries. Amateurs using batteries in the field, particularly for emergency communications, may want to maintain the ability to use primary batteries for times when recharging for secondary batteries is not available.

7.13.1 Choices of Secondary Batteries

The following discussion examines today's most popular secondary battery systems according to specific energy, years of service life, load characteristics, safety, price, self-discharge, environmental issues, maintenance and disposal. **Table 7.3** compares the characteristics of four commonly used rechargeable battery systems showing average performance rating at the time of publication in 2013.

The lithium-ion family is divided into three major battery types, so named by their cathode oxides, which are cobalt, manganese and phosphate. The characteristics of these Li-ion systems are as follows:

Lithium-ion-cobalt or **lithium-cobalt** ($LiCoO_2$) — Has high specific energy with moderate load capabilities and modest service life.

Lithium-ion-manganese or **lithium-manganese** ($LiMn_2O_4$) — Is capable of high charge and discharge currents but has low specific energy and modest service life.

Lithium-ion-phosphate or **lithium-phosphate** ($LiFePO_4$) — often abbreviated LiPo. Is similar to lithium-manganese; nominal voltage is 3.3 V/cell; offers long cycle life, has a good safety record but exhibits higher self-discharge than other Li-ion systems.

Another type of lithium-ion cell is the

Table 7.3
Characteristics of Commonly Used Rechargeable Batteries

Specification	*Lead Acid*	*NiCd*	*NiMH*	*Li-ion Cobalt*	*Li-ion Manganese*	*Li-ion Phosphate*
Specific energy (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal resistance[1] (mΩ)	<100 12 V pack	100-200 6 V pack	200-300 6 V pack	150-300 7.2 V	25-75[2] per cell	25-50[2] per cell
Cycle life[4] (80% DoD)	200-300	1000[3]	300-500[3]	500-1000	500-1000	1000-2000
Fast-charge time	8-16 h	1 h typical	2-4 h	2-4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge	Low. Cannot tolerate trickle charge.	Low. Cannot tolerate trickle charge.
Self-discharge/month (room temp)	5%	20%[5]	30%[5]	<10%[6]	<10%[6]	<10%[6]
Cell voltage (nominal)	2 V	1.2 V[7]	1.2 V[7]	3.6 V[8]	3.8 V[8]	3.3 V
Peak load current (best result)	5C[9] (0.2 C)	20 C (1 C)	5 C (0.5 C)	>3 C (<1 C)	>30 C (<10 C)	>30 C (<10 C)
Operating temp.[10] (discharge only)	–20 to 60° C	–40 to 60° C	–20 to 60° C	–20 to 60° C	–20 to 60° C	–20 to 60° C
Maintenance requirement	3-6 months[11]	30-60 days	60-90 days	Not required	Not required	Not required
Safety requirements	Thermally stable	Thermally stable, fuse protection common	Thermally stable, fuse protection common	Protection circuit mandatory	Protection circuit mandatory	Protection circuit mandatory
In use since	Late 1800s	1950	1990	1991	1996	2006
Toxicity	Very high	Very high	Low	Low	Low	Low

Table Notes:
[1] Internal resistance of a battery pack varies with milliampere-hour (mAh) rating, wiring and number of cells. Protection circuit of lithium-ion adds about 100 mΩ.
[2] Based on 18650 cell size. Cell size and design determines internal resistance.
[3] Cycle life is based on battery receiving regular maintenance.
[4] Cycle life is based on the depth of discharge (DoD). Shallow DoD improves cycle life.
[5] Self-discharge is highest immediately after charge. NiCd loses 10% in the first 24 hours, then declines to 10% every 30 days. High temperature increases self-discharge.
[6] Internal protection circuits typically consume 3% of the stored energy per month
[7] The traditional voltage is 1.25 V; 1.2 V is more commonly used.
[8] Low internal resistance reduces the voltage drop under load and Li-ion is often rated higher than 3.6 V/cell. Cells marked 3.7 V and 3.8 V are fully compatible with 3.6 V.
[9] Capable of high current pulses; needs time to recuperate.
[10] Applies to discharge only; charge temperature is more confined.
[11] Maintenance may be in the form of equalizing or topping charge to prevent sulfation
(Table courtesy of Cadex)

popular *lithium-ion-polymer* or *Li-polymer*. While Li-ion systems get their name from their unique cathode materials, Li-polymer differs by having a distinct architecture in which a gelled electrolyte replaces the usual porous separator between the anode and cathode. The gelled electrolyte acts as a catalyst to enhance the electrical activity of the other battery materials.

7.13.2 Lead Acid Batteries

Most lead acid batteries used today are *maintenance-free* types in which the liquid electrolyte is sealed inside the battery in liquid or gel form. Two similar types are used: the *sealed lead acid* (SLA) and the *valve-regulated lead acid* (VRLA). SLA batteries have capacities up to about 30 Ah. VRLA batteries are larger and have capacities from 30 Ah to several thousand Ah. **Table 7.4** summarizes the advantages and limitations of lead acid battery systems.

Applying the right voltage limit when charging lead acid systems is critical and will be a compromise between capacity when recharged and maintaining the battery's internal materials. A low charge limit voltage may shelter the battery but this causes poor performance and a buildup of *sulfation* on the negative plate. A high voltage limit improves performance but it promotes irreversible grid corrosion on the positive plate. Temperature also changes the voltage threshold.

Lead acid does not lend itself to fast charging and a fully saturated charge requires 14 to 16 hours. The battery must always be stored at full state-of-charge to avoid sulfation. Lead acid is not subject to memory, but correct charge and float voltages are important to get a long life (see the section on charging below). While NiCd loses approximately 40% of its stored energy in three months, lead acid self-discharges the same amount in one year.

Lead acid batteries are inexpensive on cost-per-watt basis but are less suitable for repeated deep cycling. A full discharge causes strain and each discharge/charge cycle permanently robs the battery of a small amount of capacity. The fading becomes more acute as the battery falls below 80% of its nominal capacity. Depending on the depth of discharge and operating temperature, lead acid for deep-cycle applications provides 200 to 300 discharge/charge cycles.

High temperature reduces the number of available cycles. As a guideline, every 8° C (13° F) rise above the optimum temperature of 25° C (77° F) cuts battery life in half.

Lead acid batteries are rated at a 5-hour (0.2 C) and 20-hour (0.05 C) discharge, and the battery performs best when discharged slowly. Lead acid can deliver high pulse currents of several C if done for only a few seconds, making lead acid well suited as a *starter battery*.

STARTER AND DEEP-CYCLE BATTERIES

The *starter* battery is designed to crank an engine with a momentary high power burst; the *deep-cycle* battery, on the other hand, is built to provide continuous power. The starter battery is made for high peak power and does not tolerate deep cycling well. The deep-cycle battery has a moderate power output but permits cycling.

Starter batteries have a CCA rating in amperes and a very low internal resistance. Deep-cycle batteries are rated in Ah or minutes of runtime. A starter battery cannot be swapped with a deep-cycle battery and vice versa because of their different internal construction. **Table 7.5** compares the typical life of starter and deep-cycle batteries when deep-cycled.

ABSORBENT GLASS MAT (AGM)

AGM is an improved lead acid battery in which the electrolyte is absorbed in a mat of fine glass fibers. This makes the battery spill-proof. AGM has very low internal resistance, is capable of delivering high currents and offers long service even if *occasionally* deep-cycled. It also stands up well to high and low temperatures and has a low self-discharge. AGM has a higher specific power rating for high load currents and allows faster charge times (up to five times faster) than conventional lead acid. AGM has a slightly lower specific energy and higher manufacturing cost.

AGM batteries are sensitive to overcharging. They can be charged to 2.40 V/cell without problems but the float charge should be reduced to 2.25 to 2.30 V/cell and summer temperatures may require lower voltages. Automotive charging systems designed for flooded lead acid often have a fixed float voltage setting of 14.40 V (2.40 V/cell) and a direct replacement with an AGM battery could result in overcharge on a long drive.

Heat can be a problem for AGM and other gelled electrolyte batteries. Manufacturers recommend halting charge if the battery core reaches 49° C (120° F). However, AGM batteries can sit in storage for long periods before a recharge to prevent sulfation becomes necessary.

Table 7.4
Advantages and Limitations of Lead Acid Batteries

Advantages	Inexpensive and simple to manufacture; lowest cost per watt-hour
	Mature and well-understood technology; provides dependable service
	Low self-discharge; lowest among rechargeable batteries
	High specific power, capable of high discharge currents
Limitations	Low specific energy; poor weight-to-energy ratio
	Slow charge; fully saturated charge takes 14 hours
	Must always be stored in charged condition
	Limited cycle life; repeated deep-cycling reduces battery life
	Flooded version requires watering
	Not environmentally friendly
	Transportation restrictions on the flooded type

(Table courtesy of Cadex)

Table 7.5
Cycle Performance of Starter and Deep-Cycle Batteries

Depth of Discharge	*Starter Battery*	*Deep-cycle Battery*
100%	12-15 cycles	150-200 cycles
50%	100-120 cycles	400-500 cycles
30%	130-150 cycles	1000 and more cycles

(Table courtesy of Cadex)

7.13.3 Nickel-based Batteries

NICKEL-CADMIUM (NiCd)

The standard NiCd remains one of the most rugged and forgiving batteries but needs proper care to attain longevity. Nickel-based batteries also have a flat discharge curve that ranges from 1.25 to 1.0 V/cell. **Table 7.6** summarizes the advantages and limitations of NiCd battery systems.

NICKEL-METAL-HYDRIDE (NiMH)

NiMH provides 40% higher specific energy than standard NiCd, but the decisive advantage is the absence of toxic metals. NiMH also has two major advantages over Li-ion: price and safety. NiMH is offered in AA and AAA sizes.

NiMH is not without drawbacks. It has a

Table 7.6

Advantages and Limitations of NiCd Batteries

Advantages	Fast and simple charging even after prolonged storage High number of charge/discharge cycles; provides over 1000 charge/discharge cycles with proper maintenance Good load performance; rugged and forgiving if abused Long shelf life; can be stored in a discharged state Simple storage and transportation; not subject to regulatory control Good low-temperature performance Economically priced; NiCd is the lowest in terms of cost per cycle Available in a wide range of sizes and performance options
Limitations	Relatively low specific energy compared with newer systems Memory effect; needs periodic full discharges Environmentally unfriendly; cadmium is a toxic metal and cannot be disposed of in landfills High self-discharge; needs recharging after storage

(Table courtesy of Cadex)

Table 7.7

Advantages and Limitation of NiMH Batteries

Advantages	30-40% higher capacity than a standard NiCd Less prone to memory than NiCd Simple storage and transportation; not subject to regulatory control Environmentally friendly; contains only mild toxins Nickel content makes recycling profitable
Limitations	Limited service life; deep discharge reduces service life Requires complex charge algorithm Does no absorb overcharge well; trickle charge must be kept low Generates heat during fast-charge and high-load discharge High self-discharge; chemical additives reduce self-discharge at the expense of capacity Performance degrades if stored at elevated temperatures; should be stored in a cool place at about 40% state-of-charge

(Table courtesy of Cadex)

lower specific energy than Li-ion and also has high self-discharge, losing about 20% of its capacity within the first 24 hours, and 10% per month thereafter. New types of NiMH such as the Eneloop from Sanyo, ReCyko by GP and others have reduced the self-discharge by a factor of six, increasing storage life by the same amount at the sacrifice of some capacity. **Table 7.7** summarizes the advantages and limitations of NiMH battery systems.

7.13.4 Lithium-based Batteries

The specific energy of Li-ion is twice that of NiCd and the high nominal cell voltage of 3.60 V as compared to 1.20 V for nickel systems contributes to this gain. The load characteristics are good, and the flat discharge curve offers effective utilization of the stored energy in a desirable voltage spectrum of 3.70 to 2.80 V/cell. Li-ion batteries vary in performance according to the choice of cathode materials. **Table 7.8** presents the characteristics of common Li-ion battery chemistries and **Table 7.9** summarizes the advantages and limitations of lithium-ion battery systems.

Lithium-polymer employs a gelled electrolyte in a micro-porous separator between the anode and cathode. Li-polymer is a construction technique and not a type of battery chemistry, so it can be applied to any of the lithium battery chemistries. Most Li-polymer battery packs are based on Li-cobalt. Charge and discharge characteristics of Li-polymer are identical to other Li-ion systems and this chemistry does not require a special charger.

Fig 7.49 compares the specific energy of lead, nickel and lithium-based systems. While Li-cobalt is the clear winner in terms of higher

Table 7.8

Characteristics of the Four Most Commonly Used Lithium-ion Batteries

Specifications	*Li-cobalt* *$LiCoO_2$ (LCO)*	*Li-manganese* *$LiMn_2O_4$ (LMO)*	*Li-phosphate* *$LiFePO_4$ (LFP)*	*NMC*[1] *$LiNiMnCoO_2$*
Voltage (V)	3.60	3.80	3.30	3.60/3.70
Charge limit (V)	4.20	4.20	3.60	4.20
Cycle life[2]	500-1000	500-1000	1000-2000	1000-2000
Operating temperature	Average	Average	Good	Good
Specific energy (Wh/kg)	150-190	100-135	90-120	140-180
Specific Power (C)	1	10, 40 pulse	35 continuous	10
Safety	Average[3]	Average[3]	Very safe[4]	Safer than Li-cobalt[4]
Thermal runaway[5] (°C/°F)	150/302	250/482	270/518	210/410
Cost	Raw material high	30% less than cobalt	High	High
In use since	1994	1996	1999	2003

Table Notes

[1] NMC (nickel-manganese-cobalt), NCM, CMN, CNM, MNC and MCN are basically the same. The order of Ni, Mn and Co does not matter much

[2] Application and environment govern cycle life; the numbers do not always apply correctly

[3] Requires protection circuit and cell balancing of multi cell pack. Requirements for small formats with 1 or 2 cells can be relaxed

[4] Needs cell balancing and voltage protection

[5] A fully charged battery raises the thermal runaway temperature, a partial charge lowers it

(Table courtesy of Cadex)

Table 7.9
Advantages and Limitations of Li-ion Batteries

Advantages	High specific energy Relatively low self-discharge; less than half that of NiCd and NiMH Low maintenance. No periodic discharge is needed; no memory
Limitations	Requires protection circuit to limit voltage and current Subject to aging, even if not in use (life span is similar to other chemistries) Transportation regulations apply when shipping in larger quantities

(Table courtesy of Cadex)

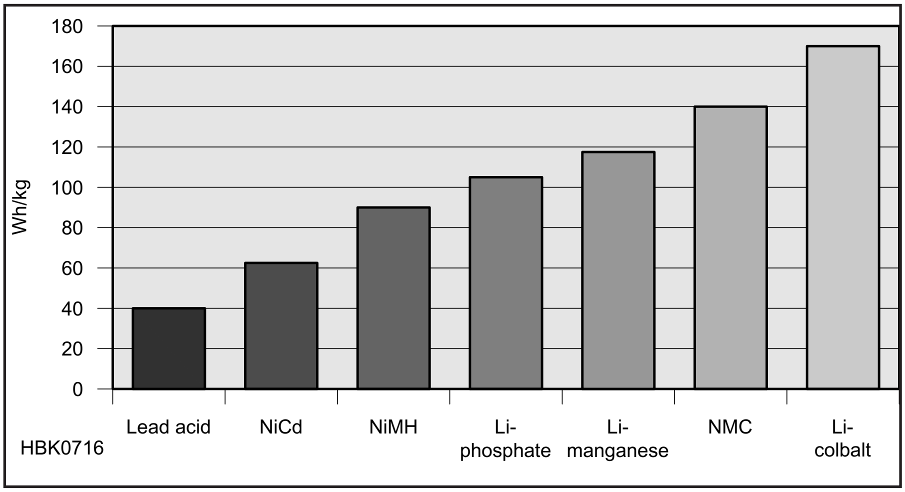


Fig 7.49 — Typical energy densities of lead, nickel- and lithium-based batteries

capacity than other systems, this only applies to specific energy. In terms of specific power and thermal stability, Li-manganese and Li-phosphate are superior.

7.13.5 Charging Methods

The performance and longevity of rechargeable batteries are to a large extent governed by the quality of the charger. Choosing a quality charger is important considering the costs of battery replacement and poor performance.

CHARGERS

This discussion focuses on third-party chargers designed to charge and maintain individual cells or batteries. *Fleet chargers* designed for maintaining many batteries of a common type in a company or agency environment are often provided by the equipment OEM and usually have special features for battery conditioning.

"Smart" chargers include valuable additional features beyond simply applying current to a battery. Temperature protection is particularly important to slow or prevent charging below freezing or above recommended thresholds when the battery is hot. Advanced lead acid chargers adjust the float and trickle charge thresholds based on temperature and battery age. **Table 7.10** summarizes the types of third-party chargers.

There are two common charge methods: voltage limiting (VL) and current limited (CL). Lead and lithium-based chargers cap the voltage at a fixed threshold. When reaching the cutoff voltage, the battery begins to saturate and the current drops while receiving the remaining charge on its own timetable. Full charge detection occurs when the current drops to a designated level.

Nickel-based batteries charge with a controlled current and the voltage is allowed to fluctuate freely. A slight voltage drop after a steady rise indicates a fully charged battery. The voltage drop method works well in terminating a fast charge, but the charger should detect and protect against shorted or mismatched cells. Most chargers include temperature sensors to end the charge if the temperature exceeds a safe level. (Some batteries also have internal temperature sensors.)

A temperature rise is normal as nickel-based batteries approach full charge. When in "ready" mode, the battery must cool down to room temperature. Heat causes stress and prolonged exposure to elevated temperature shortens battery life. Extended trickle charge also inflicts damage on nickel-based batteries, which should not be left in the charger continuously or beyond a few days.

A lithium-based battery should not get warm in a charger, and if this happens either the battery or charger may be faulty. Li-ion chargers do not apply a trickle charge and disconnect the battery electrically when fully charged. If the battery is left in the charger, a recharge may occur when its open circuit voltage drops below a set threshold. It is not necessary to remove Li-ion batteries from a charger.

SIMPLE GUIDELINES WHEN BUYING A CHARGER

• Use the correct charger for battery chemistry. Most chargers service one chemistry only.

• The battery voltage must agree with the charger. Do not charge if different.

• The Ah rating of a battery can be somewhat higher or lower than specified on the charger. A larger battery will take longer to charge than a smaller one and vice versa.

• The higher the amperage of the charger, the shorter the charge time will be, subject to limits on how fast the battery can be charged.

• Accurate charge termination and correct trickle charge prolong battery life.

• When fully saturated, a lead acid charger should switch to a lower voltage; a nickel-based charger should have a trickle charge;

Table 7.10
Charger Characteristics

Type	*Chemistry*	*C-rate (C)*	*Time*	*Charge Termination*
Slow	NiCd, Lead acid	0.1	14 h	Continuous low charge or fixed timer. Subject to overcharge. Remove battery when charged.
Rapid	NiCd, NiMH, Li-ion	0.3-0.5	3-6 h	Senses battery by voltage, current, temperature, and time-out timer
Fast	NiCd, NiMH, Li-ion	1	1+ h	Same as rapid charger with faster service
Ultra-Fast	Li-ion, NiCd, NiMH	1-10	10-60 min	Applies ultra-fast charge to 70% SoC; limited to specialty batteries

All values specified over 0°C to 45°F (32°F to 113°F) range

(Table courtesy of Cadex)

a Li-ion charger provides no trickle charge.

• Chargers should have a temperature override to end charge on a malfunctioning battery.

• Observe the temperature of the charger and battery. Lead acid batteries stay cool during charge; nickel-based batteries elevate the temperature toward the end of charge and should cool down after charge; Li-ion batteries should stay cool throughout charge.

SLOW CHARGERS

This type of charger applies a fixed current of about 0.1 C (one-tenth of the rated capacity) as long as the battery is connected. Slow chargers have no full-charge detection, charge current is always applied, and the charge time for a fully discharged battery is 14 to 16 hours. Most slow chargers have no "ready" indicator.

When fully charged, a slow charger keeps NiCd batteries lukewarm to the touch. Some overcharge is acceptable and the battery does not need to be removed immediately when ready. Leaving the battery in the charger can cause internal crystal growth that leads to "memory effects" in NiCd batteries.

Charging a battery with a lower Ah rating than specified for the charger will cause the battery to heat up as it approaches full charge due to the higher charging rate. Because slow chargers have no provision to lower the current or terminate the charge, the excessive heat will shorten the life of the battery.

The opposite can occur when a slow charger is charging a larger battery than it is rated for. In this case, the battery may never reach full charge and remains cold. Battery performance will be poor because of insufficient charge. Repeated partial charging can also cause crystal growth and memory effects.

RAPID CHARGERS

Falling between a slow and fast charger, the rapid charger is designed for nickel and lithium-based batteries. Unless specially designed, the rapid charger cannot service both types of batteries.

Rapid chargers are designed to charge fully discharged batteries and battery packs in 3 to 6 hours. When full charge is reached, the charger switches to a "ready" state. Most rapid chargers include temperature protection.

FAST CHARGERS

The fast charger typically applies charge at a 1 C rate so that a fully discharged battery is recharged in a little over 1 hour. As the battery approaches full charge, the charger may reduce the charge current (particularly for NiCd), and when the battery is fully charged, the charger switches to a trickle or maintenance charge mode.

Most nickel-based fast chargers accommodate NiCd and NiMH batteries and apply the same charging algorithm, but cannot charge Li-ion batteries. To service a Li-ion pack, specialty dual-mode chargers can read a security code on the battery to switch to the right charger setting.

Lead acid batteries cannot be fast-charged and the term "fast charge" is a misnomer for lead acid chargers. Most lead acid chargers charge the battery in 14 hours; anything slower may be a compromise. Lead acid can be charged relatively quickly to 70% of full charge with the important saturation charge consuming the remaining time. A partial charge at high rate is acceptable provided the battery receives a fully saturated charge once every few weeks to prevent sulfation.

ULTRA-FAST CHARGERS

Large NiCd and Li-ion batteries can be charged at a very high rate (10 C is typical) up to 70% of full charge. Ultra-fast charging stresses batteries. If possible, charge the battery at a more moderate current. An ultra-fast charger should offer user-selectable rates to optimize the charging requirements.

At a rate of 10 C, a battery can be charged in a few minutes but several conditions must be observed:

• The battery must be designed to accept an ultra-fast charge.

• Ultra-fast charging only applies during the first charge phase and charge current must be lowered once the 70% state-of-charge (SoC) threshold is reached.

• All cells in a pack must be balanced and in good condition. Older batteries with high internal resistance will heat up and are no longer suitable for ultra-fast charging.

• Ultra-fast charging can only be done at moderate temperatures. Low temperatures slow the chemical reaction and the unabsorbed energy results in gassing and heat buildup.

• The charge must include temperature compensation and other safety provisions to end the charge if the battery is overly stressed.

CHARGING FROM A USB PORT

The universal serial bus (USB) interface has become ubiquitous on computers and consumer electronics. It is increasingly used on radio equipment. A drawing and pin connections for the USB interface are available in the **Component Data and References** chapter.

USB hubs are specified to provide 5 V and 500 mA of current. (Current can only flow out of a USB interface.) While this would be enough to charge a small Li-ion battery, it could overload the hub if other devices are attached. Many hubs limit the current and will shut down if overloaded, so charging capacity is quite limited.

The most common USB chargers are designed for single-cell Li-ion batteries. The charge begins with a constant current charge to 4.20 V/cell, at which point the voltage levels off and current begins to decrease. Due to voltage drops in the USB cable and charger circuit, the hub may not be able to fully charge the battery. This will not damage a Li-ion battery but it will deliver shorter than expected runtimes.

CHARGING LEAD ACID

Lead acid batteries should be charged in three stages as shown in **Fig 7.50**:

1 — constant-current charge

2 — topping charge

3 — float charge

The constant-current charge applies the bulk of the charge and takes up roughly half of the required charge time. The topping charge continues at a lower charge current and provides saturation. The float charge compensates for the loss caused by self-discharge.

During the constant-current charge the battery charges to 70% SoC in 5 to 8 hours and the remaining 30% is supplied by the slower topping charge that lasts another 7 to 10 hours. The topping charge is essential for the well-being of the battery. If topping charge is not performed, the battery will eventually lose the ability to accept a full charge and performance will decrease because of sulfation. The float charge maintains the battery at full charge.

The switch to topping charge happens when the battery reaches the set voltage limit. Current begins to drop as the battery starts to saturate and full charge is reached when the current decreases to 3% of the rated current. A battery with high leakage may never reach this level and a timer is required to start charging termination.

The correct setting of the charge voltage is critical, ranging from 2.3 to 2.45 V per cell. The threshold is selected as a compromise between charging to maximum capacity and creating internal corrosion and gassing. The battery voltage also shifts with temperature, with warmer temperatures requiring slightly lower voltage thresholds. If variable voltage thresholds are not available in the charger, it is better to use a lower voltage threshold for safety.

Once fully charged through saturation, the battery should not dwell at the *topping voltage* for more than 48 hours and must be reduced to the *float voltage* level. This is especially critical for sealed systems because they are less able to tolerate overcharge than the flooded type due to heating and gas (hydrogen) generation. The recommended float voltage of most lead acid batteries is 2.25 to 2.27 V/cell. Manufacturers recommend lowering the float charge at ambient temperatures above 29° C (85° F). Not all chargers feature float charge. If the charger remains at the topping voltage and does not drop below 2.30 V/cell, remove the charger after a maximum of 48 hours of charge.

Aging batteries develop imbalances between cells that can result in overcharge and

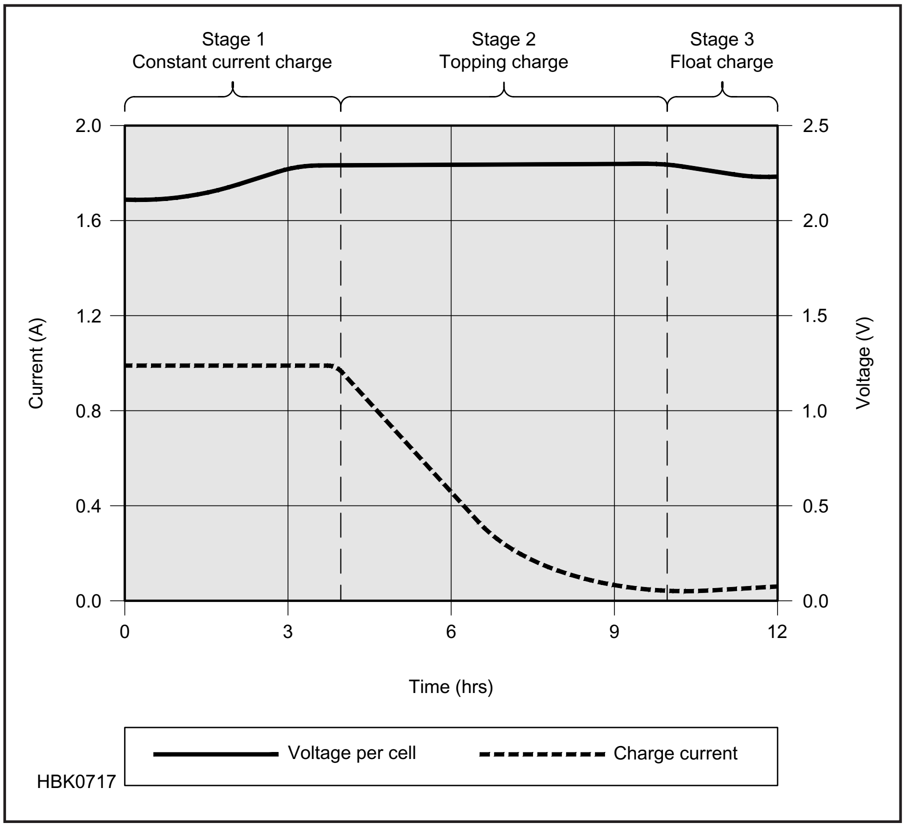


Fig 7.50 — Charge stages of a lead acid battery. The battery is fully charged when the current drops to a pre-determined level or levels out in stage 2. The float voltage must be reduced at full charge. (Courtesy of Cadex)

gassing from weak cells. This can also cause a strong cell to be undercharged and develop sulfation. Some battery manufacturers have developed cell-balancing devices that compensate for cell imbalance.

Lead acid batteries must always be stored in a charged state. A topping charge should be applied every six months to prevent the voltage from dropping below 2.10 V/cell. With AGM, these requirements can be somewhat relaxed.

Measuring the open circuit voltage (OCV) while in storage provides a reliable indication of the battery's state-of-charge (SoC). A voltage of 2.10 V at room temperature indicates a charge of about 90%. (That is equivalent to 12.6 V for a typical six-cell "12 V" lead acid battery.) Such a battery is in good condition and needs only a brief full charge prior to use. If the OCV is lower, the battery must be charged to prevent sulfation. Cool temperatures increase OCV slightly and warm temperatures lower it. Use OCV as an SoC indicator after the battery has rested for a few hours to allow the effects of charging to dissipate.

SIMPLE GUIDELINES FOR CHARGING LEAD ACID BATTERIES

• Charge in a well-ventilated area. Hydrogen gas generated during charging is explosive.

• Choose the appropriate charge program for flooded, gel and AGM batteries. Follow the manufacturer's specifications of voltage thresholds.

• Charge lead acid batteries after each use to prevent sulfation. Do not store on low charge.

• The plates of flooded batteries must always be fully submerged in electrolyte. Fill battery with distilled or de-ionized water to cover the plates if low. Never add electrolyte.

• Fill water level to designed level *after* charging. Overfilling a discharged battery can result in overflow and acid spillage.

• Formation of gas bubbles in a flooded lead acid battery is an indication of approaching full charge.

• Reduce float charge if the ambient temperature is higher than 29° C (85° F).

• Do not allow a lead acid battery to freeze and never charge a frozen battery.

• Do not charge at temperatures above 49° C (120° F).

CHARGING NICKEL-CADMIUM

Battery manufacturers recommend that new NiCd batteries be slow-charged for 16 to 24 hours before use. A slow charge brings all cells in a battery pack to an equal charge level. This is important because each cell within the NiCd battery may have self-discharged at its own rate. Furthermore, during long storage the electrolyte tends to gravitate to the bottom of the cell and the initial trickle charge helps redistribute the electrolyte to eliminate dry spots on the separator. The cells will reach optimal performance after several charge/discharge cycles.

Full-charge Detection by Temperature

Full-charge detection of sealed nickel-based batteries is more complex than for lead acid and lithium-ion systems. Low-cost chargers often use temperature sensing to end the fast-charge, but this can be inaccurate due to internal and external temperature differences. Charger manufacturers use 50° C (122° F) as the temperature cutoff. Although any prolonged temperature above 45° C (113° F) is harmful, brief overshoot is acceptable if temperature will drop quickly when the charger changes to the "ready" state.

Some microprocessor-controlled chargers sense the rate of temperature increase with time, using the rapid temperature rise toward the end of charge to trigger the "ready" state. This is referred to as *delta temperature over delta time* or dV/dt. A rate of 1° C (1.8° F) per minute terminates charging. This keeps the battery cooler, but the cells need to charge reasonably fast for temperature to rise at the required rate. An absolute temperature of 60° C (140° F) terminates charging under any circumstances.

Chargers relying on temperature inflict harmful overcharges when fully charged batteries are inserted into the charger, such as if a hand-held radio is left in the charger between each use. This is not the case with Li-ion batteries where the charger uses voltage as the SoC indicator.

Full-charge Detection by Voltage Signature

Advanced chargers terminate charging when a defined voltage signature or profile with time occurs, referred to as *negative delta V* or NDV. This provides more precise full-charge detection for nickel-based batteries than temperature-based methods. Charging is terminated when the battery voltage drops as full charge is reached. NDV is the recommended method for NiCd cells that do not include an internal thermistor for temperature control and avoids overcharging of fully-charged batteries. NDV requires a charge rate of at least 0.5 C to generate a reliably measurable change in voltage and works best with fast charging. At a charge rate of 1 C, a fully discharged battery is recharged in about an hour.

Fig 7.51 illustrates the relationship of cell voltage, pressure, and temperature of a charging NiCd battery. Up to about 70% SoC, the

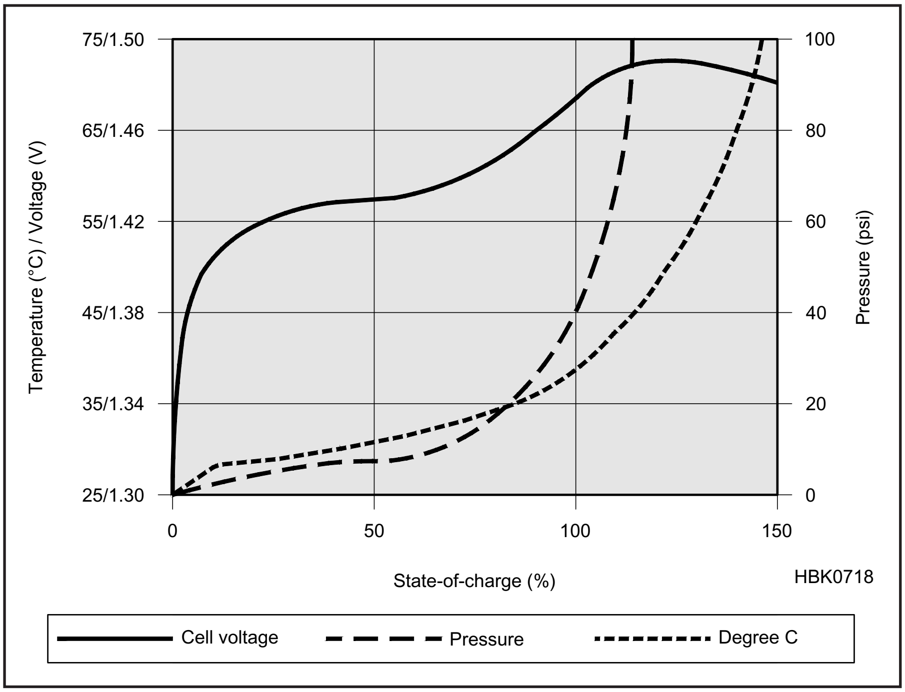


Fig 7.51 — Charge characteristics of a NiCd cell. Above 70% state-of-charge, temperature and cell pressure rise quickly. NiMH has similar charge characteristics. (Courtesy of Cadex)

battery accepts almost all of the energy supplied (called *charge efficiency*). Above 70%, the battery loses ability to accept charge, begins to generate gases so that pressure rises, and temperature increases rapidly.

Ultra-high-capacity NiCd batteries tend to heat up more than standard batteries when charging at 1 C and higher rates due to their higher internal resistance. Applying a high current during initial charge and tapering to a lower rate achieves good results with all nickel-based batteries and moderates temperature rise.

Some chargers can "burp" a charging battery by applying a load to generate a discharge pulse to cause gases to recombine and lower internal pressure. The result is a cooler and more effective charge than with conventional dc charging. Pulse charging does not apply to lead and lithium-based systems.

After full charge, the NiCd battery receives a trickle charge of between 0.05 C and 0.1 C to compensate for self-discharge. To avoid possible overcharge, trickle charging should be done at the lowest possible rate and the batteries should be removed from the charger after more than a few days.

CHARGING NICKEL-METAL-HYDRIDE

The charging algorithm for NiMH is similar to NiCd with the exception that NiMH is more complex. The NDV method of measuring full charge has difficulty because the voltage drop at full charge is very small — about 5 mV/cell. As a result, modern chargers combine the various methods of measuring voltage and temperature into a composite algorithm that reacts depending on battery condition.

Some advanced chargers apply an initial fast charge at 1 C. After reaching a certain voltage threshold, a few minutes rest is taken to allow the battery to cool. Charging then resumes at lower currents as the charge progresses to full charge. This is known as the "step-differential charge" and works well for all nickel-based batteries, achieving an extra capacity of about 6% above basic chargers. A drawback of this method is that the fast-charge stress on the battery will shorten overall battery life by 10 to 20%.

NiMH cannot absorb overcharge well and the trickle charge current must be limited to around 0.05 C. In comparison, a basic NiCd charger trickle charges at 0.1 C. This higher trickle charge and the need for sensitive full-charge detection render the basic NiCd chargers unsuitable for NiMH batteries. On the other hand, NiCd cells can be charged in a NiMH charger at the lower trickle charge rate.

Slow charging should not be used for NiMH batteries. At the charging rate of 0.1 to 0.3 C, the voltage and temperature profiles make it very difficult to measure full charge accurately so the charger must depend on a timer. Harmful overcharge will occur if a fixed timer is used, particularly when charging partially or fully charged batteries. The same is true for charging old batteries with reduced capacity.

Inexpensive chargers are prone to incorrect charging because of the difficulty in correctly sensing full charge. Remove the batteries from the charger when you think they are fully charged. For high charge rates, remove the batteries when they are warm to the touch. It is better to remove the batteries and recharge them before use than to leave them in the charger where they might be overcharged and damaged.

SIMPLE GUIDELINES ON CHARGING NICKEL-BASED BATTERIES

- Do not charge at high or freezing temperatures; room temperature is best.
- Do not use chargers that allow the batteries to heat; remove the batteries when warm to the touch.
- Nickel-based batteries are best fast charged.
- NiMH chargers can charge NiCd batteries but not vice versa.
- High charge current or overcharging on an aging battery may cause heat build-up.
- Do not leave a nickel-based battery in the charger for long periods, even with correct trickle charge. Remove and apply a brief charge before use.
- Nickel- and lithium-based batteries require different charge algorithms and cannot share the same charger unless it can switch between the different chemistries.

CHARGING LITHIUM-ION

The Li-ion charger is a voltage-limiting device that is similar to the lead acid system. The difference lies in a higher voltage per cell, tighter voltage tolerance and the absence of trickle or float charge at full charge. Li-ion cannot accept overcharge — any extra charging causes stress.

Most Li-ion cells charge to 4.20 V/cell with a tolerance of ±50 mV/cell. **Fig 7.52** shows the voltage and current signature as lithium-ion passes through the stages for constant current and topping charge. The charge rate of a typical consumer Li-ion battery is between 0.5 and 1 C in Stage 1 and the charge time is about three hours. Manufacturers recommend charging the 18650 cell at 0.8 C or less. The cell should remain cool during the charging process although there may be a slight temperature rise of a few degrees when reaching full charge. Full charge occurs when the battery reaches the voltage threshold and the current drops to 3% of the rated current, or if the charging current reaches a constant value and does not decrease further. The latter may be due to elevated self-discharge.

Li-ion does not need to be fully charged, as is the case with lead acid, nor is it desirable to do so. In fact, it is better not to fully charge so as not to stress the battery. Choosing a lower voltage threshold or eliminating saturation

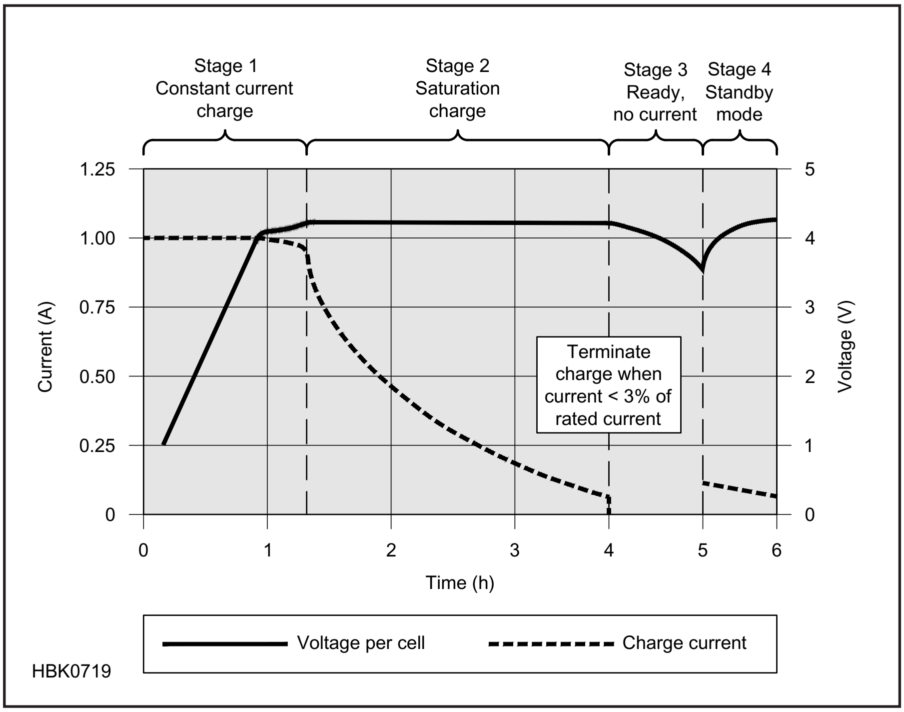


Fig 7.52 — Charge stages of lithium ion. Li-ion is fully charged when the current drops to a predetermined level or levels out at the end of Stage 2. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops to 4.05 V/cell (Stage 4). (Courtesy of Cadex)

charge prolongs battery life at the cost of reduced runtime. Without a saturation stage, the battery is usually charged to around 85% of capacity.

Once charging is terminated, the battery voltage begins to drop and this eases the voltage stress. Over time, the open circuit voltage (OCV) will settle to between 3.60 and 3.90 V/cell. A battery receiving a fully saturated charge will keep the higher voltage longer than a battery that was fast charged and terminated without a saturation charge.

If a lithium-ion battery must be left in the charger for operational readiness, some chargers apply a brief topping charge to compensate for the small self-discharge of the battery and its protective circuit. It is common to let the battery voltage drop to 4.00 V/cell and then recharge to 4.05 V/cell to reduce voltage-related stress and prolong battery life. Battery-powered devices should be turned off when charging their battery. Otherwise, the *parasitic load* of the device can confuse the charger, distorting the charge cycle and stressing the battery.

Overcharging Lithium-ion

Lithium-ion systems operate safely within the designated operating voltages; however, the battery becomes unstable if inadvertently charged to a voltage higher than specified. Prolonged charging above 4.30 V/cell forms plating of metallic lithium on the anode, while the cathode material becomes an oxidizing agent, loses stability and produces CO_2. Cell pressure rises until the internal *current interrupt device* (CID) disconnects the current at 1380 kPa (200 psi).

Should the pressure rise further, a safety membrane bursts open at 3450 kPa (500 psi) and the cell might eventually vent with flame. The thermal runaway moves lower when the battery is fully charged; for Li-cobalt this threshold is between 130-150° C (266-302° F), for nickel-manganese-cobalt (NMC) between 170-180° C (338-356° F), and manganese is 250° C (482° F). Li-phosphate enjoys similar and better temperature stabilities than manganese.

Lithium-ion is not the only battery that is a safety hazard if overcharged. Lead and nickel-based batteries are also known to melt down and cause fires if improperly handled. Properly designed charging equipment is paramount for all battery systems.

SIMPLE GUIDELINES FOR CHARGING LITHIUM-BASED BATTERIES

- A battery-powered device should be turned off while charging.
- Charge at a moderate temperature. Do not charge below freezing.
- Lithium-ion does not need to be fully charged; a partial charge is better.
- Chargers use different methods for "ready" indication and may not always indicate a full charge.
- Discontinue using a charger and/or battery if the battery gets excessively warm.
- Before prolonger storage, apply some charge to bring a pack to about half charge.

SUMMARY OF CHARGING

Batteries have unique needs and **Table 7.11** explains how to satisfy these needs with correct handling. Because of similarities within the battery families, only lead, nickel and lithium systems are covered. Along with these guidelines, you can prolong battery life by following three simple rules: keep the battery at moderate temperatures, control the level and rate of discharge, and avoid abusing the battery.

7.13.6 Discharge Methods

C-RATE

According to the definition of *coulomb,* a current of 1 ampere is a flow of 1 coulomb (C) of charge per second. Today, the battery industry uses *C-rate* to scale the charge and discharge current of a battery.

Most portable batteries are rated at 1 C, meaning that a 1000 mAh battery that is discharged at 1 C should under ideal conditions provide a current of 1000 mA for 1 hr. The same battery discharging at 0.5 C would provide 500 mA for 2 hours, and at 2 C, the 1000 mAh battery would deliver 2000 mA for 30 minutes. 1 C is also known as a one-hour discharge; a 0.5 C is a two-hour discharge, a 2 C is a half-hour discharge, and so on.

A battery's capacity — the amount of energy a battery can hold — can be measured with a *battery analyzer*. The analyzer discharges the battery at a calibrated current while measuring the time it takes to reach its specified end-of-discharge voltage. If a 1000 mAh battery could provide 1000 mA for 1 hour, 100% of the battery's nominal energy rating would be reached.

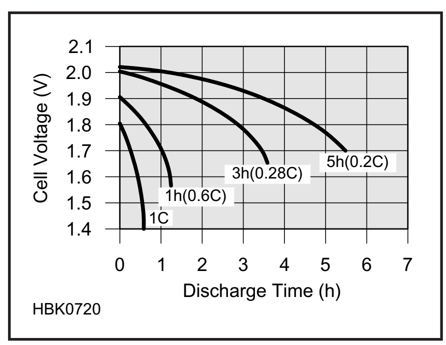


Fig 7.53 — Typical discharge curves of lead acid as a function of C-rate. Smaller batteries are rated at a 1 C discharge rate. Due to sluggish behavior, lead acid is rated at 0.2 C (5 hours) and 0.05 C (20 hours). (Courtesy of Cadex)

Table 7.11
Best Charging Methods

Frequently Asked Question	*Lead Acid (Sealed, flooded)*	*Nickel-Based (NiCd and NiMH)*	*Lithium-ion (Li-ion, Polymer)*
How should I prepare? a new battery	Battery comes fully charged. Apply topping charge	Charge 14-16 h. Priming may be needed.	Apply a topping charge before use. No priming needed
Can I damage a battery with incorrect use?	Yes, do not store partially charged, keep fully charged	Battery is robust and the performance will improve with use.	Keep some charge. Low charge can turn off protection circuit.
Do I need to apply a full charge?	Yes, partial charge causes sulfation.	Partial charge is fine.	Partial charge better than a full charge.
Can I disrupt a charge cycle?	Yes, partial charge causes no harm.	Interruptions can cause heat buildup.	Yes, partial charge causes no harm.
Should I use up all battery energy before charging?	No, deep discharge wears the battery down. Charge more often.	Apply scheduled discharges only to prevent memory.	No, deep discharge wears the battery down.
Do I have to worry about "memory"?	No memory	Discharge NiCd every 1-3 months.	No memory
How do I calibrate a "smart" battery?	Not applicable	Apply discharge/charge when the fuel gauge gets inaccurate. Repeat every 1-3 months.	Apply discharge/charge when the fuel gauge gets inaccurate. Repeat every 1-3 months.
Must I remove the battery when fully charged?	Depends on charger; needs correct float voltage	Remove after a few days in charger.	Not necessary; charger turns off
How do I store my battery?	Keep cells above 2.10 V, charge every 6 months	Store in cool place; a total discharge causes no harm.	Store in cool place partially charged, do not fully drain
Is the battery allowed to heat up during charge?	Battery may get lukewarm toward the end of charge.	Battery gets warm but must cool down on ready.	Battery may get lukewarm toward the end of charge.
How do I charge when cold?	Slow charge (0.1C): 0°-45°C (32°-113° F) Fast charge (0.5-1C): 5°-45° C (41°-113° F)	Slow charge (0.1C): 0°-45° C (32°-113° F) Fast charge (0.5-1C): 5°-45° C (41°-113° F)	Do not charge above 50° C (122° F) Do not charge above 50° C (122° F)
Can I charge at hot temperatures?	Above 25° C, lower threshold by 3 mV/°C.	Battery will not fully charge when hot	Do not charge above 50° C (122° F)
What should I know about chargers?	Charger should float at 2.25-2.30 V/cell when ready.	Battery should not get too hot; should include temp sensor.	Battery must stay cool; no trickle charge when ready.

(Table courtesy of Cadex)

If the discharge only lasted 30 minutes before reaching the specified voltage, the battery has a capacity of 50% of its nominal rating.

When discharging a battery at different rates a higher C-rate will produce a lower capacity reading due to the internal resistance turning some of the energy into heat instead of delivering it as current to a load. Lower C-rate discharges will produce a higher capacity.

For example, to obtain a reasonably good capacity rating, manufacturers commonly rate lead acid batteries at 0.05 C, or a 20-hour discharge. **Fig 7.53** illustrates the discharge times of a lead acid battery at various loads expressed in C-rate.

DEPTH OF DISCHARGE

The end-of-discharge voltage for lead acid is 1.75 V/cell; for nickel-based systems it is 1.00 V/cell; and for most Li-ion it is 3.00 V/cell. At this level, roughly 95% of the battery's stored energy has been spent and voltage would drop rapidly if discharge were to continue. Most devices prevent operation beyond the specified end-of-discharge voltage. When removing the load after discharge, the voltage of a healthy battery gradually recovers toward the nominal voltage.

Because of internal resistance, wiring, protection circuits and contact resistance, a high load current lowers the battery voltage and the end-of-discharge voltage threshold should be lowered accordingly. The cutoff voltage should also be lowered when discharging at very cold temperatures. **Table 7.12** shows typical end-of-discharge voltages of various battery chemistries. The lower end-of-discharge voltage for higher loads compensates for the losses from internal battery resistance.

Since the cells in a battery pack can never be perfectly matched, a negative voltage potential can occur across a weaker cell on a multi-cell pack if the discharge is allowed to continue beyond a safe cutoff point. Known as *cell reversal*, the weak cell suffers damage to the point of developing a permanent electrical short circuit. The larger the number of cells in the pack, the greater the likelihood that a cell might reverse under heavy load. Over-discharge, particularly at low temperatures, is a large contributor to battery failure of cordless power tools, especially for nickel-based packs. Li-ion packs have protection circuits and the failure rate is lower.

Table 7.12

Recommended End-of-Discharge Voltages in V/Cell

End-of-discharge	*Li-manganese*	*Li-phosphate*	*Lead-acid*	*NiCd/NiMH*
Normal load	3.00	2.70	1.75	1.00
Heavy load	2.70	2.45	1.40	0.90

(Table courtesy of Cadex)

DISCHARGING AT HIGH AND LOW TEMPERATURES

Batteries achieve optimum service life if used at 20° C (68° F) or slightly below, and nickel-based chemistries degrade rapidly when cycled at high ambient temperatures. Higher temperature operation lowers internal resistance and speeds up the chemical reactions but shortens service life if prolonged.

The performance of all battery chemistries drops drastically at low temperatures. At –20° C (–4° F) most nickel, lead, and lithium-based batteries stop functioning. Although NiCd can be used down to –40° C (–40° F), the permissible discharge is only 0.2 C (5-hour rate). Lead acid also has the problem of the electrolyte freezing which can crack the enclosure. Lead acid electrolyte also freezes more easily at a low charge.

SIMPLE GUIDELINES FOR DISCHARGING BATTERIES

- Battery performance decreases with cold temperature and increases with heat.
- Heat increases battery performance but shortens cycle life by a factor of two for every 10° C (18° F) above 25-30° C (18° F above 77-86° F).
- Only charge at moderate temperatures. Check the manufacturer's specifications for charging below freezing.
- Use heating blankets if batteries need rapid charging at cold temperatures.
- Prevent over-discharging. Cell reversal can cause an electrical short circuit.
- Use a larger battery if repetitive deep discharge cycles cause stress.
- A moderate dc discharge is better for a battery than pulsed loads.
- Lead acid systems are sluggish and require a few seconds of recovery between heavy loads.

7.13.7 Battery Handling

This section touches on the most important aspects of handling batteries when they are new, during their service life, and how to store and dispose of them.

FORMATTING AND PRIMING BATTERIES

Rechargeable batteries may not deliver their full rated capacity when new and will require *formatting* — a process that essentially completes the manufacturing process. Li-ion systems require less care in this regard, but cycling these batteries after long storage has been reported to improve performance. *Priming* is a conditioning cycle that is applied to improve battery performance during usage or after prolonged storage. Priming applies mainly to nickel-based batteries.

Formatting of lead acid batteries occurs by applying a charge, followed by a discharge and recharge as part of regular use. Gradually increase the load on a new battery, allowing it to reach full capacity after 50 to 100 cycles.

Manufacturers advise to trickle charge a nickel-based battery pack for 16 to 24 hours when new and after a long storage. This allows the individual cells to reach an equal charge level. A slow charge also helps to redistribute the electrolyte to eliminate dry spots on the separator that may have formed due to gravity. Applying several charge/discharge cycles through normal use or with a battery analyzer completes the formatting process. This can require from five to seven cycles or as many as 50 cycles depending on battery quality.

Cycling also restores lost capacity when a nickel-based battery has been stored for six months or longer. Storage time, state-of-charge, and storage temperature all affect battery recovery. The longer the storage and the higher the temperature, the more cycles are required to regain full capacity.

Lithium-ion does not need formatting when new, nor does it require the level of maintenance that nickel-based batteries do. Maximum capacity is available immediately. A discharge/charge cycle may be beneficial for calibrating a "smart" battery but this does not improve the internal chemistry.

Testing and Monitoring Batteries

Several sections of the "Testing and Monitoring" chapter from *Batteries in a Portable World* are provided on the CD-ROM accompanying this book. The information covers measuring internal resistance and state-of-charge, measuring capacity, and special techniques for measuring nickel- and lithium-based batteries.

STORING BATTERIES

The recommended storage temperature for most batteries is 15° C (59° F) and the extreme allowable temperature is –40° C to 50° C (–40° F to 122° F) for most chemistries. While lead acid must be kept at full charge during storage, nickel and lithium-based chemistries should be stored at around 40% state-of-charge.

Storage will always cause batteries to age. **Table 7.13** illustrates the *recoverable capacity* of lithium and nickel-based batteries at various temperatures and charge levels over one year. Recoverable capacity is the available battery capacity after storage with a full charge.

A sealed lead acid battery can be stored up to two years. It is important to apply a charge when the battery falls to 70% SoC, typically 2.07 V/cell or 12.42 V for a 12 V pack.

Nickel-metal-hydride can be stored for about three years. The capacity drop that occurs during storage can partially be reversed with priming.

Primary alkaline and lithium batteries can be stored for up to 10 years with minimum capacity loss.

SIMPLE GUIDELINES FOR STORING BATTERIES

- Remove batteries from equipment and store in a dry and cool place.
- Avoid freezing. Batteries freeze more easily if in a discharged state.
- Charge lead acid before storing and monitor the voltage frequently; apply a charge if below 2.10 V/cell.
- Nickel-based batteries can be stored for five years and longer, prime before use.

Table 7.13

Estimated Recoverable Capacity After Storage For 1 Year

Temp (°C)	*Lead acid at full charge*	*Nickel-based at any charge*	*Lithium-ion (Li-cobalt) 40% charge*	*Lithium-ion (Li-cobalt) 100% charge*
0	97%	99%	98%	94%
25	90%	97%	96%	80%
40	62%	95%	85%	65%
60	38% (after 6 months)	70%	75%	60% (after 3 months)

(Table courtesy of Cadex)

• Lithium-ion must be stored in a charged state, ideally 40%.

• Discard Li-ion if the voltage has stayed below 2.00 V/cell for more than a week.

RECYCLING BATTERIES

The main objective for recycling batteries is to prevent hazardous materials from entering landfills. Lead acid and NiCd batteries are of special concern.

Under no circumstances should batteries be incinerated, as fire can cause an explosion. Wear approved gloves when touching electrolyte. On exposure to skin, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Automotive and larger lead acid batteries can be recycled through auto parts stores and battery dealers. A recycling fee is usually charged when the battery is purchased.

Smaller batteries, including smaller SLA, can be recycled at many electronics and hardware stores, or your local municipal recycling center. Perform an Internet search for battery recyclers in your area.

It is helpful to create a specific location or designate a container for spent batteries at your home, office or workbench. This makes it easy to recycle the batteries by keeping them together in one spot.

7.13.8 DC-AC Inverters

For battery-powered operation of ac-powered equipment, dc-ac inverters are used. An inverter is a dc-to-ac converter that provides 120 V ac. Inverters come with varying degrees of sophistication. The simplest type of inverter switches directly at 60 Hz to produce a square-wave output. This is no problem for lighting and other loads that don't care about the input waveform. However, some equipment will work poorly or not at all when supplied with square wave power because of the high harmonic content of the waveform.

The harmonic content of the inverter output waveform can be reduced by the simple expedient of reducing the waveform duty cycle from 50% (for the square wave) to about 40%. For many loads, such as computers and other electronic devices, this may still not be adequate, and so many inverters use waveform shaping to approximate a sine-wave output. The simplest of these methods is a resonant inductor-capacitor filter. This adds significant weight and size to the inverter. Most modern inverters use high-frequency pulse-width modulation (PWM) techniques to synthesize the 60 Hz sinusoidal output waveform, much like a switching power supply. See **Fig 7.54**.

Inverters are usually rated in terms of their VA or "volt-ampere product" capability although sometimes they will be rated in watts. Care is required in interpreting inverter ratings. A purely resistive load operating from a sinusoidal voltage source will have a sinusoidal current flowing in phase with the voltage. In this case, VA, the product of the voltage (V) and the current (A), will equal the actual power in watts delivered to the load so that the VA and the watt ratings are the same. Some loads, such as motors and many rectifier power supplies, will shift the phase of load current away from the source voltage; or the load current will flow in short pulses as shown earlier for capacitor input filters. In these cases (which are very common), the VA product for that type of load can be much larger than the delivered power in watts. In the absence of detailed knowledge of the load characteristics it is prudent to select an inverter with a VA or wattage capability of 25% or more above the expected load.

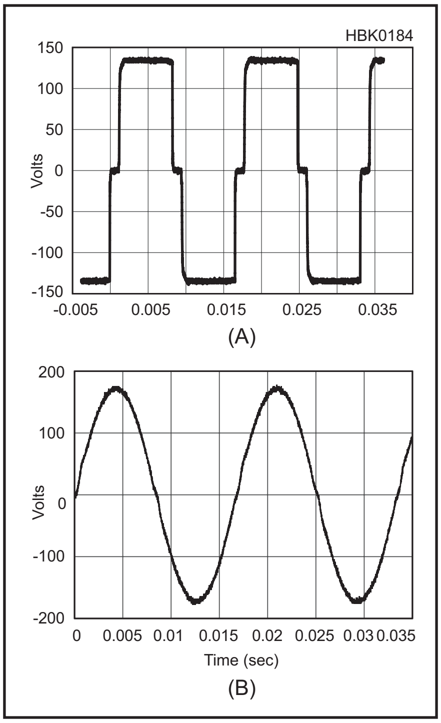


Fig 7.54 — Output waveforms of typical dc-ac inverters. At A, the output of a modified sine wave inverter. Note the stepped square waves. At B, the output of a "pure sine wave" inverter. Note the close approximation of a commercial ac sine wave.

7.13.9 Selecting a Battery for Mobile Operation

There are two basic modes of mobile operation: *in-motion*, and *stationary*. Each mode has unique power requirements and thus different battery requirements. To satisfy these needs, there are three basic battery types. It is important to understand the differences between the types and to apply them properly.

Standard vehicle batteries are referred to as *SLI* (starting, lights, ignition) or just *starter* batteries. Their primary function is to start the engine and then act as a power filter for the alternator which is the actual long-term power source. The most important rating of an SLI battery is the *cold cranking amps* (CCA) rating — the number of amps that the battery can produce at 32 °F (0 °C) for 30 seconds.

Batteries designed for repeated cycles of charging and discharging use are often called *deep-cycle* although the term is widely overused. A true deep-cycle battery is designed to be repeatedly discharged to 20% remaining capacity. The term "deep cycle" is a misnomer, as all lead-acid batteries are considered discharged when their output voltage drops below 10.5 V at some specified current draw as outlined by the Battery Council Institute (BCI — **www.batterycouncil.org**). At 10.5 V, a six-cell lead-acid battery is considered discharged.

Marine batteries are designed to be stored without charging for up to two years, yet still maintain enough power to start a marine engine. Contrary to common practice, they're not really designed for extended low-current power delivery. Marine batteries often have hybrid characteristics between SLI and deep-cycle batteries.

To differentiate true deep-cycle batteries from SLI and marine batteries, examine a battery's *reserve capacity* (RC). A battery's RC rating is the number of minutes that the battery can deliver 25 A while maintaining an output voltage above 10.5 V. Deep cycle batteries typically have RC ratings 20% or more higher than SLI batteries and perhaps 50% higher under ICAS (intermittent, commercial, and amateur service) conditions. A deep-cycle battery has a lower CCA rating than an SLI battery due to its internal construction that favors long-term power delivery over high-current starting loads.

With these facts in mind, we can now select the correct battery for our style of mobile operating. For in-motion operation with power outputs up to 200 W, a second trunk-mounted battery is seldom needed if the power cabling wire size is chosen correctly. (See the **Assembling a Station** chapter for information on wire sizes in mobile applications.)

When an amplifier is added for higher output power levels, it is often less expensive to add a second trunk-mounted battery than to install larger cables to the main battery. In these cases, the second battery can be of almost any type, as long as it is lead-acid. The second battery should be connected in parallel to the vehicle's main SLI battery. The battery's ampere-hour rating should be close to that of the vehicle's main SLI battery.

All secondary wiring should be properly fused, as outlined in the **Assembling a**

Station chapter's section on mobile installations. The use of relays and circuit breakers should be avoided. Remember, should a short circuit occur, good-quality lead-acid batteries can deliver upwards of 3000 A which exceeds the break circuit ratings of most relays and circuit breakers. A better solution is a FET switch such as those made by Perfect Switch (**www.perfectswitch.com**).

Assuming the second battery is mounted inside the vehicle's passenger compartment or in the trunk, it should be an AGM type. AGM (Absorption Glass Mat) batteries do not outgas explosive hydrogen gas under normal operating conditions. Flooded (liquid electrolyte) batteries should *never* be used in an enclosed environment.

For stationary operation, select a battery with a large RC rating because it will not be continuously charged. There are two main considerations; the ampere-hour rating (Ah) and the reserve capacity rating, typically listed as C/8, C/10, or C/20, with units of hours. (C is the battery's capacity in Ah.) Dividing the Ah rating by the load amperage (8, 10 or 20 A) will give you the reserve capacity in hours, but the actual ampere-hours any given battery can deliver before the voltage reaches 10.5 V (nominal discharge level) will vary with the load, both average and peak. Heavier loads will reduce the actual ampere-hours available.

Automotive batteries are arranged in BCI group sizes (**www.batterystuff.com/kb/tools/bci-battery-group-sizes.html**), from 21 through 98. Generally speaking, the larger the group size the larger the battery and the higher the Ah rating. For example, size 24 (small car) has an average rating of 40 Ah, and size 34 (large car) has an average rating of 55 Ah. Exact ratings, including their reserve capacity, are available from the manufacturers' websites listed below. A good rule of thumb is to select a battery as physically large as you have room for, consistent with the highest RC rating for any given Ah rating.

Batteries are heavy, and need to be properly secured inside a battery box or by using factory-supplied brackets. For example, a BIC group 34 (average SLI size) battery weighs about 55 pounds. Some battery models (such as the Optima) come supplied with mounting brackets and terminal protection covers. Even though battery boxes aren't always needed, they should be used as a safety precaution to prevent accidental contact with the terminals and can protect the battery from external items. Battery restraints should be adequate to provide 6 Gs of lateral and 4 Gs of vertical retention, ruling out sheet metal screws and most webbing material. Use the proper brackets!

There are three other considerations: isolating the battery electrically, recharging the battery, and output voltage regulation. Diode-based battery isolators are not all equal. Models with FET bypass switches are the preferred type because of the low voltage-drop across the FET.

If you have wired the battery in parallel with the vehicle's main SLI battery, recharging is taken care of whenever the vehicle is running. If you plan on operating in stationary mode, you'll need a separate recharging system. Most vehicle factory-installed trailer wiring systems also include a circuit for charging RV or boat "house" batteries. Check with your dealer's service personnel about these options.

Voltage regulators, commonly called "battery boosters," are almost a necessity for stationary operation. A model with a low-voltage cutoff should be used to avoid discharging the battery below 10.5 V, as discharging a lead-acid battery beyond this point drastically reduces its charge-cycle life — the number of full-charge/full-discharge cycles. (See the November 2008 *QST* Product Review column.)

For additional information on battery ratings, sizes, and configuration, visit these websites:

optimabatteries.com, www.exide.com
www.interstatebatteries.com
www.lifelinebatteries.com

7.14 Glossary of Power Source Terms

Bleeder — A resistive load across the output or filter of a power supply, intended to quickly discharge stored energy once the supply is turned off.

Boost converter — A switchmode converter in which the output voltage is always greater than or equal to the input voltage.

Buck converter — A switchmode converter in which the output voltage is always less than or equal to the input voltage.

Buck-boost converter — A switchmode converter in which the magnitude of the output voltage can be either greater or less than the input voltage.

C-rate — The charging rate for a battery, expressed as a ratio of the battery's ampere-hour rating.

CCA (cold cranking amps) — A measure of a battery's ability to deliver high current to a starter motor.

Circular mils — A convenient way of expressing the cross-sectional area of a round conductor. The area of the conductor in circular mils is found by squaring its diameter in mils (thousandths of an inch), rather than squaring its radius and multiplying by pi. For example, the diameter of 10-gauge wire is 101.9 mils (0.1019 inch). Its cross-sectional area is 10380 CM, or 0.008155 square inches.

Core saturation (magnetic) — That condition whereby the magnetic flux in a transformer or inductor core is more than the core can handle. If the flux is forced beyond this point, the permeability of the core will decrease, and it will approach the permeability of air.

Crowbar — A last-ditch protection circuit included in many power supplies to protect the load equipment against failure of the regulator in the supply. The crowbar senses an overvoltage condition on the supply's output and fires a shorting device (usually an SCR) to directly short-circuit the supply's output and protect the load. This causes very high currents in the power supply, which blow the supply's input-line fuse.

Darlington transistor — A package of two transistors in one case, with the collectors tied together, and the emitter of one transistor connected to the base of the other. The effective current gain of the pair is approximately the product of the individual gains of the two devices.

DC-DC converter — A circuit for changing the voltage of a dc source to ac, transforming it to another level, and then rectifying the output to produce direct current.

Deep-cycle — A battery designed for repeated charge-discharge cycles to 20% of remaining capacity.

Equalizing resistors — Equal-value bypassing resistors placed across capacitors connected in series for use in a high-voltage power supply to keep the voltages across the capacitors in the string relatively constant.

Fast recovery rectifier — A specially doped rectifier diode designed to minimize the time necessary to halt conduction when the diode is switched from a forward-biased state to a reverse-biased state.

Flyback converter — A transformer-coupled version of the **buck-boost converter**.

***Forward converter* —** A **buck converter** with multiple isolated outputs at different voltage levels and polarities.

Foldback current limiting — A special type of current limiting used in linear power supplies, which reduces the current through the supply's regulator to a low value under short circuited load conditions in order to protect the series pass transistor from excessive power dissipation and possible destruction.

Ground fault (circuit) interrupter (GFI or GFCI) — A safety device installed between the household power mains and equipment where there is a danger of personnel touching an earth ground while operating the equipment. The GFI senses any current flowing directly to ground and immediately switches off all power to the equipment to minimize electrical shock. GFCIs are now standard equipment in bathroom and outdoor receptacles.

Input-output differential — The voltage drop appearing across the series pass transistor in a linear voltage regulator. This term is usually stated as a minimum value, which is that voltage necessary to allow the regulator to function and conduct current. A typical figure for this drop in most three-terminal regulator ICs is about 2.5 V. In other words, a regulator that is to provide 12.5 V dc will need a source voltage of at least 15.0 V at all times to maintain regulation.

Inverter — A circuit for producing ac power from a dc source.

Li-ion — Lithium-ion, a type of rechargeable battery that is about ⅓ the weight and ½ the volume of a **NiCd** battery of the same capacity.

Low dropout regulator — A three-terminal regulator designed to work with a low minimum input-output differential value.

Marine — A battery designed to retain significant energy over long periods of time without being continuously charged.

NiCd — Nickel cadmium, a type of rechargeable battery.

NiMH — Nickel metal hydride, a type of rechargeable battery that does not contain toxic substances.

Peak inverse voltage (PIV) — The maximum reverse-biased voltage that a semiconductor is rated to handle safely. Exceeding the peak inverse rating can result in junction breakdown and device destruction.

Power converter — Another term for a power supply.

Power processor — Another term for a power supply.

Primary battery — A battery intended for one-time use and then discarded.

RC (reserve capacity) — A measure of a battery's ability to deliver current over long periods.

Regulator — A device (such as a Zener diode) or circuitry in a power supply for maintaining a constant output voltage over a range of load currents and input voltages.

Resonant converter — A form of dc-dc converter characterized by the series pass switch turning on into an effective series-resonant load. This allows a zero current condition at turn-on and turn-off. The resonant converter normally operates at frequencies between 100 kHz and 500 kHz and is very compact in size for its power handling ability.

Ripple — The residual ac left after rectification, filtration and regulation of the input power.

RMS — *R*oot *M*ean *S*quare. Refers to the effective value of an alternating voltage or current, corresponding to the dc voltage or current that would cause the same heating effect.

Secondary battery — A battery that may be recharged many times. Also called a *storage battery*.

Secondary breakdown — A runaway failure condition in a transistor, occurring at higher collector-emitter voltages, where hot spots occur due to (and promoting) localization of the collector current at that region of the chip.

Series pass transistor,* or *pass transistor — The transistor(s) that control(s) the passage of power between the unregulated dc source and the load in a regulator. In a linear regulator, the series pass transistor acts as a controlled resistor to drop the voltage to that needed by the load. In a switch-mode regulator, the series pass transistor switches between its ON and OFF states.

SLI (starter, lights, ignition) — An automotive battery designed to start the vehicle and provide power to the lighting and ignition systems.

SOA (Safe Operating Area) — The range of permissible collector current and collector-emitter voltage combinations where a transistor may be safely operated without danger of device failure.

Surge — A moderate-duration perturbation on a power line, usually lasting for hundreds of milliseconds to several seconds.

Switching regulator — Another name for a switchmode converter.

Switchmode converter — A high-efficiency switching circuit used for dc-dc power conversion. Switching circuits are usually much smaller and lighter than conventional 60 Hz, transformer-rectifier circuits because they operate at much higher frequencies — from 25 to 400 kHz or even higher.

Three-terminal regulator — A device used for voltage regulation that has three leads (terminals) and includes a voltage reference, a high-gain error amplifier, temperature-compensated voltage sensing resistors and a pass element.

Transient — A short perturbation or "spike" on a power line, usually lasting for microseconds to tens of milliseconds.

Varistor — A surge suppression device used to absorb transients and spikes occurring on the power lines, thereby protecting electronic equipment plugged into that line. Frequently, the term MOV (*M*etal *O*xide *V*aristor) is used instead.

Volt-Amperes (VA) — The product obtained by multiplying the current times the voltage in an ac circuit without regard for the phase angle between the two. This is also known as the apparent power delivered to the load as opposed to the actual or real power absorbed by the load, expressed in watts.

Voltage multiplier — A type of rectifier circuit that is arranged so as to charge a capacitor or capacitors on one half-cycle of the ac input voltage waveform, and then to connect these capacitors in series with the rectified line or other charged capacitors on the alternate half-cycle. The voltage doubler and tripler are commonly used forms of the voltage multiplier.

Voltage regulation — The change in power supply output voltage with load, expressed as a percentage.

7.15 References and Bibliography

REFERENCES

1) Landee, Davis and Albrecht, *Electronic Designer Handbook*, 2nd edition, (McGraw-Hill, 1977), page 12-9. This book can frequently be found in technical libraries and used book stores. The power supply section is well worth reading.
2) Severns and Bloom, *Modern DC-to-DC Switchmode Power Converter Circuits,* (Van Nostrand Reinhold, 1984, ISBN: 0-442-21396-4). A reprint of this book is currently available at the Power Sources Manufacturers Association website, **www.psma.com**.
3) Fair-Rite website, **www.fair-rite.com**
4) **www.mag-inc.com**

OTHER RESOURCES

M. Brown, *Power Supply Cookbook,* (Butterworth-Heinemann, 2001).
I. Buchmann, *Batteries In a Portable World*, (Cadex Electronics, 2011).
J. Fielding, ZS5JF, *Power Supply Handbook,* (RSGB, 2006).
K. Jeffrey, *Independent Energy Guide,* (Orwell Cove Press, 1995). Includes information on batteries and inverters.

7.16 Power Source Projects

Construction of a power supply or accessory — basic to all of the radio equipment we operate and enjoy — can be one of the most rewarding projects undertaken by a radio amateur. Final testing and adjustment of most power-supply projects requires only a voltmeter, and perhaps an oscilloscope — tools commonly available to most amateurs.

General construction techniques that may be helpful in building the projects in this chapter are outlined in the **Construction Techniques** chapter. Other chapters in the *Handbook* contain basic information about the components that make up power supplies.

Safety must always be carefully considered during design and construction of any power supply. Power supplies contain potentially lethal voltages, and care must be taken to guard against accidental exposure. For example, electrical tape, insulated tubing (“spaghetti”) or heat-shrink tubing is recommended for covering exposed wires, components leads, component solder terminals and tie-down points. Whenever possible, connectors used to mate the power supply to the outside world should be of an insulated type designed to prevent accidental contact.

Connectors and wire should be checked for voltage and current ratings. Always use wire with an insulation rating higher than the working voltages in the power supply. For supply voltages above 300 V, use wire with insulation rated accordingly. The **Component Data and References** chapter contains a table showing the current-carrying capability of various wire sizes. Scrimping on wire and connectors to save money could result in flashover, meltdown or fire.

All fuses and switches should be placed in the hot circuit(s) only. The neutral circuit should not be interrupted. Use of a three-wire (grounded) power connection will greatly reduce the chance of accidental shock. The proper wiring color code for 120 V circuits is: black — hot; white — neutral; and green — ground. For 240 V circuits, the second hot circuit generally uses a red wire.

POWER SUPPLY PRIMARY-CIRCUIT CONNECTOR STANDARD

The International Commission on Rules for the Approval of Electrical Equipment (CEE) standard for power-supply primary-circuit connectors for use with detachable cable assemblies is the CEE-22. The CEE-22 has been recognized by the ARRL and standards agencies of many countries. Rated for up to 250 V, 6 A at 65 °C, the CEE-22 is the most commonly used three-wire (grounded), chassis-mount primary circuit connector for electronic equipment in North America and Europe. It is often used in Japan and Australia as well.

When building a power supply requiring 6 A or less for the primary supply, a builder would do well to consider using a CEE-22 connector and an appropriate cable assembly, rather than a permanently installed line cord. Use of a detachable line cord makes replacement easy in case of damage. CEE-22 compatible cable assemblies are available with a wide variety of power plugs including most types used overseas.

Some manufacturers even supply the CEE-22 connector with a built-in line filter. These connector/filter combinations are especially useful in supplies that are operated in RF fields. They are also useful in digital equipment to minimize conducted interference to the power lines.

CEE-22 connectors are available in many styles for chassis or PC-board mounting. Some have screw terminals; others have solder terminals. Some styles even contain built-in fuse holders.

7.16.1 Four-Output Switching Bench Supply

This project by Larry Cicchinelli, K3PTO, describes the four-output bench power supply shown in **Fig 7.55** with three positive outputs and one negative output. The three positive outputs use identical switching regulator circuits that can be set independently to any voltage between 3.3 V and 20 V at up to 1 A. The fourth output is a negative regulator capable of about 250 mA. As built, the supply has two fixed outputs and two variable outputs, but any module can be built with variable output. (Construction diagrams and instructions, a complete parts list, and additional design details are included on this *Handbook’s* CD-ROM.)

The only dependency among the outputs is that they are all driven by a single transformer. The transformer used is rated at 25 V and 2 A — good for 50 W. Assuming that the regulator IC being used has a 75% efficiency, a total of about 37 W is available from the power supply outputs.

One of the features of a switching regulator is that you can draw more current from the outputs than what the transformer is supplying — at a lower voltage, of course — as long as you stay within the 37 W limit and maximum current for the regulator. Most of the discussion in this article will be about the

Fig 7.55 — The front panel of the four-output switching supply.

positive regulators as the negative regulator was an add-on after the original system was built.

POSITIVE REGULATOR

Fig 7.56 is the circuit for the positive regulator modules — a buck-type regulator. There are several variations of the circuit, any of which you can implement.

• L2 and C4 are optional. These two components implement a low-pass filter that will decrease high frequency noise that might otherwise appear at the output.

• The pads for R1 will accommodate a small, multi-turn potentiometer. You can insert one here or you can use the pads to connect a panel-mounted potentiometer.

• If you want a fixed output you can simply short out R1 and use R2 by itself.

• You can also insert a fixed resistor in the R1 position in the case where the calculated value is non-standard and you want to use two fixed resistors.

The formula for setting output voltage using the 3.3 V version of the regulator is based on knowing the current (in mA) through the regulator's internal voltage divider = 3.3 V / 2.7 kΩ = 1.22 mA. The sum of R1 and R2 must cause the voltage at the regulator FB pin to equal 3.3 V. Thus, R1 + R2 in kΩ = (V_{out} – 3.3) / 1.22 and V_{out} = 1.22 (R1 + R2) + 3.3. If R1 = R2 = 0, a direct connection from the output voltage to the FB pin, the calculation results in an output of 3.3 V. The leakage current of the Error Amplifier in the regulator is somewhat less than 25 nA so it can be ignored. The values for R1 and R2 are shown in the caption for Fig 7.56.

The only critical parts are R1 and R2 which form the voltage dividers for the regulator module. Even their values can be changed, within reason, as long as the ratios are maintained. If you want to have an accurate, fixed output voltage, select a value for R2 that is lower than the calculated value and use a

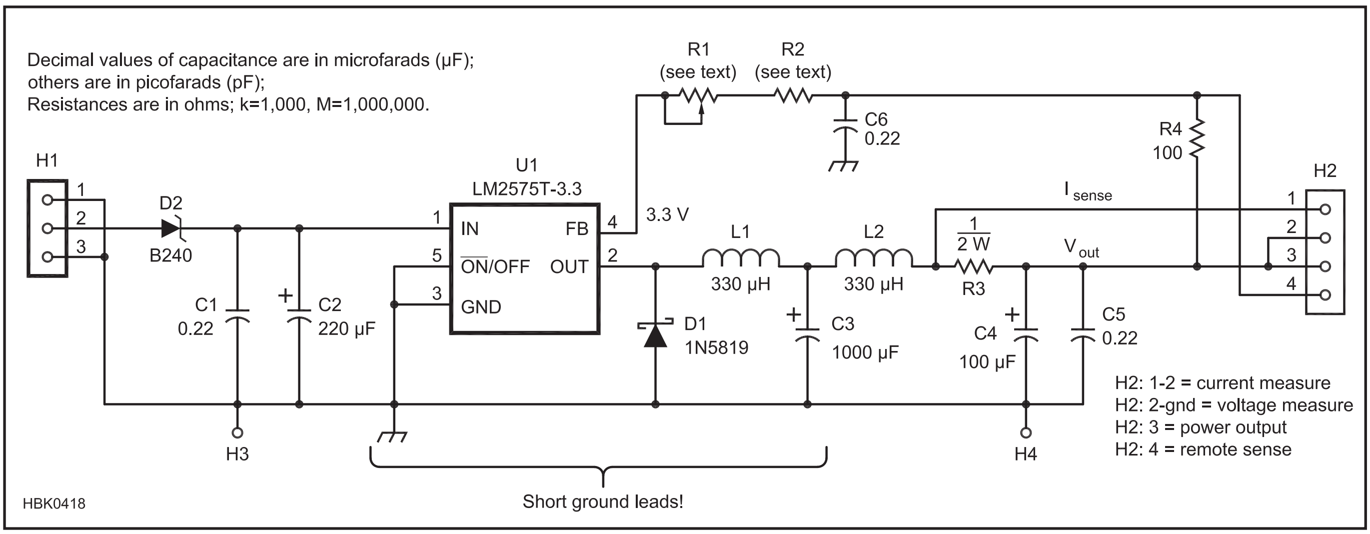


Fig 7.56 — The positive buck-type switchmode regulator uses the LM2575-3.3, a fixed-voltage regulator, with an external voltage-set resistor (R1 + R2). See text for details of the calculations needed to determine the value of R1 and R2. As noted in the text, these values are the total resistance for both parts, and can be made from one fixed resistor, one variable resistor or a combination. Some common values (R1 + R2 total) are: For a 12 V fixed supply, 7.1 kΩ; for 5 V, 1.4 kΩ; for a 3.3 to 20 V variable supply, 0-13.7 kΩ (use a 15 kΩ pot); for 5 to 15 V, 1.4-9.6 kΩ (use 1 kΩ fixed-value resistor and a 1 kΩ pot). A full parts list is included on the *Handbook* CD-ROM.

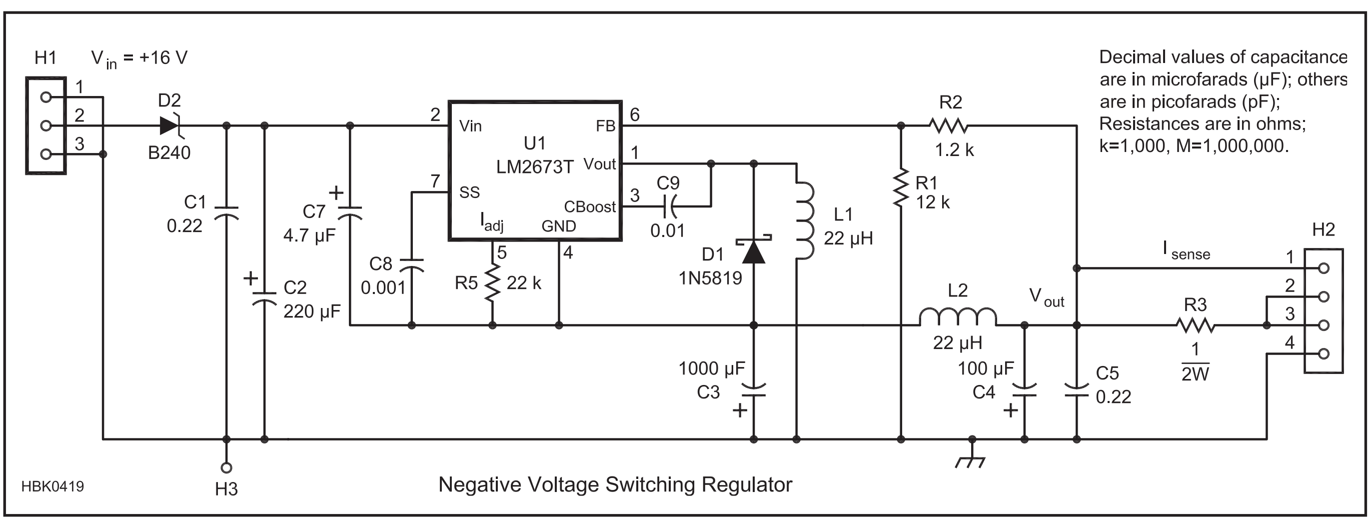


Fig 7.57 — The negative regulator uses the LM2673T in a buck-boost circuit. This circuit inverts the output voltage from the input voltage. A full parts list is included on the *Handbook* CD-ROM.

potentiometer for R1 to set the voltage exactly. The value of C3 is not especially critical; however, it should be a low-ESR (equivalent series resistance) type that is intended for use in switchmode circuits.

NEGATIVE REGULATOR

The negative regulator is a buck-boost configuration — it converts a positive voltage into a negative one — see **Fig 7.57**. This design uses many of the same component values as the positive regulators except the regulator IC is an LM2673 to improve circuit stability. The author was unable to implement the current measuring circuit within a feedback loop. Several configurations introduced a significant low frequency noise component to the output voltage. There was also some 50 kHz noise present on the output, but an additional low-pass filter on the output reduced it considerably.

REMOTE SENSING

Many power supplies use remote sensing to compensate electronically for the voltage drop in the wires carrying current to the load. Even with relatively short wires, there can be significant voltage drop between the regulator and its load. There is provision for remote sensing in this circuit described in the support information for this project on the book's CD-ROM.

If you are not going to use remote sensing then you should insert a jumper in place of R4 in Fig 7.56. R4 (100 Ω) is there for protection just in case the remote sense connection is missing. If you do not want to use remote sensing you can simplify the digital panel meter (DPM) switch wiring to use a two-pole switch instead of the three-pole model listed. In this case, do not use S2.2 and connect S1.2 to the common of S2.3 instead of S2.2.

SUB-CIRCUIT INTERCONNECTION

Fig 7.58 shows the connections among the parts of the system: regulator boards, the digital panel meter (DPM), and rectifier circuit. The components used for the main rectifier circuit can be mounted on a terminal strip and do not need to be on a printed-circuit board.

THE DIGITAL PANEL METER

Another feature of the unit is the DPM which can be switched to measure the output voltage (H2 pin 1 to ground) as well as the current draw (voltage between H2 pins 1 and 2) for each of the positive supplies. Fig 7.58 shows the 3-pole, 4-position rotary switch (S2) that selects which power supply to monitor and a 3PDT toggle switch (S1) that selects between measuring voltage and current.

In order to measure the voltage drop across the 1 Ω current sense resistors, the DPM needs either an isolated power supply or some more circuitry. This system uses an isolated power supply. A series regulator is used simply because they are somewhat easier to implement and the DPM has a very low current requirement. All components except the transformer are mounted on a piece of perforated board. Since the 1.2 mA current for the feedback circuit flows through the current sense resistor it will be included in the value displayed by the DPM when current is selected.

The DPM also has a set of jumpers that allow you to set the decimal point location. As can be seen in Fig 7.58, one pole of the toggle switch selects its location.

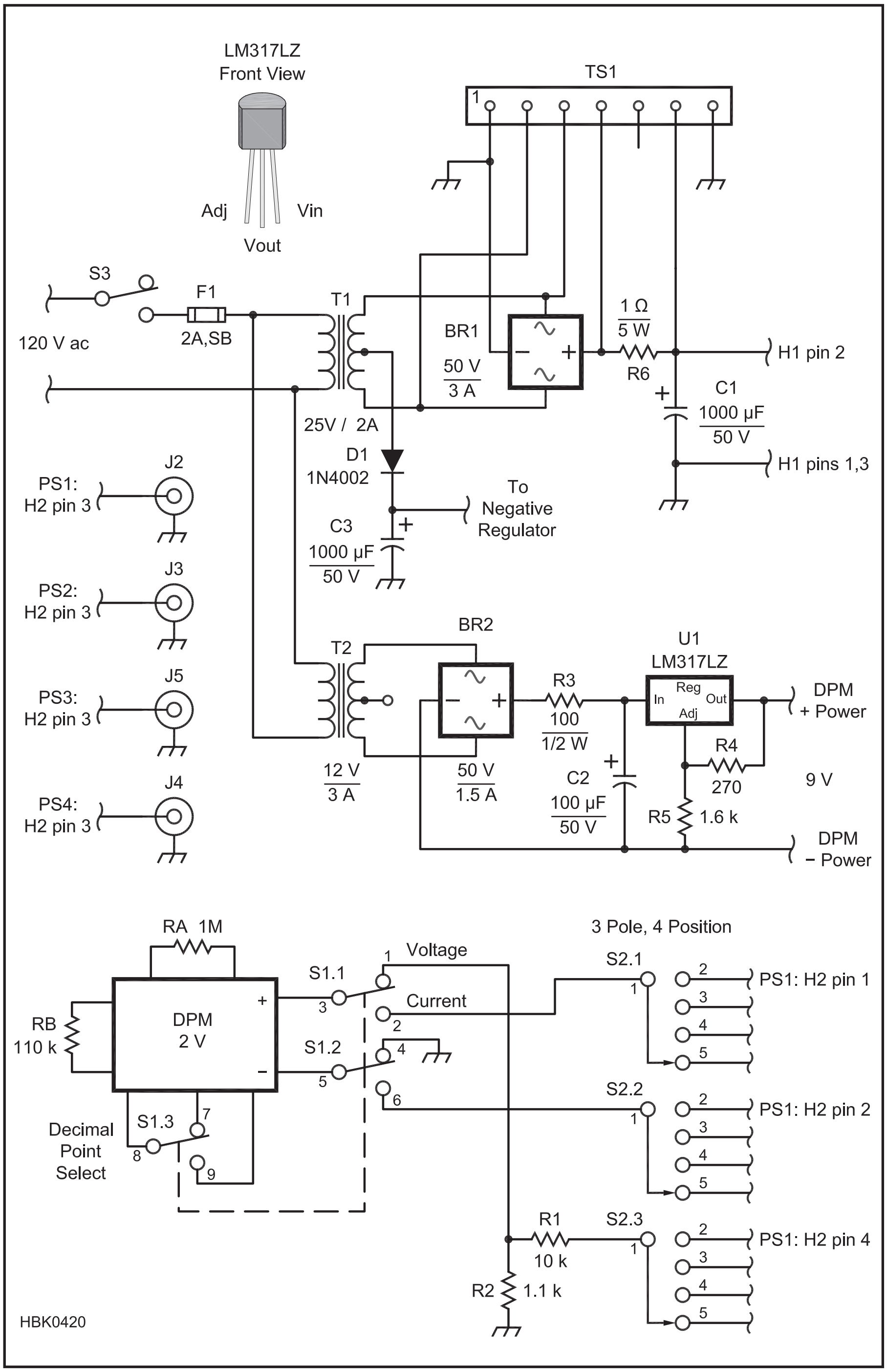


Fig 7.58 — Rectifier and metering schematic. The panel meter is switched between the four modules with a rotary switch (S2) and between voltage and current with a 3PDT toggle (S1). A separate rectifier provides power for the negative supply and a separate three-terminal regulator circuit provides power to the DPM. A full parts list is included on the *Handbook* CD-ROM.

CONSTRUCTION DETAILS

Both the DPM and the regulators use pin headers for all of the connections that come off the boards (see the parts list for details). This allows assembly of the subsystems without having to consider any attached wires. Wire lengths can be determined later, then install the mating connectors on the wires and simply push them onto the pins.

PC boards are available from FAR Circuits (**www.farcircuits.net**), a company that provides a lot of boards for ham-related projects. A caution regarding the circuit boards is in order — the boards do not have plated through holes so you will have to be sure that you solder the through-hole components on *both* sides of the board.

Artwork for the PC board layout, Gerber files, and a drill file are available on the CD-ROM included with this book. The schematic capture software *DipTrace* was used in the development of this project. Source files for the schematic and PCB files are also available on the CD-ROM.

7.16.2 12 V, 15 A Linear Power Supply

This power supply is a linear 12 V, 15 A design by Ed Oscarson, WA1TWX. It is suitable for typical mobile radios and offers adjustable output voltage and current limiting. Supply regulation is excellent, typically exhibiting a change of less than 20 mV from no load to 15 A. This basic design, with heftier components and additional pass transistors, can deliver over 30 A — enough to supply a 100 W class transceiver. (All numbered notes, additional circuit design information, a discussion of how to change the supply voltage and/or current ratings, construction and testing notes, a PCB template and a complete parts list are available on the CD-ROM included with this *Handbook*.)

CIRCUIT DESCRIPTION

Fig 7.59 is the supply's schematic. The ac line input is fused by F1, switched on and off by S1 and filtered by FL1. F1 and S1 are rated at about ¼ of the output current requirement (for 15 A output, use a 4 or 5 A slow-blow fuse or a similarly rated circuit breaker). FL1 prevents any RF from the secondary or load from coupling into the power line and prevents RF on the power line from disturbing supply operation. If your ac power line is clean, and you experience no RF problems, you can eliminate FL1, but it's inexpensive insurance.

When discharged, filter capacitor C1 looks like a short circuit across the output of rectifier U2 when ac power is applied. That usually subjects the rectifier and capacitor to a large inrush current, which can damage them. Fortunately a simple and inexpensive means of inrush-current limiting is available. Keystone Carbon Company (and others) produce a line of inrush-current limiters (thermistors) for this purpose. The device (RT1) is placed in series with one of the transformer primary leads. RT1 has a current rating of 6 A[1], and a cold resistance of 5 Ω. When it's hot, RT1's resistance drops to 0.11 Ω. Such a low resistance has a negligible effect on supply operation. Thermistors run *hot* so they must be mounted in free air, and away from anything that can be damaged by heat.[2,3]

The largest and most important part in the power supply is the transformer (T1). If purchased new, it can also be the most costly. Fortunately, a number of surplus dealers offer power transformers that can be used in this supply.

T1 produces 17 V ac RMS at 20 A; the center tap is not used. Bridge rectifier U2 provides full-wave rectification. Full-wave rectification reduces the ripple component of current that flows in the filter capacitor, resulting in less power dissipation in the capacitor's internal resistance. U2's voltage rating should be at least 50 V, and its current rating about 25% higher than the normal load requirement; a 2 A bridge rectifier will do. U2 is secured to the chassis or a heat sink because it dissipates heat.

C1 is a computer-grade electrolytic. Any capacitor value from 15,000 to 30,000 µF will suffice. This version uses a 19,000 µF, 40 V capacitor. The capacitor's voltage rating should be at least 50% higher than the expected no-load rectified de voltage. In this supply, that voltage is 25 V, and a 40 V capacitor provides enough margin,

R5, a 75 Ω, 20 W bleeder resistor, is connected across C1's terminals to discharge the supply when no load is attached or one is removed, Any resistance value from 50 Ω to 200 Ω is fine; adjust the resistor's wattage rating appropriately.

At the terminals of C1, we have a dc voltage, but it varies widely with the load applied. When keying a CW transmitter or switching a rig from receive to full output, 5 V swings can result. The dc voltage also has an ac ripple component of up to 1.5 V under full load. Adding a solid-state regulator (U1) provides a stable output voltage even with a varying input and load.

VOLTAGE REGULATOR IC AND PASS TRANSISTORS

The LM723 used at U1 has a built-in voltage reference and sense amplifier, and a 150 mA drive output for a pass-transistor array. U1's voltage reference provides a stable point of comparison for the internal regulator circuitry. In this supply, it's connected to the non-inverting input of the voltage-sense op amp. The reference is set internally to 7.15 V, but the absolute value is not critical because an output-voltage adjustment (R12) is provided. What is important is that the voltage is stable, with a specified variation of 0.05% per 1000 hours of operation. This is more than adequate for the supply.

For the regulator to work properly, its ground reference must be at the same point as the output ground terminal. The best way to ensure this is to use the output GROUND terminal (J4) as a single-point ground for all of the supply grounds. Run wires to J4 from each component requiring a ground connection. Fig 7.59 attempts to show this graphically through the use of parallel connections to a single circuit node.

The output pass transistor array consists of a TIP112 Darlington-pair transistor (Q5) driving three 2N3055 power transistors (Q1-Q3). This two-stage design is less efficient than connecting the power transistors directly to the LM723, but Q5 can provide considerably more base current to the 2N3055s than the 150 mA maximum rating of the LM723. You can place additional 2N3055s in parallel to increase the output current capacity of the supply.

This design is not fussy about the pass transistors or the Darlington transistor used. Just ensure all of these devices have voltage ratings of at least 40 V. Q5 must have a 5 A (or greater) collector-current rating and a beta of over 100. The pass transistors should be rated for collector currents of 10 A or more, and have a beta of at least 10.[5]

Resistors R17, R18 and R19 prevent leakage current through the collector-base junction from turning on the transistor by diverting it around the base-emitter junction. When the pass transistors are hot, at the V_{CE} encountered in this design, the leakage current can be as high as 3 mA. The resulting drop across the 33 Ω resistors is 0.1 V — safely below the turn-on value for V_{BE}.

When unmatched transistors are simply connected in parallel they usually don't equally share the current.[6] By placing a low-value resistor in each transistor's emitter lead (emitter-ballasting resistors, R1-R3), equal current sharing is ensured. When a transistor with a lower voltage drop tries to pass more current, the emitter resistor's voltage drop increases, allowing the other transistors to provide more current. Because the voltage-sense point is on the load side of the resistors, the transistors are forced to dynamically share the load current.

With a 5 A emitter current, 0.25 V develops across each 0.05 Ω resistor, producing 1.25 W of heat. Ideally, a resistor's power rating should be at least twice the power it's called upon to dissipate. To help the resistors dissipate the heat, mount them on a heat sink,

[1]See the full article on the *Handbook* CD-ROM for a list of numbered notes.

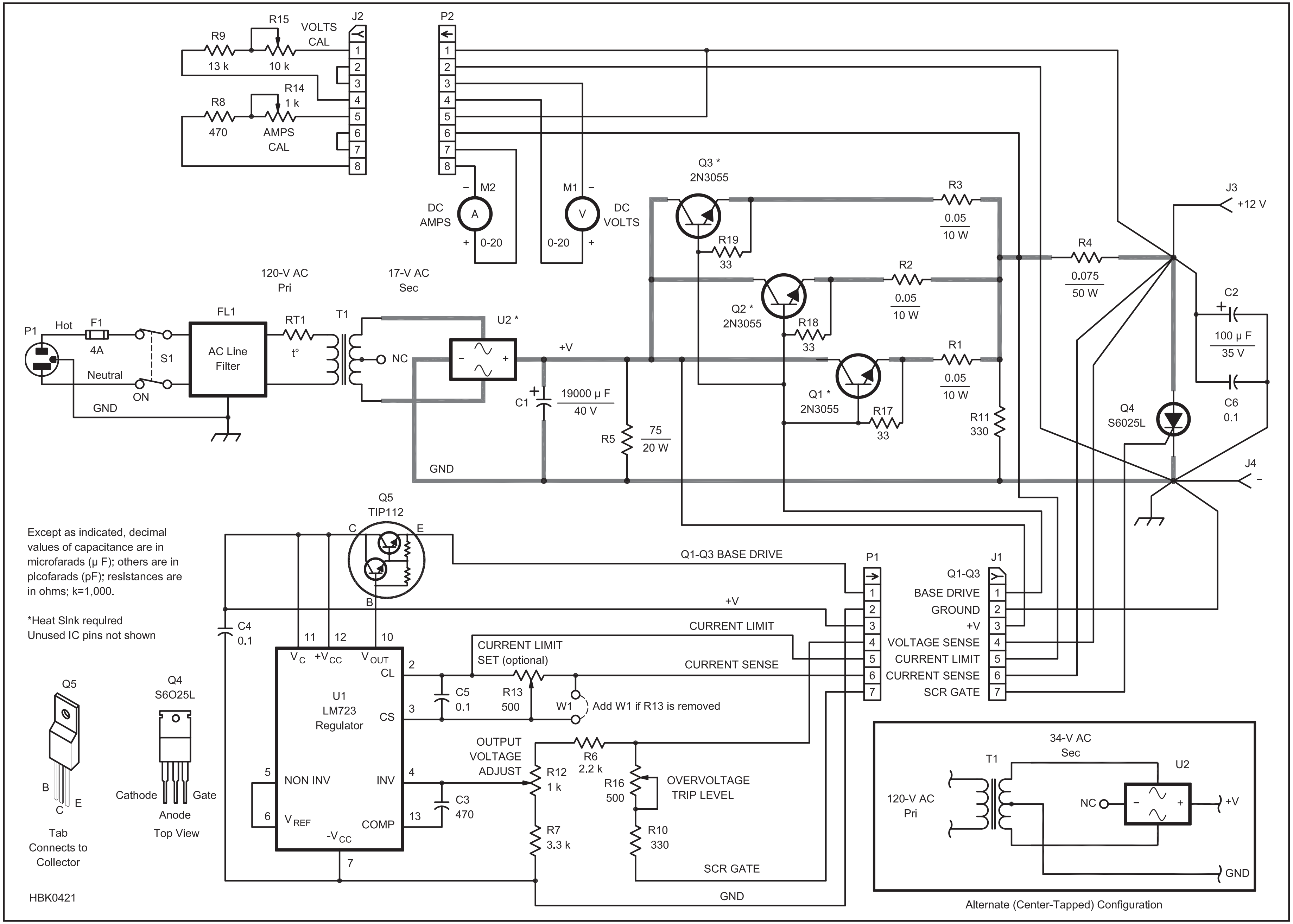


Fig 7.59 — Schematic of the 12 V, 15 A power supply. A parts list may be found on the *Handbook* CD-ROM. Equivalent parts can be substituted. The bold lines indicate high-current paths that should use heavy-gauge (#10 or #12 AWG) wire. This schematic graphically shows wiring to a single-point ground; see text. The majority of the parts used in this supply are available as surplus components.

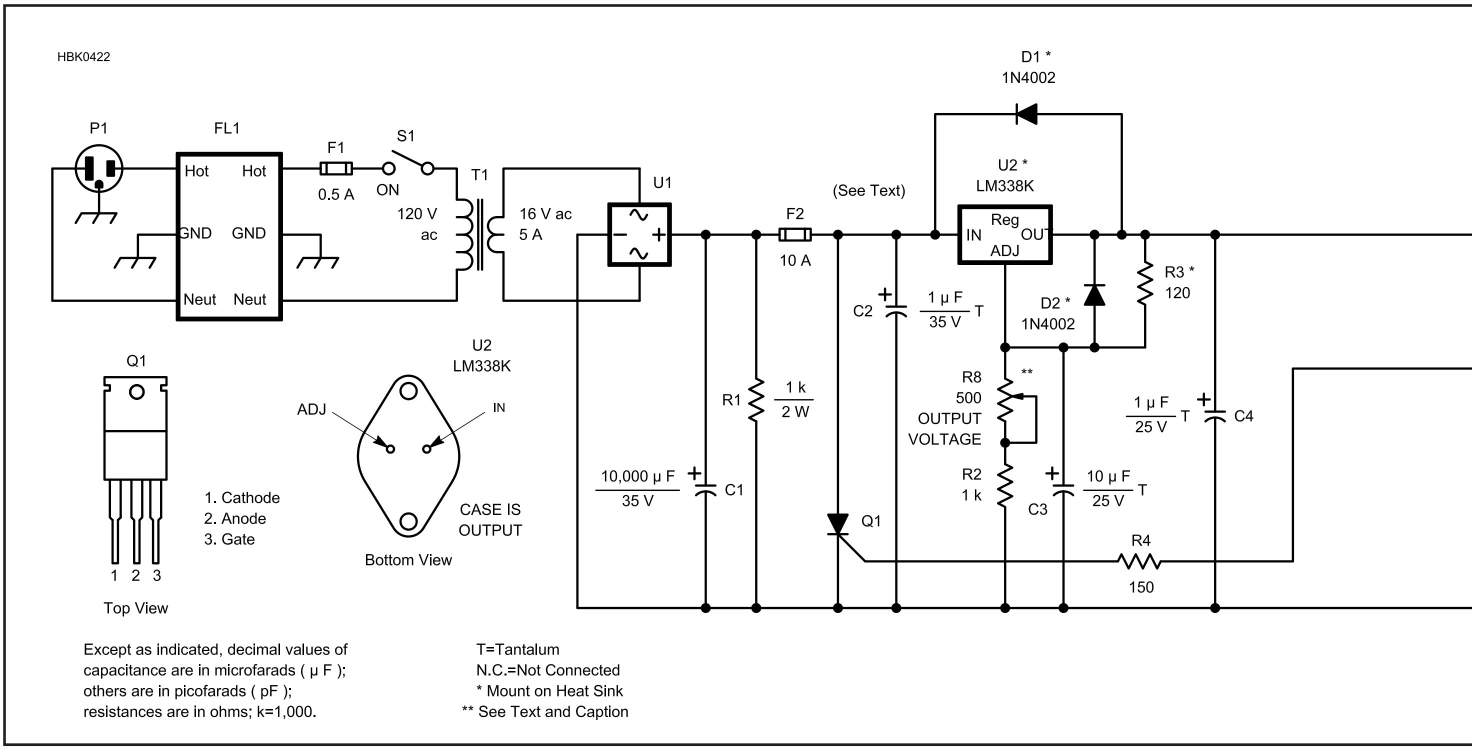


Fig 7.60 — Schematic for the 13.8 V, 5 A power supply. Unless otherwise specified, resistors are ¼ W, 5% tolerance. A PC board and U3 are available from FAR Circuits (www.farcircuits.net). The PC board has mounting holes and pads to allow for handling different trimmer-potentiometer footprints. A PC board template is available on the CD-ROM for this book. The author may be contacted at scskits@charter.net for assistance in obtaining parts and printed-circuit boards.

C1 — 10,000 μF, 35 V electrolytic.
C2, C4 — 1 μF, 35 V tantalum.
C3 — 10 μF, 35 V tantalum.
C5 — 0.1 μF, 25 V ceramic disc.
D1-D3 — 1N4002.
DS1 — Red LED.
F2 — Fast-acting 10 A fuses; three required (see text).
F1 — Fast-acting 0.5 A fuse.
FL1— Ac-line filter.
Q1 — BT152 400 V, 25 A SCR in TO-220A package (NTE5554)
R8 — 500 Ω, single-turn trimmer potentiometer.
R9 — 500 Ω or 1 kΩ, single-turn trimmer potentiometer.
S1 — SPST panel-mount switch.
T1 — 120 V primary, 16- to 20 V, 5 A secondary.
U1 — 100-PIV, 6 A bridge rectifier.
U2 — LM338K 5 A adjustable power regulator in a TO-3 package.
U3 — MC3423P1 overvoltage protection IC.
Misc: two panel-mount fuse holders; line cord; heat sinks for TO-3 case transistors; TO-3 mounting kit and heat-sink grease; black and red binding posts; chassis or cabinet; PC board; hardware, rubber hoods, heat-shrink tubing or electrical tape for F1 and FL1, hook-up wire.

or secure them to a metal chassis. You can use any resistor with a value between 0.065 and 0.1 Ω, but remember that the power dissipated is higher with higher-value resistors (10 W resistors are used here).

At the high output currents provided by this supply, the pass transistors dissipate considerable power. With a current of 5 A through each transistor-and assuming a 9 V drop across the transistor — each device dissipates 45 W. Because the 2N3055's rating is 115 W when used with a properly sized heat sink, this dissipation level shouldn't present a problem. If the supply is to be used for continuous-duty operation, increase the size of the heat sink and mount it with the fins oriented vertically to assist in air circulation.

The output-voltage sense is connected through a resistive divider to the negative input of U1. U1 uses the difference between its negative and positive inputs to control the pass transistors that in turn provide the output current. C3, a compensation capacitor, is connected between this input and a dedicated compensation pin to prevent oscillation. The output voltage is adjusted by potentiometer R12 and two fixed-value resistors, R6 and R7.[7] The voltage-sense input is connected to the supply's positive output terminal, J3.

Current sensing is done through R4, a 0.075 Ω, 50 W resistor connected between the emitter-ballasting resistors and J3. R4's power dissipation is much higher than that of R1, R2 or R3 because it sees the total output current. At 15 A, R4 dissipates 17 W. At 20 A, the dissipated power increases to 30 W.

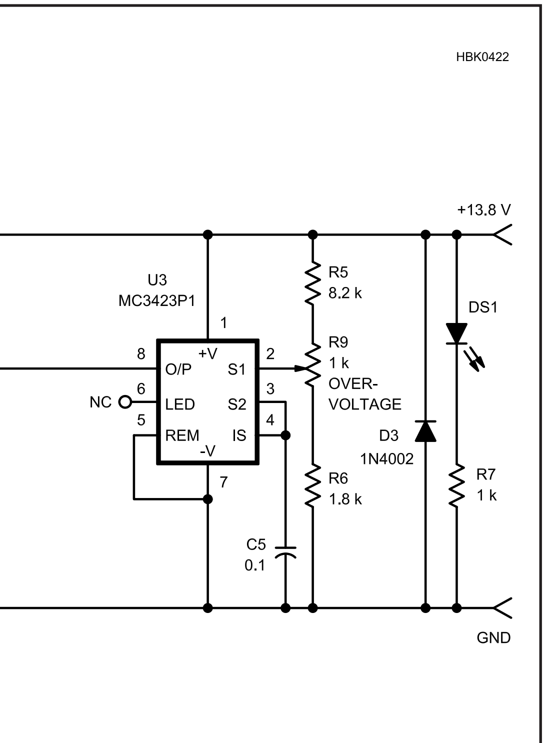
U1 provides current limiting via two sense inputs connected across R4. Limiting takes place when the voltage across the sense inputs is greater than 0.65 V.[8] For a 15 A maximum output-current limit, this requires a 0.043 Ω resistor. By using a larger-value sense resistor and a potentiometer, you can vary the current limit. Connecting potentiometer R13 across R4 provides a current-limiting range from full limit voltage (8.7 A limit) to no limit voltage. This allows the current limit to be fine-tuned, if needed, and also permits readily available resistor values (such as the author's 0.075 Ω resistors) to be used. A current limit of 20 A is at the top end of the ammeter scale.

R20 maintains a small load of 35-40 mA depending on power supply output voltage. This reduces the effect of leakage current in the pass transistors and keeps the regulator's feedback action active, even if no external load is connected.

METERING

Voltmeter M1 is a surplus meter. R8 and potentiometer R15 provide for voltmeter calibration. If the correct fixed-value resistor is available, R15 can be omitted. The combined value of the resistor and potentiometer is determined by the full-scale current requirement of the meter used.[9]

Ammeter M2 is actually a voltmeter (also surplus) that measures the potential across R4. The positive side of M2 connects to the high



side of R4. R8 and potentiometer R14 connect between the positive output terminal (J3) and the negative side of M2 to provide calibration adjustment. The values of R8 and R14 are determined by the coil-current requirements of the meter used. (Digital panel meters or a dedicated DMM can be used instead of separate analog meters.)

OUTPUT WIRING AND CROWBAR CIRCUIT

The supply output is connected to the outside world by two heavy-duty banana jacks, J3 and J4. C2, a 100 μF capacitor, is soldered directly across the terminals to prevent low-frequency oscillation. C6, a 0.1 μF capacitor, is included to shunt RF energy to ground. Heavy-gauge wire must be used for the connections between the pass transistors and J3 and between chassis ground and J4. The voltage-sense wire must connect directly to J3 and U2's ground pin must connect directly to J4 (see Fig 7.59). This provides the best output voltage regulation.

An over-voltage crowbar circuit prevents the output voltage from exceeding a preset limit. If that limit is exceeded, the output is shunted to ground until power is removed. If the current-limiting circuitry in the supply is working properly, the supply current-limits to the preset value. If the current limiting is not functioning, the crowbar causes the ac-line fuse to blow. Therefore, it's important to use the correct fuse size: 4 to 5 A for a 15 A supply.

The crowbar circuit is a simple design based on an SCR's ability to latch and conduct until the voltage source is removed. The SCR (Q4) is connected across output terminals J3 and J4. (The SCR can also be connected directly across the filter capacitor, C1, for additional protection.) R10 and potentiometer R16 in series with the Q4's gate provide a means of adjusting the trip voltage. The prototype crowbar is set to conduct at 15 V. The S6025L SCR is rated at 25 A and should be mounted on a metal chassis or heat sink. (Note: Some SCRs are isolated from their mounting tabs, others are not. The S6025L and the 65-ampere S4065J are isolated types. If the SCR you use is not isolated, use a mica washer or thermal pad to insulate it from the chassis or heat sink.)

The bold lines in Fig 7.59 indicate high-current paths that should use heavy-gauge (#10 or #12 AWG) wire. Traces that are connected to the output terminals in the schematic by individual lines should be connected directly to the terminals by individual wires. This establishes a 4-wire measurement, where the heavy wires carry the current (and have voltage drops) and the sense wires carry almost no current and therefore voltage errors are not caused by voltage drops in the wiring. If desired, the sense wire can be carried out to the load, but that may introduce noise into the sense feedback circuit, so use caution if that is done.

7.16.3 13.8 V, 5 A Linear Power Supply

This power supply was designed by Ben Spencer, G4YNM, provides 13.8 V dc at 5 A, suitable for many low-power transceivers and accessories. It features time-dependent current limiting and short-circuit protection, thermal overload protection within the safe operating area of the regulator IC, and overvoltage protection for the equipment it powers. The prototype supply powers a 25 W transmitter that continually draws 4.5 A.

Construction, testing and calibration are straightforward, requiring no special skills or equipment. Many of the components can be found in junk boxes, or purchased at hamfests or from mail-order suppliers.

CIRCUIT DESCRIPTION

Fig 7.60 is the power supply schematic. Incoming ac line current is filtered by a chassis-mounted line filter (FL1) and, after passing through the fuse (F1), is routed S1 to T1.

U1 rectifies, and C1 filters, the ac output of T1. U2 is an LM338K voltage regulator. This IC features a current-limited continuous output of 5 A, with a guaranteed peak output of 7 A. It also has on-chip thermal and safe-operating-area protection for itself. U2's output voltage is set by two resistors (R2 and R3) and a trimmer potentiometer (R8), which allows for adjustment over a small range. U2's input and output are bypassed by C2, C3, and C4. D1 and D2 protect U2 against these capacitors discharging through it.

Overvoltage protection is provided by an SCR, Q1, across the regulator input. Normally, Q1 presents an open circuit, but under fault conditions, it's triggered and short-circuits the unregulated dc input to ground. This discharges C1 through F2 which is rated at 10 A in order for C1 to quickly discharge below 12 V, avoiding damage to connected equipment.

U3, an overvoltage-protection IC, continuously monitors the output voltage. When the output voltage rises above a predetermined level, U3 starts charging C5. If the overvoltage duration is sufficiently long, U3 triggers Q1. This built-in delay (about 1 ms) allows short transient noise spikes on the output voltage to be safely ignored while still triggering the SCR if a true fault occurs. The monitored voltage is set by R5 and R6 and trimmer potentiometer R9, which allows for adjustment over a limited range.

D3 protects the supply from reverse-polarity discharge from connected equipment. The presence of output voltage is indicated by an LED, DS1. R7 is a current limiting resistor for DS1.

CONSTRUCTION

How you construct your supply depends on the size of the components and enclosure you use. General physical layout is not important, although there are a couple of areas that require some attention. In the unit shown in **Fig 7.61**, FL1, the fuse holders, S1, the heat sink. DS1 and the binding posts are mounted on the front and rear enclosure panels. T1 and the PC board are secured to the enclosure's bottom plate. C1's mounting clamp is attached to the rear panel. Bleeder resistor R1 is connected directly across C1's terminals. D3 is soldered directly across the output binding posts.

U2, D1, D2 and R3 are all mounted directly on the heat sink with the transistor pins and solder lugs acting as a terminal strip. It's important to keep R3 attached as closely as possible to U2's terminals to prevent instability. Use a TO-3 mounting kit and heat-conductive grease or thermal pad to electrically isolate U2 from the heat sink.

Mount U2, C1, and the PC board close to each other and keep the wire runs between these components as short as possible. Excessively long wire runs may lead to unpredictable behavior.

Cover all ac-input wiring (use insulated wire and heat-shrink tubing) to prevent electrical shock and route the ac wiring away from the dc wiring. Mount the heat sink on the enclosure with fins oriented vertically. Louvers or ventilation holes in the cabinet will help cool internal components.

TEST AND CALIBRATION

An accurate multimeter covering ranges of 30 V dc and 10 A dc is required. A variable resistive load with a power rating of 100 W is also needed; this can he made using a heat-sink-mounted 2N3055 power transistor and a couple of components as shown in the next project.

First, set R8 (OUTPUT VOLTAGE) fully clockwise and R9 (OVERVOLTAGE) fully counterclockwise. Insert a fuse in the dc line at F2. Connect the ac line, turn on S1 and check that DS1 lights. Measure the output voltage: it should be about 12 V. Adjust R8 counterclockwise until you obtain 14.2 V output; this sets the trip voltage.

While monitoring the output voltage, gradually adjust R9 clockwise until the voltage suddenly falls to zero. This indicates that the SCR has triggered and blown F2. Disconnect the ac line cord from the wall socket. *Don't make any adjustment to R9!* Instead, adjust R8 fully clockwise.

With the ac line cord removed, check that F2 is open. Replace F2 with a new fuse (now you know why two of the three fuses are called for). Reconnect the ac line cord, and while continually monitoring the output voltage, gradually adjust R8 until Q1 again triggers at 14.2 V, blowing F2. If you find the adjustment of R9 to be too sensitive, use a 500 Ω potentiometer in its place and reduce the value of R5 (if necessary) to provide the required adjustment range.

Again disconnect the line cord from the wall socket, set R8 fully clockwise, replace F2 (there's the third fuse!) and reset R8 for 13.8 V. This completes the voltage calibration and overvoltage protection tests. The power supply is now set to 13.8 V output, with the overvoltage protection set for 14.2 V.

Adjust R2 of the variable resistive load in Fig 7.62 to maximum resistance (minimum load current) and connect it to the power supply output in series with the ammeter. Turn on the power supply and gradually adjust R2 until a current of 5 A flows. Decrease the resistance further and check that the current limits between 5.5 A and 0.5 A.

Finally, be thoroughly unpleasant and apply a short circuit via the ammeter. Check that the current-limiting feature operates correctly. The prototype limited at approximately 3.5 A. Disconnect the ac line cord and test equipment, dose up the case and your power supply is ready for service.

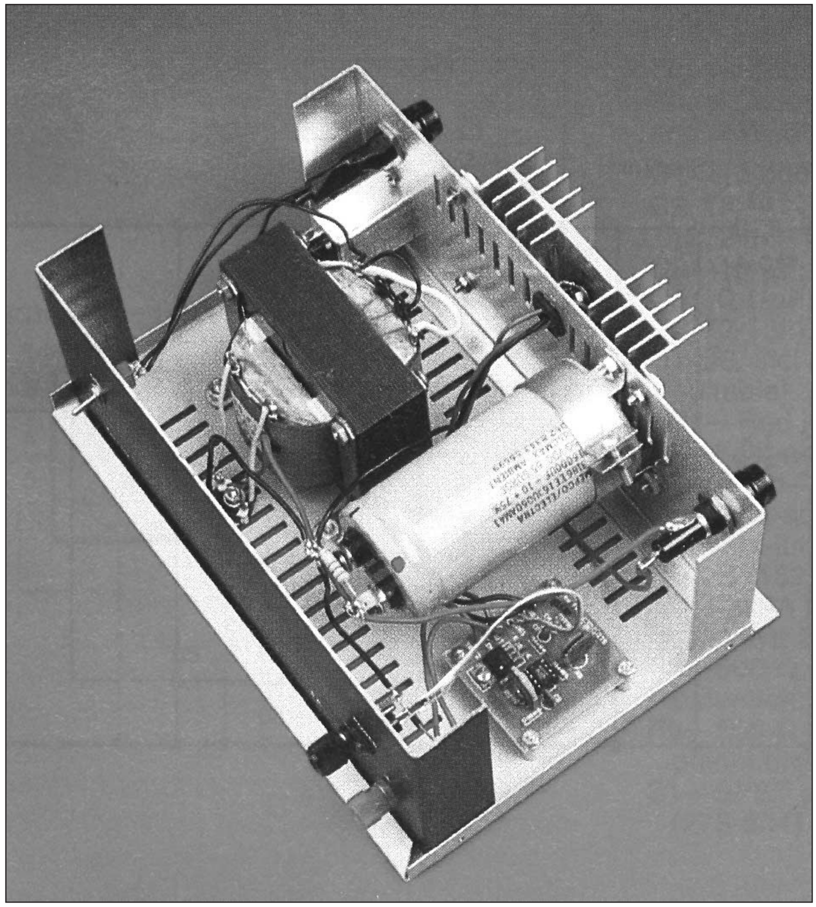


Fig 7.61 — Physical layout of the 13.8 V, 5 A power supply. On the rear panel, left, are the ac-line filter and F1. The regulator's heat sink is at the middle of the panel and F2 is to the right. At the bottom of the enclosure, in front of T1, is the diode bridge rectifier. Because C1 is too tall to mount vertically within the Hammond #1426O cabinet, its mounting clamp is secured to the inside rear panel. Immediately to the right of C1 is the PC board. On the front panel are the on/off switch, LED power-on indicator and output-voltage binding posts.

7.16.4 Adjustable Resistive Load

Fig 7.62 shows the schematic of an adjustable resistive load that can be used to test and adjust power supplies at currents up to 10 A if the 2N3055 transistor is mounted on an adequate heat sink. R1 and R2 vary the base bias to control the collector current of Q1. For extended use, be sure to use a large heat sink with adequate ventilation. Use heavy wire through the current meter to the collector and from the emitter of Q1.

7.16.5 Inverting DC-DC Converter

It's often the case that you need +V and –V when all you have is +V. For example, you need +12 V and –12 V, but all that's available is +12 V. It would be really handy to have a "black box" that would give you –V out when you put +V in, and work over a range of voltages without adjustment. This project by Jim Stewart, which originally appeared in the January 2013 issue of *Nuts and Volts Magazine* (**www.nutsvolts.com**), fills that need by using a switchmode voltage mirror to supply more than 100 mA without a significant drop in voltage.

The following text summarizes how the circuit works. A PDF version of the complete article is included on the CD-ROM that comes with this book. It contains more details about the circuit's design, plus construction and testing information. A PCB and parts kit is available from the *Nuts and Volts* online store, as well. An ExpressPCB file (PV2NV.PCB) is available for download at **www.nutsvolts.com/index.php?/magazine/article/january2013_Stewart**.

CIRCUIT DESIGN

The circuit in **Fig 7.63** is a buck-boost dc-dc converter as described earlier in this chapter. This particular design has five important parameters:

- Input voltage: V_{IN}
- Output voltage: V_{OUT}
- Load resistance: R_{LOAD}
- Oscillation frequency: f
- Inductance value: L

The parameters are related to each other by $f \times L < (V_{IN} / V_{OUT})^2 \times (R_{LOAD} / 8)$. For $V_{IN} = V_{OUT}$, the equation simplifies to

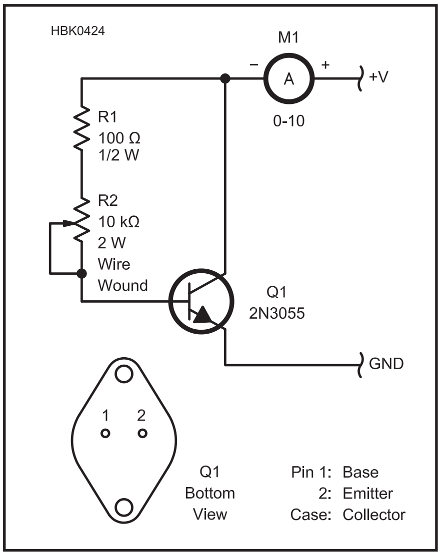


Fig 7.62 — An active resistive load to use in testing power supplies up to 10 A with adequate heat sinking. Adjustment of R2 is sensitive.
M1 — Multimeter or ammeter capable of measuring 10 A.
Q1 — 2N3055; mount on heat sink.

$f \times L < (R_{LOAD} / 8)$. (See the complete article on the CD-ROM for the derivation of these equations.)

Fig 7.63 shows the schematic of the circuit. A square wave oscillator (U2) drives a MOSFET (Q2) that, in turn, drives a PNP switching transistor (Q3). The oscillator is enabled/disabled by the output of the comparator (U1) with inputs that are a set point voltage (V_S on the comparator's + input) and a feedback voltage (V_F at the comparator's – input). (Comparators are described in the **Analog Fundamentals** chapter.) The frequency of the oscillator is $f = 1 / 2.2 (R7 \times C3)$.

When the output voltage, V_{OUT}, is the correct value, V_S exceeds V_F by a few µV and the oscillator is disabled by Q1 so that the PNP switch is off. When V_S is less than V_F, the oscillator is enabled and the PNP transistor switches on and off. V_S is half the input voltage $V_S = V_{IN}/2$ as set by the R3-R4 voltage divider.

V_F is set by the R1-R2 divider to equal $V_{IN}/2$ when the output voltage $V_{OUT} = -V_{IN}$. D2 is a commutating diode that blocks +V from the output while charging the inductor. It then provides a current path for the discharging inductor to transfer charge to the output capacitor.

The switching action continues until the voltage on the capacitor equals $-V_{IN}$. At that point, the comparator disables the oscillator and Q3 stays OFF. When voltage across the capacitor drops, the comparator enables the oscillator and the inductor is pumped up again.

Since there is a single input voltage, each op-amp uses a resistor divider to "split the rail" to create a signal ground. That allows the negative input to sense positive and negative voltages with respect to the positive input. C2 and C4 bypass the signal grounds to the supply voltage ground.

C1 and C5 are low-ESR (equivalent series resistance — see the **Electrical Fundamentals** chapter) aluminum electrolytic capacitors. Tantalum capacitors might be a bit better, but are more expensive. ESR determines how much power the capacitor can safely dissipate. $P_{DISS} = I^2_{RC} \times ESR$, where I_{RC} is the ac ripple current in the capacitor. The capacitors chosen are rated for a maximum ripple current of 840 mA.

D1 and D2 are Schottky diodes that can go from conducting to non-conducting very quickly, allowing a high switching frequency. They also have a low voltage drop when conducting to reduce power loss. D1 limits the output voltage in case the feedback fails.

Q3 is a ZTX550 PNP transistor, chosen because its specifications suit this application well:

- Maximum power dissipation, P_{MAX} = 1 W @ 25 °C
- Maximum continuous collector current, I_C = 1 A

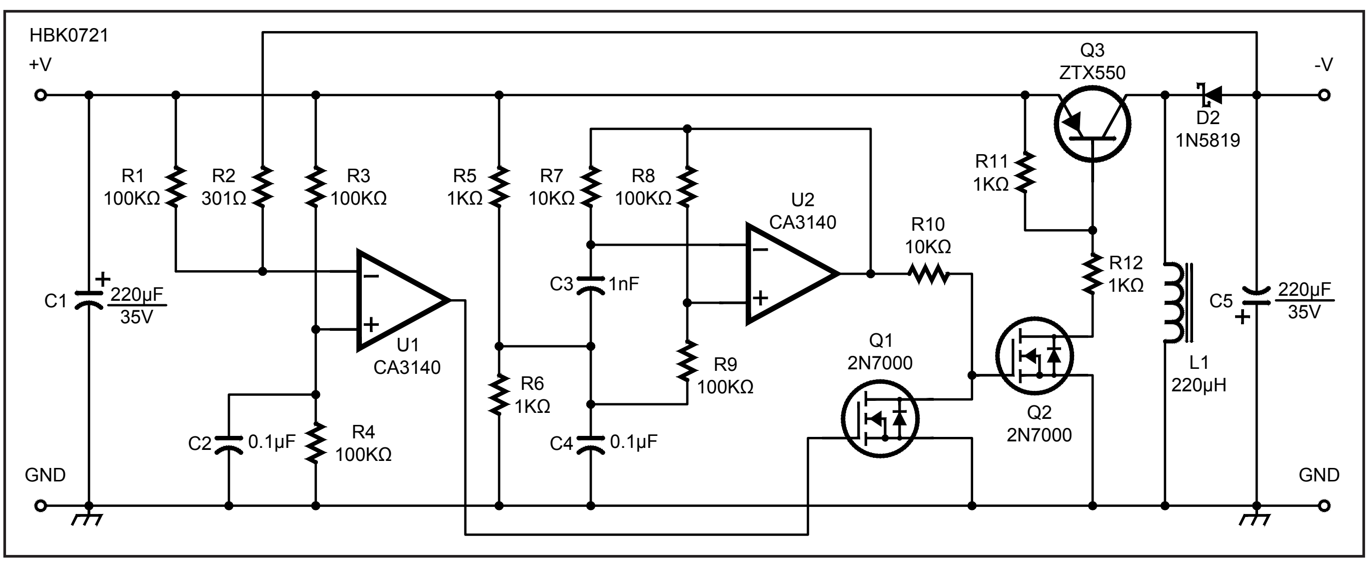


Figure 7.63 — A voltage mirror dc-dc power converter based on a buck-boost converter. The negative output —V is equal in magnitude to the positive input voltage +V at an output current up to approximately 100 mA

C1 — 220 µF, 35 V (Digi-Key part #493-1578-ND or equiv).
C2 — 0.1 µF, 50 V, ceramic.
C3 — 1 nF film, 5% (Digi-Key part #399-5871-ND or equiv).
C4 — 0.1 µF, 50 V, ceramic.
C5 — 220 µF, 35 V (Digi-Key part #493-1578-ND or equiv).
D1 — Not required, do not install.
D2 — Schottky, 1 A, 1N5819 or equiv.
L1 — 220 µH (Digi-Key part #811-1316-ND or equiv).
Q1, Q2 — 2N7000.
Q3 — ZTX550 PNP.
R1, R3, R4, R8, R9 — 100 kΩ, ¼ W, 1%.
R2 — 301 kΩ, ¼ W, 1%.
R5, R6, R11, R12 — 1 kΩ, ¼ W, 1%.
R7, R10 — 10 kΩ, ¼ W, 1%.
U1, U2 — CA3140.
Terminal Blocks (optional) — Two-position, 5 mm spacing (Jameco part #2094485 or equiv).

• Maximum collector-base voltage, $V_{CBO} = 60$ V

• Maximum saturation voltage, $V_{CE} = 0.25$ V @ $I_C = 150$ mA

• Transition frequency, $f_T = 150$ MHz minimum

• Package: E-Line (slightly smaller than TO-92)

For this design, the chosen values are L = 220 µH, f = 45 kHz, and $R_{LOAD} = 100\ \Omega$. Verifying that f × L is less than R_{LOAD} / 8, $f \times L = (45 \times 10^3) \times (220 \times 10^{-6}) = 9900 \times 10^{-3} = 9.9\ \Omega$ and $R_{LOAD} / 8 = 100/8 = 12.5\ \Omega$ which is less than R_{LOAD} / 8 = 12.5. Higher values of R_{LOAD} (lower output current) also satisfy the equation. Increasing the value of L or f will require that the circuit be tested to verify that it works.

7.16.6 High-Voltage Power Supply

This two-level, high-voltage power supply was designed and built by Dana G. Reed, W1LC. It was designed primarily for use with an RF power amplifier. The supply is rated at a continuous output current of 1.5 A, and will easily handle intermittent peak currents of 2 A. The 12 V control circuitry and the low-tap setting of the plate transformer secondary make it straightforward to adapt the design to homemade tube amplifiers.

The step-start circuit is straightforward and ensures that the rectifier diodes are current-limited when the power supply is first turned on. A 6 kV meter is used to monitor high-voltage output.

Fig 7.64 is a schematic diagram of the bi-level supply. An ideal power supply for a high-power linear amplifier should operate from a 240 V circuit, for best line regulation. A special, hydraulic/magnetic circuit breaker also serves as a disconnect for the plate transformer primary. Don't substitute a standard circuit breaker, switch or fuses for this breaker; fuses won't operate quickly enough to protect the amplifier or power supply in case of an operating abnormality. The 100 kΩ, 3 W bleeder resistors are of stable metal-oxide film design. These resistors are wired across each of the 14 capacitors to equalize voltage drops in the series-connected bank. This choice of bleeder resistor value provides a lighter load (less than 25 W total under high-tap output) and benefits mainly the capacitor-bank filter by yielding much less heat as a result. A reasonable, but longer bleed-down time to fully discharge the capacitors results — about nine minutes after power is removed. A small fan is included to remove any excess heat from the power supply cabinet during operation.

POWER SUPPLY CONSTRUCTION

The power supply can be built in a 23½ × 10¾ × 16-inch cabinet. The plate transformer is quite heavy, so use ⅛-inch aluminum for the cabinet bottom and reinforce it with aluminum angle for extra strength and stability. The capacitor bank will be sized for the specific capacitors used. This project employed ⅜-inch thick polycarbonate for reasonable mechanical stability and excellent high-voltage isolation. The full-wave bridge consists of four commercial diode block assemblies.

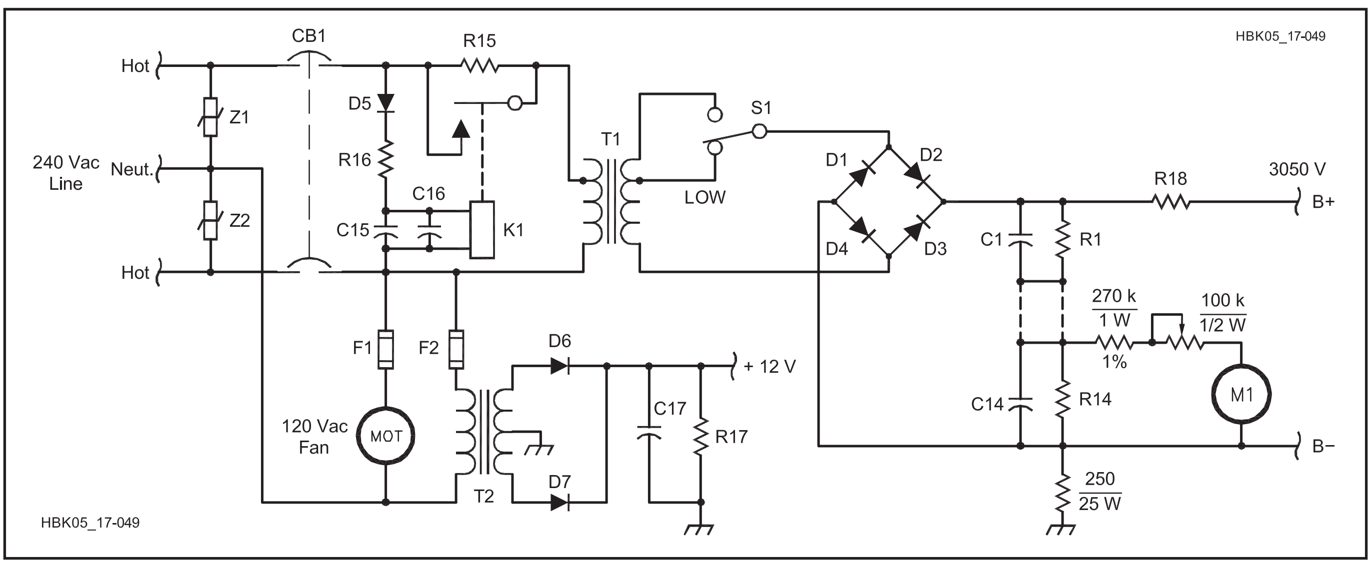


Fig 7.64 — Schematic diagram of the 3050 V/5400 V high-voltage power supply.

C1-C14 — 800 µF, 450 V electrolytic.
C15, C16 — 4700 µF, 50 V electrolytic.
C17 — 1000 µF, 50 V electrolytic.
CB1 — 20 A hydraulic/magnetic circuit breaker (TE Connectivity/Potter & Brumfield W68-X2Q12-20 or equiv). 40 A version required for commercial applications/ service (TE Connectivity/Potter & Brumfield W92-X112-40).
D1-D4 — String of 1000 PIV, 6 A diodes (6A10 or equiv).
D5 — 1000 PIV, 3 A, 1N5408 or equiv.
D6, D7 — 200 PIV, 3 A, 1N5402 or equiv.
F1, F2 — 0.5 A, 250 V (Littelfuse 313 Series, 3AG glass body or equiv).
K1 — DPDT power relay, 24 V dc coil; both poles of 240 V ac/25 A contacts in parallel (TE Connectivity/Potter & Brumfield PRD-11DYO-24 or equiv).
M1 — High-voltage meter, 6 kV dc full scale. (Important: Use a 1 mA or smaller meter movement to minimize parallel-resistive loading at R14. Also, select series meter-resistor and adjustment-potentiometer values to calibrate your specific meter. Values shown are for a 1 mA meter movement.)
MOT1 — Cooling fan, 119 mm, 120 V ac, 30-60 CFM, (EBM Pabst 4800Z or equiv).
R1-R14 — Bleeder resistor, 100 kΩ, 3 W, metal oxide film.
R15 — 50 Ω, 100 W.
R16 — 3.9 kΩ, 25 W.
R17 — 30 Ω, 25 W.
R18 — 20 Ω, 50 W.
S1 — Ceramic rotary, 2 position tap-select switch (optional). Voltage rating between tap positions should be at least 2.5 kV. Mount switch on insulated or ungrounded material such as a metal plate on standoff insulators, or an insulating plate, and use only a *nonconductive* or otherwise *electrically-isolated* shaft through the front panel for safety.
T1 — High-voltage plate transformer, 220/240 V primary, 2000/3500 V, 1.5 A CCS JK secondary, Hypersil C-core (Hammond Engineering, www.hammfg.com). Primary 220 V tap fed with nominal 240 V ac line voltage to obtain modest increase in specified secondary voltage levels.
T2 — 120 V primary, 18 V CT, 2 A secondary (Mouser 41FJ020).
Z1-Z2 — 130 V MOV.

POWER SUPPLY OPERATION

When the front-panel breaker is turned on, a single 50 Ω, 100 W power resistor limits primary inrush current to a conservative value as the capacitor bank charges. After approximately two seconds, step-start relay K1 actuates, shorting the 50 Ω resistor and allowing full line voltage to be applied to the plate transformer. No-load output voltages under low- and high-tap settings as configured and shown in Fig 7.64 are 3050 V and 5400 V, respectively. Full-load levels are somewhat lower, approximately 2800 V and 4900 V. If a tap-select switch is used as described in the schematic parts list, it should only be switched when the supply is off.

7.16.7 Reverse-Polarity Protection Circuits

*The following material was collected from various public-domain sources by Terry Fletcher, WAØITP(**www.wa0itp.com/revpro.html**) and published in the* QRP Quarterly*, Spring 2012 issue. (**www.qrparci.org**)*

DC power is the standard for most amateur radios and accessories, usually a nominal 12 V (10.5 to 13.8 V). There are many different types of connectors used for dc power — from screw terminals to custom-molded multi-pin designs. This makes it easy to accidentally apply power with reversed polarity and damage equipment. Even a few milliseconds of reversed power can be sufficient to destroy a semiconductor or burn out a narrow PCB trace. This can be a particular problem when using 9 V batteries as it is easy to reverse the snap-on connector when changing or installing a battery.

The following collection of circuits illustrates ways to protect equipment from reverse-polarity dc power. The suitability of the circuits depends on the equipment and power source. All dc power sources, particularly batteries, should be fused or current-limited to mitigate fire hazards and other damage from overheating wires and other conductors.

Fig 7.65 shows several passive circuits that dissipate some power due to the series forward voltage drop of the diodes. At currents above 1 A, the power dissipated can easily exceed 1 W and the maximum junction temperature of the diode can be exceeded without some sort of thermal protection or heat sinking. (The shunt diode circuit in Fig 7.65D does not dissipate power.) **Fig 7.66** shows two methods of using an electromechanical relay that avoid the forward voltage drop of diode-based protection circuits. Which circuit you choose depends on the type of equipment and constraints on power dissipation and voltage drop.

PASSIVE CIRCUITS

Blocking diode (Fig 7.65A) — A series diode is very simple and inexpensive. Its PIV rating should be at least twice the expected applied voltage — 50 V PIV is a good minimum value for automotive and 12 V dc use. Its maximum average forward current rating should be several times the expected maximum steady-state current draw.

Remember that a silicon junction diode's forward voltage drop, V_f, is at least 0.6 V and can approach 1.0 V at high forward current. This can result in significant power dissipation ($P = V_f \times I_f$) and cause the diode's maximum rated junction temperature to be exceeded unless some means of cooling the diode is provided.

The forward voltage drop of the diode will also reduce the voltage available to the equipment being powered. This will raise the minimum allowable power supply voltage for the equipment to operate properly. For example, if a piece of equipment is rated to operate properly at or above 11 V, a series diode with V_f = 0.6 V raises the minimum allowable power supply voltage to 11 + 0.6 = 11.6 V. This may be significant in battery-powered installations.

The Schottky barrier diode shown as an alternate may be a better choice due to its forward voltage drop being lower by several tenths of a volt, reducing power dissipation. A Schottky diode may be used in place of any of the diodes in Figures 7.65 and 7.66. Be sure the reverse current leakage of the Schottky diode is acceptable.

Full-wave bridge rectifier (Fig 7.65B) — The full-wave circuit has the advantage of always supplying voltage with the proper polarity to the equipment being powered.

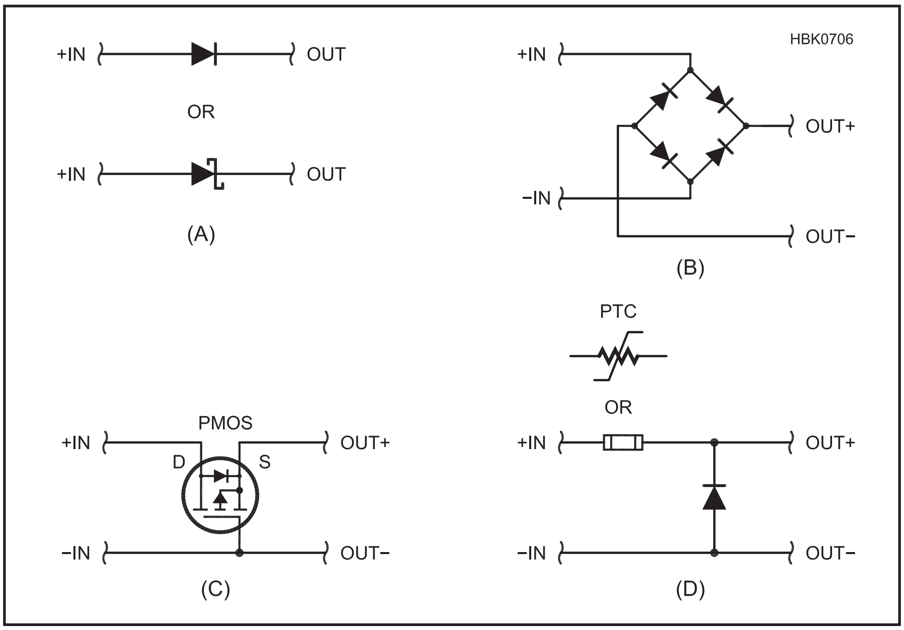


Fig 7.65 — Passive circuits for reverse-polarity protection. Series diode (A). Full-wave rectifier (B). PMOS MOSFET with integral body diode shown as separate component (C). Shunt diode (D). Schottky barrier diodes may be used in all circuits as a substitute for silicon junction rectifiers. See text for circuit comparison.

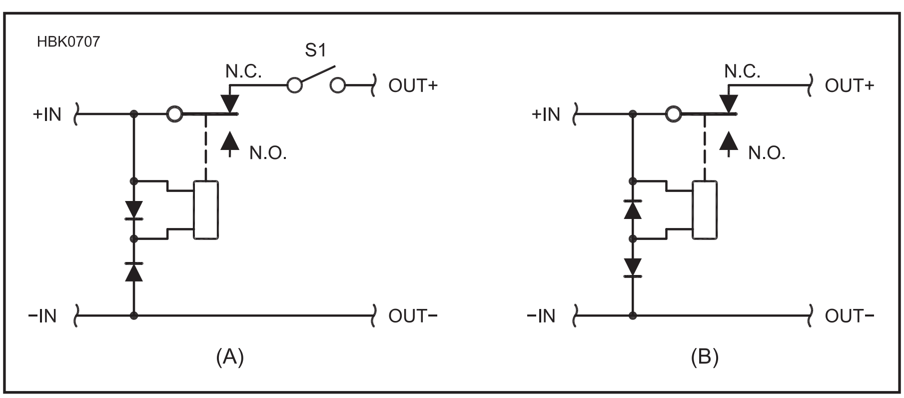


Fig 7.66 — Relay-based circuits for reverse-polarity protection. Normally-closed contacts (A) and normally-open contacts (B). See text for circuit comparison.

Full-wave rectifiers are also available as integrated packages, making them easy to install. Remember that the forward voltage drop and power dissipation of this circuit will be twice that of the single series diode because two diodes are always in series with supply current.

PMOS P-channel MOSFET (Fig 7.65C) — This circuit uses a P-channel enhancement-mode (PMOS) MOSFET that conducts current with the gate connected as shown. PMOS devices have low on-resistance ($R_{ds(on)}$) and high maximum current ratings. Devices with on-resistance of 0.050 Ω and lower are commonly available. For more information about using PMOS and NMOS devices for polarity protection see Maxim Electronics Application Note 636, "Reverse-Current Circuitry Protection" (**www.maxim-ic.com/app-notes/index.mvp/id/636**). N-channel devices may also be used in the current return or ground lead, but opening the return connection can create other problems inside the equipment and with other devices on the same power circuits.

Shunt diode with fuse (Fig 7.65D) — These configurations use a single diode that acts to blow a fuse (either a fusible-link or positive temperature coefficient PTC resettable device) if reverse polarity voltage is applied. The advantage of this circuit is that no power is dissipated by the diode during normal operation. The diode must be sufficiently rated to handle the high surge current from shorting the power source and have current ratings significantly higher than the fuse current rating.

If the diode fails shorted or in a low-resistance state, it will continue to blow the fuse until replaced. If the diode fails open or high-resistance, it will no longer protect the circuit. If shunt diode protection is used and the fuse opens, check the diode to be sure it has not failed as well.

RELAY-BASED CIRCUITS

Relay-based circuits have the advantage of little to no voltage drop, even at high currents as long as the contact ratings are sufficient. The circuits are more complex than the diode-based circuits in the preceding section but can generally handle more current and are not damaged by reverse polarity voltages. The circuits reset themselves automatically.

Relay with normally-closed contacts (Fig 7.66A) — There is no current drain through the relay coil until reverse-polarity is applied. However, there will be a few milliseconds during which reverse polarity voltage is applied if no power switch (S1) is used or the power switch is closed. This is generally enough time for damage to occur so this circuit is only recommended if a power switch is used to turn the equipment ON and OFF.

Relay with normally-open contacts (Fig 7.66B) — The relay contacts close and supply power to the equipment only when applied voltage has the proper polarity. The relay coil draws current continuously during normal operation. This may be unacceptable for low-power and battery-powered equipment.

7.16.8 Automatic Sealed Lead-Acid Battery Charger

After experiencing premature failure of the battery in his Elecraft K2 transceiver, Bob Lewis, AA4PB, began searching for an automatic battery charger. Although this charger was designed specifically for use with the Power-Sonic PS-1229A sealed lead-acid (SLA) battery used in the Elecraft K2 transceiver, its design concepts have wide ranging applications for battery operated QRP rigs of all types. Comments pertaining to the SLA batteries and chargers apply across the board and the charger described here can be used with any similar battery. (See the Batteries section of this chapter for more information on SLA batteries.)

USING A THREE-MODE CHARGER

The author first attempted to use a commercial automatic three-mode charger. However, most three-mode chargers work by sensing current and are never intended to charge a battery under load.

Three-mode chargers begin the battery charging process by applying a voltage to the battery through a 500 mA current limiter. This stage is known as *bulk-mode* charging. As the battery charges, its voltage begins to climb. When the battery voltage reaches 14.6 V the charger maintains the voltage at that level and monitors the battery charging current. This is known as the *absorption mode*, sometimes called the *overcharge mode*. By this time, the battery has achieved 85% to 95% of its full charge. As the battery continues to charge — with the voltage held constant at 14.6 V — the charging current begins to drop.

When the charging current falls to 30 mA, the three-mode charger switches to *float mode* and lowers the applied voltage to 13.8 V. At 13.8 V, the battery becomes self-limiting, drawing only enough current to offset its normal self-discharge rate. This works great — until you attach a light load to the battery, such as a receiver. The K2 receiver normally draws about 220 mA. When the charger detects a load current above 30 mA, it's fooled into thinking that the battery needs charging, so it reverts to the absorption mode, applying 14.6 V to the battery. If left in this condition, the battery is overcharged, shortening its service life.

UC3906 IC CHARGERS

Chargers using the UC3906 SLA charge-controller IC work just like the three-mode charger described earlier except that their return from float mode to absorption mode is based on voltage rather than current. Typically, once the charger is in float mode it won't return to absorption mode until the battery voltage drops to 90% of the float-mode voltage (or about 12.4 V). Although this is an improvement over the three-mode charger, it still has the potential for overcharging a battery to which a light load is attached.

First, let's look at the situation where a UC3906-controlled charger is in absorption mode and you turn on the K2 receiver, applying a load. The battery is fully charged, but because the load is drawing 220 mA, the charging current never drops to 30 mA and the charger remains in absorption mode, thinking that it is the battery that is asking for the current. As with the three-mode charger, the battery is subject to being overcharged.

If we remove the load by turning off the K2, the current demand drops below 30 mA and the charger switches to float mode (13.8 V). When the K2 is turned on again, because the charger is able to supply the 220 mA for the receiver, the battery voltage doesn't drop, so the charger stays in float mode and all is well. However, if the transmitter is keyed (increasing the current demand), the charger can't supply the required current, so it's taken from the battery and the battery voltage begins to drop. If we un-key the transmitter before the battery voltage reaches 12.4 V, the charger stays in float mode. Now it takes much longer for the charger to supply the battery with the power used during transmit than it would have if the charger had switched to absorption mode.

Let's key the transmitter again, but this time keep it keyed until the battery voltage drops below 12.4 V. At this point, the charger switches to the absorption mode. When we un-key the transmitter, we're back to the situation where the charger is locked in absorption mode until we turn off the receiver.

WHY WORRY?

So why this concern about overcharging an SLA battery? At 13.8 V, the battery self-limits, drawing only enough current to offset its self-discharge rate (typically about 0.001 times the battery capacity, or 2.9 mA for a 2.9 Ah battery). An SLA battery can be left in this float-charge condition indefinitely without overcharging it. At 14.6 V, the battery takes more current than it needs to offset the self-discharge. Under this condition, oxygen and hydrogen are generated faster than they can be recombined, so pressure inside the battery increases. Plastic-cased SLA batteries such as the PS-1229A have a one-way vent that opens at a couple of pounds per square inch pressure (PSI) and releases the gases into the atmosphere. This results in drying the gelled electrolyte and shortening the battery's service life. Both undercharging and overcharging need to be avoided to get maximum service life from the battery.

Continuing to apply 14.6 V to a 12 V SLA battery represents a relatively minor amount of overcharge and results in a gradual deterioration of the battery. Applying a potential of 16 V or excessive bulk-charging current to a small SLA battery from an uncontrolled solar panel can result in serious overcharging. Under these conditions, the overcharging can cause the battery to overheat, which causes it to draw more current and result in *thermal runaway*, a condition that can warp electrodes and render a battery useless in a few hours. To prevent thermal runaway, the maximum current and the maximum voltage need to be limited to the battery manufacturer's specifications.

DESIGN DECISION

To avoid the potential of overcharging a battery with an automatic charger locked up by the load, the author decided to design a charger that senses battery voltage rather than current in order to select the proper charging rate. A 500 mA current limiter sets the maximum bulk rate charge to protect the battery and the charger's internal power supply.

Like the three-mode chargers, when a battery with a low terminal voltage is first connected to the charger, a constant current of 500 mA flows to the battery. As the battery charges, its voltage begins to climb. When the battery voltage reaches 14.5 V, the charger switches off. With no charge current flowing to the battery, its voltage now begins to drop. When the current has been off for four seconds, the charger reads the battery voltage. If the potential is 13.8 V or less, the charger switches back on. If the voltage is still above 13.8 V, the charger waits until it drops to 13.8 V before turning on. The result is a series of 500 mA current pulses varying in width and duty cycle to provide an average current just high enough to maintain the battery in a fully charged condition. Because the repetition rate is very low (a maximum of one current pulse every four seconds) no RFI is generated that could be picked up by the K2 receiver. Because the K2's critical circuits are all well-regulated, slowly cycling the battery voltage between 13.8 V and 14.5 V has no ill effects on the transmitted or received signals.

As the battery continues to charge, the pulses get narrower and the time between pulses increases (a lower duty cycle). Now when the K2 receiver is turned on and begins drawing 220 mA from the battery, the battery voltage drops more quickly so the pulses widen (the duty cycle increases) to supply a higher average current to the battery and make up for that taken by the receiver. When the K2 transmitter is keyed, it draws about 2 to 3 A from the battery. Because the charger is current limited to 500 mA, it is not able to keep up with the transmitter demands. The battery voltage drops and the charger supplies a constant 500 mA. The battery voltage continues to drop as it supplies the required transmit current. When the transmitter is unkeyed, the battery voltage again begins to rise as the charger replenishes the energy used during transmit. After a short time, (depending on how long the transmitter was keyed) the battery voltage reaches 14.5 V and the pulsing begins again. The charger is now fully automatic, maintaining the battery in a charged condition and adjusting to varying load conditions.

The great thing about this charging system is that during transmit the majority of the required 2 to 3 A is taken from the battery. When you switch back to receive, the charger is able to supply the 220 mA needed to run the receiver and deliver up to 280 mA to the battery to replenish what was used during transmit. This means that the power source need only supply the average energy used over time, rather than being required to supply the peak energy needed by the transmitter. (You don't need to carry a heavy 3 A regulated power supply with your K2.) As long as you don't transmit more than about 9% of the time, this system should be able to power a K2 indefinitely.

Have you ever noticed that sometimes when your handheld radio has a low battery and you drop it into its charger you hear hum on the received signals? This charger's power supply is well filtered to ensure that there is no ripple or ac hum to get into the K2 under low battery voltage conditions.

CIRCUIT DESCRIPTION

The charger schematic is shown in **Fig 7.67**; the unit is dubbed the PCR12-500A, short for Pulsed-Charge Regulator for 12 V SLA batteries with maximum bulk charge rates of 500 mA. U1, an LM317 three-terminal voltage regulator, is used as a current limiter, voltage regulator and charge-control switch. A 15 V Zener diode (D2) sets U1 to deliver a no-load output of 16.2 V. R3 sets U1 to limit the charging current to 500 mA. When Q1 is turned on by the LM555 timer (U2), the ADJ pin of U1 is pulled to ground, lowering its output voltage to 1.2 V. D4 effectively disconnects the battery by preventing battery current from flowing back into U1. A Schottky diode is used at D4 because of its low voltage drop (0.4 V).

An LM358 (U4A) operates as a voltage comparator. U5, an LM336, provides a 2.5 V reference to the positive input (pin 3) of U4. R11, R12 and R13 function as a voltage divider to supply a portion of the battery voltage to pin 2 of U4A. R13 is adjusted so that when the battery terminal voltage reaches 14.5 V, the negative input of U4A rises slightly above the 2.5 V reference and its output switches from +12 V to 0 V. When this happens, the 1 MΩ resistor (R7) causes the reference voltage to drop a little and provide some hysteresis. The battery voltage must now drop to approximately 13.8 V before U4A turns back on.

U4B is a voltage follower. It pulls the trigger input (pin 2) of U2 to 0 V, causing its output to go to 12 V. U4B's output remains at 12 V until C5 has charged through R6 (approximately four seconds) and the trigger has been released by U4A sensing the battery dropping to 13.8 V or less. While the output of U2 is at 12 V, emitter/base current for Q1 flows via R5 and Q1's collector pulls U1's ADJ pin to ground, turning off the charging current.

The output of U2 also provides either +12 V or 0 V to the bicolor LED, D3. R14 and R15 form a voltage divider to provide a reference voltage to D3 such that D3 glows red when U2's output is +12 V and green when U2's output is at 0 V. When ac power is applied but U1 is switched off and not supplying current to the battery, D3 glows red. When U1 is on and supplying current to the battery, D3 is green. As the battery reaches full charge, D3 blinks green at about a four-second rate. As the battery charge increases, the on time of the green LED decreases and the off time increases. A fully charged battery may show green pulses as short as a half-second and the time between pulses may be 60 seconds or more.

T1, D1, C1 and C2 form a standard full-wave-bridge power supply providing an unregulated 20 V dc at 500 mA. U3, an LM78L12 three-terminal regulator, provides a regulated 12 V source for the control circuits.

Note that the mounting tab on U1 is not at ground potential. U1 should be mounted to a heat sink with suitable electrically insulated but thermally conductive mounting hardware to avoid short circuits. Suitable mounting hardware is included with the PC board.

OTHER BULK-CHARGE RATES

The maximum bulk-charge rate is set by the value of R3 in the series regulator circuit. The formula used to determine the value of this resistor is R (Ω) = 1200 / 1 (mA). T1 must be capable of supplying the bulk charge current and U1 must be rated to handle this current. The LM317T used here is rated for a maximum current of 1.5 A, provided it has a heat sink sufficiently large enough to dissipate the generated heat. If you increase the bulk-charge rate, you'll definitely need to increase the size of the on-board heat sink. Mounting U1 directly to the housing (be sure to use an insulator) may be a good option.

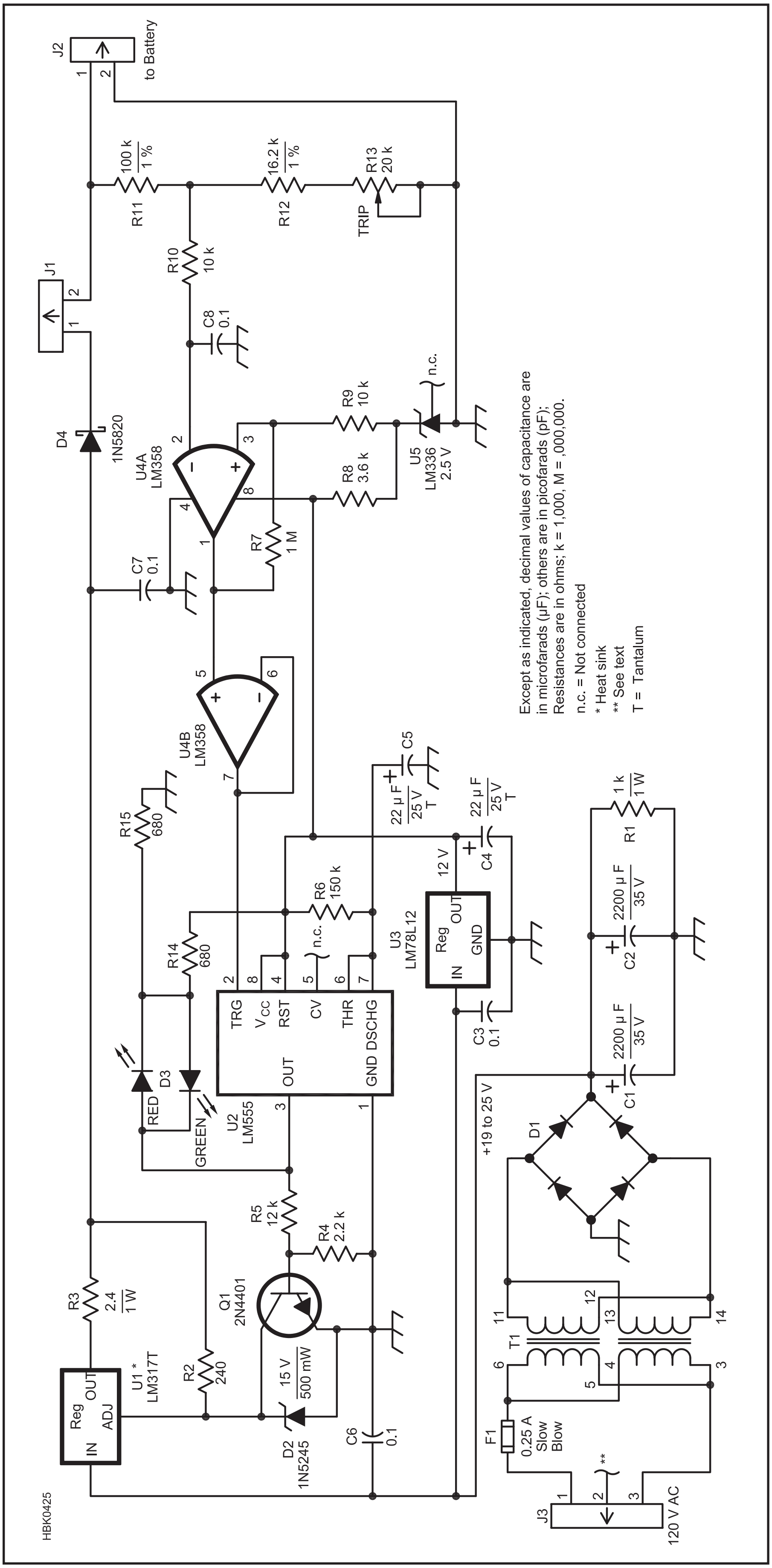


Fig 7.67 — Schematic of the SLA charger. Unless otherwise specified, resistors are ¼ W, 5%-tolerance. Equivalent parts can be substituted; n.c. indicates no connection. A PC board is available from FAR Circuits (www.farcircuits.net).
C1, C2 — 2200 µF, 35 V electrolytic.
C3, C6, C7, C8 — 0.1 µF, 50 V metalized-film.
C4, C5 — 22 µF, 25 V tantalum.
D1 — 400 V, 4 A bridge rectifier.
D2 — 1N5245 Zener diode, 15 V, 500 mW.
D3 — Bicolor LED, red-green.
D4 — 1N5820 5chottky diode.
F1 — 0.25 A slow-blow fuse.
J1 — 2-pin header, PC mount.
J2 — 2-pin connector, PC mount.
J3 — 3-pin connector, PC mount.
Q1 — 2N4401 NPN transistor.
R13 — 20 kΩ multi-turn potentiometer.
T1 — PC board mount transformer, 15 V ac, 666 mA (Digi-Key TE70043-ND). See text.
U1 — LM317T voltage regulator, TO-220 case.
U2 — LM555 timer.
U3 — LM78L12 voltage regulator, TO-92 case.
U4 — LM358 dual op amp.
U5 — LM336, 2.5 V voltage reference, TO-92 case.
Misc: PC board; TO-220 heat sink; five ¼-inch, #4-40 stand-offs; two fuse-holder clips, PC mount; two-pin shunt; two-pin connector housing; three-pin connector housing; four housing pins; enclosure

TRANSFORMER SUBSTITUTION

The transformer used for T1 is small in size and offers PC-board mounting. You can substitute any transformer rated at 15 or 16 V ac (RMS) at 500 mA or more. You may find common frame transformers to be more readily available. You can mount such a transformer to an enclosure wall and route the transformer leads to the appropriate PC-board holes.

CONSTRUCTION

There is nothing critical about building this charger. You can assemble it on a prototyping board, but a PC board and heat sink are available (**www.farcircuits.net**; see **Fig 7.68**) The specially ordered heat sink supplied with the PC board is ¼-inch higher than the one identified in the parts list and results in slightly cooler operation of U1. The remaining parts are available from Digi-Key.

Be sure to space R1 and R3 away from the board by ¼ inch or so to provide proper cooling. R13 can be a single-turn or a multi-turn pot. You'll probably find a multi-turn pot makes it easier to set the cutoff voltage to exactly 14.5 V.

R13 Adjustment

To check for proper operation and to set the trip point to 14.5 V dc, we need a test-voltage

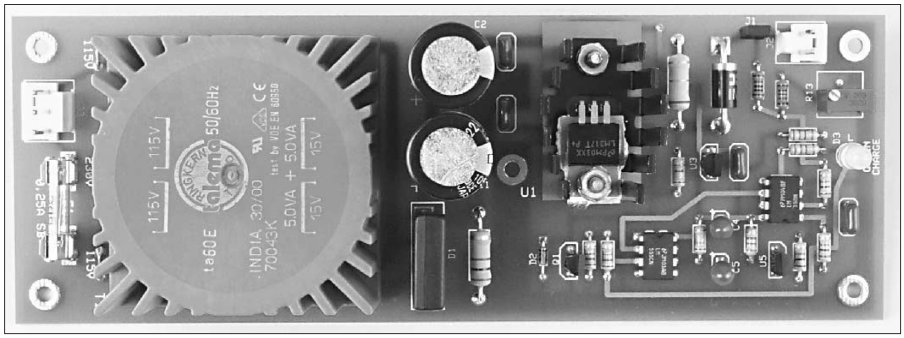


Fig 7.68 — Complete SLA charger PC board.

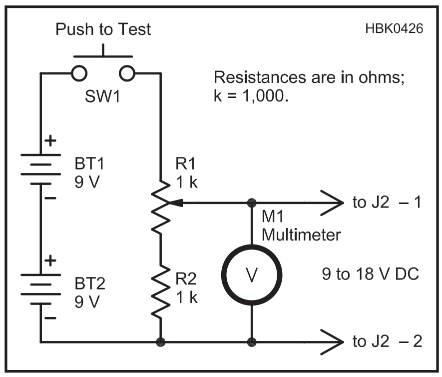


Fig 7.69 — Test voltage source for the battery charger.

source variable from 12 to 15 V dc. A convenient means of obtaining this test voltage is to connect two 9 V transistor-radio batteries in series to supply 18 V as shown in **Fig 7.69**. Connect a 1 kΩ resistor (R2) in series with a 1 kΩ potentiometer (R1) and connect this series load across the series batteries with the fixed-value resistor to the negative lead. The voltage at the pot arm should now be adjustable from 9 to 18 V. During the following procedure, be sure to adjust the voltage with the test supply connected to the charger at 12 V because the charger loads the test-voltage supply and causes the voltage to drop a little when it's connected.

Remove the jumper at J1 and apply ac line voltage to the unit at J3. Turn R13 fully counterclockwise. D3 should glow green. Connect the test voltage to J2 and adjust R1 of Fig 7.68 for an output of 14.5 V. Slowly adjust R13 clockwise until D3 glows red. To test the circuit, wait at least four seconds, then gradually reduce the test voltage until D3 turns green. At that point, the test voltage should be approximately 13.8 V. Slowly increase the test voltage again until D3 turns red. The test voltage should now read 14.5 V. If it is not exactly 14.5 V, make a minor adjustment to R13 and try again. The aim of this adjustment is to have D3 glow red just as the test voltage reaches 14.5 V.

To test the timer functioning, remove the test voltage from J2 and set it for about 15 V. Momentarily apply the test voltage to J2. D3 should turn red for approximately four seconds, then turn green. The regulator is now calibrated and ready for operation. Remove the test voltage and ac power and install the jumper at J1.

The prototype used an 8 × 3 × 2.75-inch LMB Perf137 box (Digi-Key L171-ND) to house the charger. An alternative enclosure is the Bud CU482A Convertabox, which measures 8 × 4 × 2 inches (available from Mouser). If you use the Convertabox, be sure to add some ventilation holes directly above the board-mounted heat sink. The LMB Perf box comes with a ventilated cover. If you are inclined to do some metal work, you could build your own enclosure using aluminum angle stock and sheet and probably reduce the size to perhaps 8 × 3 × 2 inches. If you use a PC-board-mounted power transformer, watch out for potential shorts between the transformer pins (especially the 120 V ac-line pins) and the case. If you use a metal enclosure, connect the safety ground (green) wire of the ac-line cord directly to the case.

OPERATION

It is very important that this charger be connected directly to the SLA battery with no diodes, resistors or other electronics in between the two. The charger works by reading the battery voltage, so any voltage drop across an external series component results in an incorrect reading and improper charging. For example, the Elecraft K2 has internal diodes in the power-input circuit, so it's necessary to add a charging jack to the transceiver that provides a direct connection to the battery. Now the K2 can be left connected to the charger at all times and be assured that its internal battery is fully charged and ready to go at a moment's notice.

7.16.9 Simple Adjustable Tracking Power Supply

This project by Bryant Julstrom, KCØZNG, was originally published in the Spring 2014 issue of the QRP ARCI *QRP Quarterly*. A PDF version of the original article, including all figures, is available on this book's CD-ROM.

The typical experimenter's bench power supply provides an adjustable positive voltage of up to 25 V at up to 1 A of current. This suffices for many circuits and projects, but others require positive and negative voltages of equal magnitude. Op-amp circuits, for example, often require ±15 V.

THE CIRCUIT

The circuit is implemented using two garden-variety ICs, an LM317 positive regulator and an LM337 negative regulator, both in TO-220 packages. (Note that the orientation of the input-common-output connections are different between the two regulators!) The input voltages of the circuit are limited only by the maximum inputs of the two regulators, ±40 V. (An alternate implementation based on the LT1033 tracking regulator is shown in the CD-ROM version of the article.) A voltmeter is switched between either of the supply's outputs and common.

Input power to the tracking regulator is supplied by a power transformer with a center-tapped secondary. The peak secondary output voltage on each side of the center-tap should be several volts higher than the maximum supply output at full load. See this chapter's section on power supply ripple to determine the minimum required filter capacitance.

In the author's case, the heaviest transformer available provided only 26 V CT (center-tapped) and the input to the regulator of ±13 V was too low. One possible solution would be to use two identical transformers with their primary windings in parallel and their secondaries in series with the connection between secondaries serving as the center-tap.

Since 24 to 28 V CT is a common secondary voltage range, however, the author chose to use the available transformer and back-to-back half-wave voltage doublers, one on either side of the secondary winding's center tap, to provide about ±26 V to the tracking regulator. This halves the current that can be drawn from the transformer, but if the transformer secondary is rated at 2 A, the resulting maximum output current of 1 A in each leg of the supply is sufficient for a wide range of projects.

Fig 7.70 shows the circuit of the tracking power supply. The author used 1N5402 rectifiers in the voltage doublers because they were available, but any 100 V diode rated at 3 A or more of average forward current will work. The two 2.2 μF capacitors should be solid tantalum types.

R4, a front-panel potentiometer, is used for voltage adjustment. R6, a 200 Ω trimmer

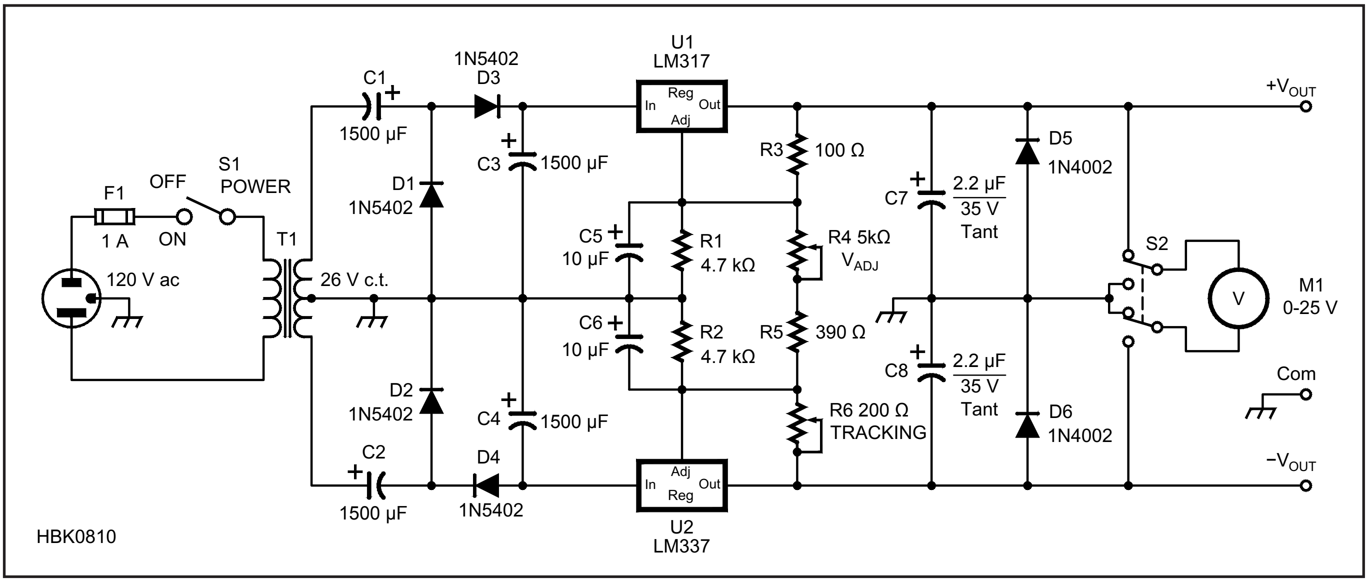


Fig 7.70 — Schematic of the adjustable tracking power supply. Regulators are mounted to the enclosure, which serves as a heat sink. Resistors are ¼ W film, 5% tolerance unless noted otherwise.

C1-C4 — 1500 µF, 50 V electrolytic.
C5, C6 — 10 µF, 50 V electrolytic.
C7, C8 — 2.2 µF, 35 V, solid tantalum.
D1-D4 — 1N5402 or equivalent.
D5, D6 — 1N4002 or equivalent.
F1 — 250 V, 1 A ac fuse and fuse holder.
M1 — 0-25 V voltmeter or equivalent.
R1, R2 — 4.7 kΩ.
R3 — 100 Ω.
R4 — 5 kΩ, panel-mount potentiometer.
R5 — 390 Ω.
R6 — 200 Ω trimmer potentiometer.
S1 — SPST toggle switch.
S2 — DPDT miniature toggle switch.
T1 — 26 V CT at 2 A secondary or equivalent (see text).
U1 — LM317adjustable positive voltage regulator.
U2 — LM337adjustable negative voltage regulator.

potentiometer, provides for fine tracking adjustment. The 390 Ω resistor (R5) sets the regulator's minimum outputs at about ±3.6 V for reasons described below.

CONSTRUCTION

As constructed, the front panel holds three binding posts (positive output, negative output, and common), two miniature toggle switches (on/off and voltmeter switching), the voltage-adjustment potentiometer and its knob, and a voltmeter. Note that the common connection of the power supply is usually left floating from the enclosure ground which must be connected to the "third-wire" ac safety ground. If desired, a binding post connected to the enclosure can be added so that a jumper can be used to connect the power supply common to the ac safety ground.

The voltmeter used by the author is a three-digit LED unit from Marlin P. Jones (**www.mpja.com**; part number 30217 ME with blue digits, also available in green and red). The meter is powered by the voltage it measures, as long as the voltage is at least 3.6 V as determined by R5 as explained previously. An analog meter or a digital meter with a separate power supply would allow lower minimum output voltages. One could augment the supply's measurements with current metering or with simultaneous measurements of both outputs.

The enclosure holds the power transformer and two circuit boards. The two voltage doublers occupy one circuit board and the tracking regulator the other. The circuit is simple enough that perforated board ("Perf-board") was used with point-to-point wiring.

The LM317 and LM337 are mounted at the edge of the regulator board and attached to the back panel, which serves as a heat sink, using mica insulators, nylon bolts, and a thin coating of heat sink compound. The rear panel also holds a snap-in IEC three-wire ac line connector. (Photographs of the finished power supply are provided in the CD-ROM version of the article.)

ADJUSTMENT AND PERFORMANCE

The only internal adjustment in the supply is the tracking potentiometer (R6), which must be set so that the two voltages track each other accurately. This is touchy, but the two voltages can be made to match within 0.1 V throughout the supply's range. The completed supply provides closely matched positive and negative voltages from ±3.6 V to about ±23 V, and a maximum current of 1 A in each leg.

The tracking adjustment and the front-panel voltage adjustment (R4) are delicate. In both cases, multi-turn potentiometers would be much easier to set. The tracking control could also be replaced with a series resistor and a smaller-value potentiometer to make adjustment less sensitive.

7.16.10 Overvoltage Protection for AC Generators

When using portable generators, there is always a possibility of damage to expensive equipment as a result of generator failure, especially from overvoltage. If the generator supplying power to this equipment puts out too much voltage, you run the risk of burning up power supplies or other electronic components. This project, by Jerry Paquette, WB8IOW, addresses the problem of increased voltage (not lower voltage) or surges and spikes lasting for a few microseconds.

Using a portable generator overvoltage protection circuit and ground-fault circuit interrupter (GFCI) as shown in **Fig 7.71** is good insurance. This overvoltage protection device must be used in conjunction with a GFCI at each station! (More information on GFCIs may be found in the **Safety** chapter.)

CIRCUIT DESCRIPTION

Refer to Fig 7.71 for this description. R1 places an intentional fault on the load side of the GFCI. With the value resistor used, the fault is limited to 10 mA. (The normal tripping threshold of a GFCI is 5 mA. This current forces the GFCI to trip in just a few milliseconds. This circuit will not function at all without the use of a GFCI. A GFCI must be used at each station. If a single GFCI were used at the generator, rather than one at

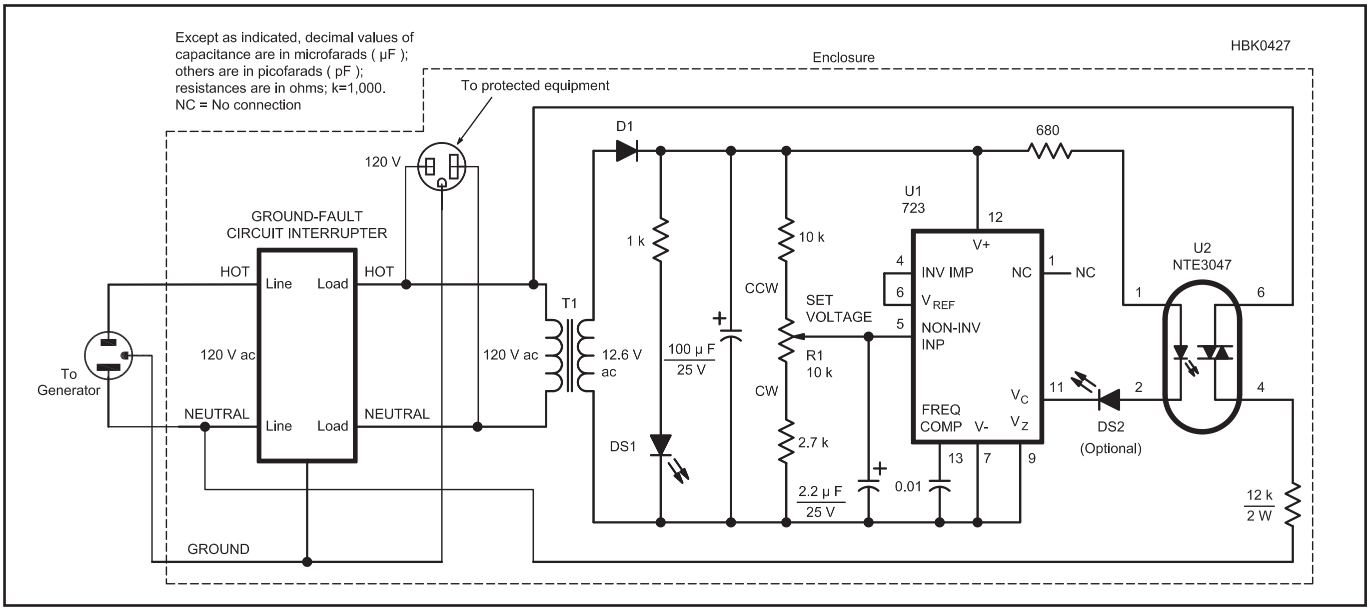


Fig 7.71 — Schematic of the Field Day equipment overvoltage-protection circuit. This circuit must be used in conjunction with a ground fault circuit interrupter (GFCI). A separate GFCI must be installed at each station. Unless otherwise specified, resistors are ¼ W, 5% tolerance. A PC board is available from FAR Circuits (www.farcircuits.net).

D1 — 200 PIV, 1 A diode; 1N4003 or equiv.
DS1, DS2 — Small LEDs.
R1 — 10 kΩ board-mounted, multi-turn potentiometer
T1 — 12.6 V ac transformer (see text).
U1 — 723 adjustable voltage regulator IC.
U2 — Optoisolator with TRIAC output; NTE3047 or equiv.

each location, premature tripping could occur. Several hundred feet of extension cords could have enough leakage to trip the GFCI.

You can see that the GFCI has separate lines (inputs) and loads (outputs). GFCI input terminals must be connected to the generator output. The GFCI ground must be tied to the ground of the generator. The load (computers, radios, etc) will plug into the GFCI or are wired to the load side of the GFCI. The primary of T1 is wired to the load side of the GFCI. The 12 kΩ/2 W resistor, however, must be wired to neutral on the *line* side of the GFCI in order for it to trip when used with generators that have windings isolated from ground. For safety, construct the entire unit in a single enclosure including the GFCI and its wiring. The generator connection can be made through a wired plug or using a male receptacle mounted on the enclosure.

T1 can be any 120 V to 12.6 V transformer capable of delivering 100 mA or more. Mounting of this transformer varies depending on the type used. All remaining components mount on a circuit board. D1 rectifies the ac from T1 and the 100 µF capacitor filters the dc. This voltage provides the power to the 723 voltage regulator.

Two fixed resistors and a potentiometer form the voltage-divider network supplying voltage to the LM723 input, pin 5. R1, the board-mounted potentiometer, has only three leads, but there are four pads on the circuit board, to accommodate different styles of pots. The 2.2 µF capacitor provides a slight delay, to prevent false tripping when the circuit is powered up. The 0.01 µF capacitor from pin 13 of the 723 to the negative supply bus should always be used. When the voltage at pin 5 goes higher than the reference voltage at pins 4 and 6, pin 11 goes low, turning on the trip indicator LED DS2 and the optical coupler LED. LED current is limited by the l kΩ resistor. The optical coupler turns on the TRIAC, which creates a 10 mA fault current between the hot wire and ground of the GFCI. DS2 will remain lit as an indicator until the 100 µF capacitor is discharged.

ADJUSTMENT

Adjustment is simple. You'll need a variable ac transformer (Powerstat or Variac). Turn R1 fully clockwise and use the variable transformer to adjust input to 130 V ac. Turn the pot counterclockwise until the GFCI trips.

7.16.11 Overvoltage Crowbar Circuit

If the regulator circuitry of a power supply should fail — for example, if a pass transistor should short — the unregulated supply voltage could appear at the output terminals. This could cause a failure in the equipment connected to the supply. The overvoltage "crowbar" circuit shown here has been shown to be effective as a last line of defense against power supply overvoltage failures. When an overvoltage condition is detected, the heavy-duty SCR is fired, becoming a short circuit — as if a crowbar (representing any over-sized conductor capable of handling the supply's short-circuit output current) had been connected across the supply, thus the name.

This circuit shown in **Fig 7.72** was originally designed for the 28 V power supply project available on the CD-ROM for this book. The use of the MC3423 overvoltage protection IC provides quicker triggering and more reliable gate drive to the SCR than comparable Zener-based circuits. Power supply builders can incorporate the overvoltage protection circuit into any dc power supply with the required component value adjustments.

The crowbar circuit is usually connected with the power input and the sense input connected together at the supply positive output and COMMON to the supply negative output. Another option is to connect power input and common across the rectifier filter capacitor and the sense input to the power supply output. In either case, the power input and common wires should be adequately sized to handle the full short-circuit current and are shown as heavy lines on the schematic.

The crowbar circuit functions as follows: the 4.7 kΩ resistor and Zener diode D1 create a supply voltage for the MC3423. U1 will function properly with a supply voltage of

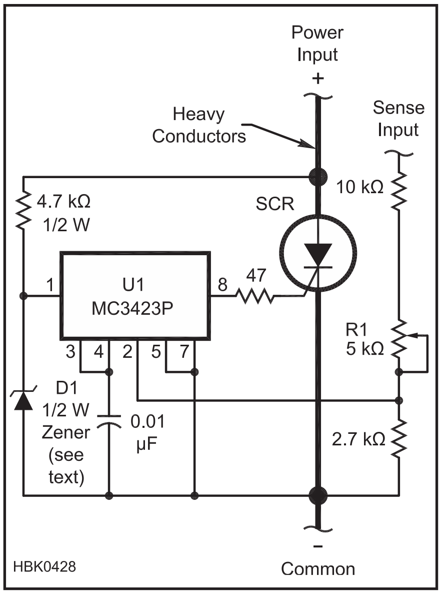


Fig 7.72 — Schematic of the over-voltage crowbar circuit. Unless otherwise specified, resistors are ¼ W, 5% tolerance. A PC board is available from FAR Circuits (www.farcircuits.net).
SCR — C38M stud-mount (TO-65 package).
U1 — MC3423P or NTE7172 voltage protection circuit, 8-pin DIP.
D1 —Zener diode, ½ W (see text).
R1 — 5 kΩ, PC board mount trimmer potentiometer.

4.5-40 V. Use a Zener diode with a voltage rating a few volts below that of the crowbar circuit positive-to-negative power input voltage. For example, if the crowbar is connected to a 12 V supply output, D1 voltage should be 6 to 9 V. The exact value is not critical.

U1 contains a 2.5 V reference and two comparators. When the voltage at pin 2 (sense terminal) reaches 2.5 V, the output voltage (pin 8) changes from the negative input voltage to the positive input voltage. This drives the gate of the SCR through the 47 Ω resistor. The trip voltage is set by the resistive divider across the + and – inputs:

$$V_{trip} = 2.5\left(1 + \frac{10\ k\Omega + R}{2.7\ k\Omega}\right)$$

The application notes for the MC3423 recommend that the resistance from the sense input to the negative input be less than 10 kΩ for minimum drift, suggesting the value of 2.7 kΩ. The value of 10 kΩ for the fixed portion of the adjustable resistance is selected for V_{trip} = 15 V at the midpoint of the 5 kΩ potentiometer (R1) travel. For other trip voltages, the fixed resistor value should be the closest standard value to

$$R_{fixed} = 2.7\ k\Omega\left(\frac{V_{trip}}{2.5} - 1\right) - 2.5\ k\Omega$$

assuming the potentiometer value remains at 5 kΩ.

When the SCR turns on, it short-circuits the inputs, causing any protective fuses or circuit breakers to open. The SCR will stay on until the current through drops below the "keep alive" threshold, at which point the SCR turns off. The SCR will stay on even if the input voltage to U1 drops below 4.5 V.

If the crowbar circuit fires due to RFI, an additional 0.01 µF capacitor should be connected from pin 2 of U1 to common and another across the D1.

More information may be found in the MC3423 datasheet and "Semiconductor Consideration for DC Power Supply Voltage Protector Circuits," ON Semi AN004E/D, both available from ON Semiconductor.

Additional Projects and Information

Additional power source projects and supporting files are included on the *Handbook* CD-ROM.