

## 9 ELECTRICAL

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### INTRODUCTION

This chapter attempts to give the reader a basic understanding of marine electrical systems and to give an appreciation of how they differ from electrical systems in a house or automobile. Wiring a house doesn't qualify a person for wiring a boat, and I hope to help the reader see and appreciate that fact.

Understanding a boat's electrical systems should:

- Assist in solving basic electrical problems underway.
- Help you communicate better with your electrician and know what standards to expect from him or her.
- Help in evaluating the quality of the electrical installation on a boat you are thinking of buying.
- Make you more aware of potentially dangerous or unsafe conditions.

What this chapter does *not* do is qualify anyone to carry out marine electrical work.

The *U.S. Code of Federal Regulations* (CFR) contains regulations pertaining to electrical systems on gasoline powered boats in *Title 33 CFR Sections 183.401-183.460*. The first section states, "This subpart applies to all boats that have gasoline engines, except outboard engines, for electrical generation, mechanical power, or propulsion," and although this statement limits the legal applicability, it would be a good idea to think of these regulations as setting a minimum standard for any boat with electrical systems onboard.

These actual regulations can be found at [www.gpoaccess.gov/cfr/index.html](http://www.gpoaccess.gov/cfr/index.html). The U.S. Coast Guard has also produced an 86-page Adobe Acrobat .pdf document that provides a good explanation of these regulations. It can be downloaded at no cost from <http://www.uscgboating.org/safety/boatbuilder/electrical/electrical.htm>. Much of the material in this section is derived from these documents.

If you are actually planning on some do-it-yourself boat wiring, it should conform to the standards established by the *American Boat and Yacht Council* (ABYC). This is an organization of boat builders and various other marine related individuals and firms that sets standards that are generally accepted as requirements for building recreational boats. They offer for purchase part or all of their standards and several books, including the three mentioned below. You

can join the ABYC and enjoy substantial discounts on their materials and books. Their website is <http://www.abycinc.org/> and their phone number is 410-956-1050.

In Canada, a government publication entitled *Construction Standards for Small Vessels, Section 8: Electrical Systems* can be found and downloaded for free at <http://www.tc.gc.ca/MarineSafety/tp/TP1332/section8.htm>. The Canadian standards are quite similar to U.S. standards.

Obtain, read, and thoroughly understand one or more of the following publications:

- *Boatowner's Mechanical and Electrical Manual* by Nigel Calder (Camden, Maine: International Marine, 1996), \$49.95. Thoroughly covers all boat systems, not just electrical.
- *Boatowners Illustrated Handbook of Wiring* by Charlie Wing (Camden, Maine: International Marine, 1993), \$29.95.
- *Boating Magazine's Powerboater's Guide to Electrical Systems* by Ed Sherman (International Marine/Ragged Mountain Press, 2000), \$22.95.

Finally, get a qualified person to coach you and inspect your work

## ELECTRICITY BASICS

### INTRODUCTION

This section deals with the essentials of electricity, and starts with explanations of volts, amperes, and resistance, and then works through explanations of how solenoids, motors, generators, transformers, and other basic electrical devices work. Understanding these fundamentals will help you follow the discussions on 12-volt and 120-volt electrical systems later on.

### Basic Principles

#### *Current, Voltage, and Resistance*

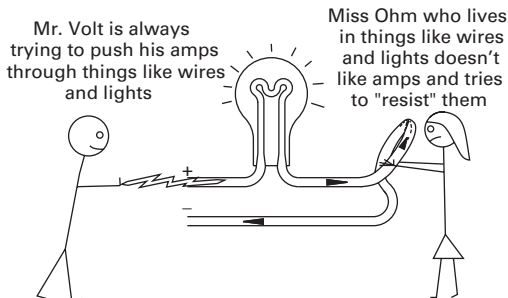
The three fundamental units used in working with electricity circuits are the volt, ampere, and ohm. A helpful analogy in explaining these three units compares electricity flowing through a wire to water flowing through a pipe.

*Amperes*, commonly called **amps**, are a measure of the amount of electricity or current flowing through the wire. You can think of the **current (I)** as the electricity flowing through a wire just as water flows through a pipe. The amp is

the measure of the amount of current flowing, just as gallons per minute is the measure of the water flowing.

To get water to actually flow through a pipe you need pressure produced by something like gravity or a pump. Water pressure is measured in units such as pounds/square inch (kg/sq m or P). Electrical current also needs an equivalent to pressure to make it flow, and that equivalent is electrical **potential** (pressure) or **voltage** (V) and it is measured in **volts**. A battery, generator, or alternator is the most common means of inducing a voltage to get an electrical current flow.

When water flows through a pipe it encounters resistance, and the smaller the pipe the greater the resistance to water flowing through it. The electrical analogy is also called **resistance** (R) and it is measured in **ohms**, and just as in a pipe, the smaller the wire the greater the resistance to flow (of current). The voltage (in volts) pushes the current (in amps) through the wire or device, which resists (in ohms) the flow.



**FIGURE 9-1: Mr. Volt and Miss Ohm**

Current, voltage, and resistance are related by equation 9-1, which is known as Ohm's law. Note: In many texts "E" (for electromotive force) is used instead of "V" to represent volt-

$$I = \frac{V}{R}$$

Where: I = Current in Amperes (A)  
 V = Voltage or potential in Volt (V)  
 R = Resistance in Ohms ( $\Omega$ )

**EQUATION 9-1: Ohm's Law**

age in equations. We'll use "V" in this book since it's more intuitive.

From the equation, it follows that current is proportional to voltage and inversely proportional to resistance and 1 volt will push 1 amp of current through 1 ohm of resistance.

We can solve equation 9-1 for V, knowing I and R:

$$V = I \times R$$

Or R, knowing V and I

$$R = \frac{V}{I}$$

Example using equation 9-1: A light bulb at a voltage of 120 V (volt) with a resistance of 145  $\Omega$  (ohms) will have a current flow of:

$$I = \frac{V}{R} = \frac{120V}{145\Omega} = 0.83A$$

### **Direct and Alternating Current**

There are two kinds of electrical current, which are direct current and alternating current.

**Direct current (DC)** is electrical current that flows constantly in one direction only, from positive to negative (by convention). A boat's 12-volt electrical system uses DC current produced by either batteries or the alternator on the boat engine.

**Alternating current (AC)** refers to electrical current that alternates flow direction several times per second. The 120 V current we use in our houses or boats, alternates 60 times per second (50 in Europe), so that within each 1/60 second the flow is forward and backward once. The number of cycles per second is named the **Hertz (Hz)**, so that our 120 V current that alternates at 60 times per second is called 60 Hertz current. The traditional name used for this unit was **cycles per second (cps)** and this is still sometimes used. Often the reference to per second is dropped and a shortened form is used, as in 60 cycle electricity or 60 cycle power, so be prepared to read or hear any or all of these terms and know that they mean the same thing.

## BASIC ELECTRICAL CIRCUITS

### Closed and Open Circuits

Here is where the analogy with water through a pipe starts to break down. Whereas the water can pass through a circuit of pipes, valves, and pumps, and then discharge from the end of the circuit (an open circuit), the electrical current must always run through a **closed circuit** that is a closed or continuous loop (figure 9-2).

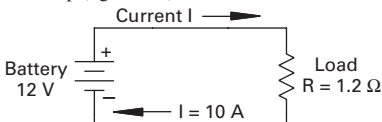


FIGURE 9-2: A Closed Circuit

Current is considered to flow from the **positive (+)** side of a power source to the **negative (-)** side.

On a boat, the **loads** can be lights, heaters, electric motors, or electronic devices. When current passes through a load, there is a **voltage drop** from one side to the other which can be calculated using the  $V = I \times R$  formula. In figure 9-2, the voltage drop over the load is  $V = I \times R = 10 \text{ A} \times 1.2 \Omega = 12 \text{ V}$ .

In figure 9-3 a switch has been introduced that is off (**open**). The circuit is an **open circuit** and no current will flow.

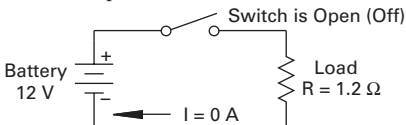


FIGURE 9-3: An Open Circuit

### Series Connections of Loads

A **series** connection refers to the connection of sources or loads in sequence, one after the other. Any number of devices

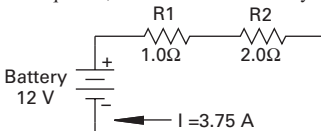


FIGURE 9-4: Loads Connected in Series

may be connected in the series. Figure 9-4 on the previous page shows two resistors connected in series so that current flows from one to the other.

Total resistance of all the resistors in series is simply the sum of all the resistances. This makes intuitive sense, and in the water analogy, corresponds to two restrictions in a pipe circuit, which present more resistance than just one.

$$R_t = R_1 + R_2 + \dots + R_n$$

#### *EQUATION 9-2: Combining Series Resistances*

The amount of current flowing is the same throughout the circuit and is:

$$I = \frac{V}{R_t} = \frac{V}{R_1 + R_2 + \dots + R_n}$$

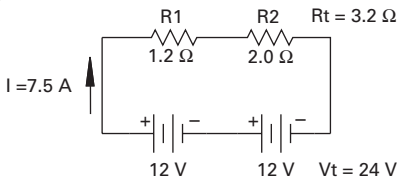
Example using values from figure 9-4 on the previous page.

#### **Series Connection of Voltage Sources**

$$I = \frac{12V}{1.2\Omega + 2.0\Omega} = \frac{12V}{3.2\Omega} = 3.75A$$

Next we'll look at connecting voltage sources, such as batteries, in series.

In figure 9-5 there are now two batteries connected in series



*FIGURE 9-5: Voltage Sources Connected in Series*

with the same resistances as in figure 9-4. When voltage sources, such as batteries, are connected in series, the voltages are simply added together to obtain the total voltage.

$$V_t = V_1 + V_2 + \dots + V_n$$

#### *EQUATION 9-3: Combining Series Voltage Sources*

Current will now be calculated as:

$$I = \frac{V_t}{R_t} = \frac{V_1 + V_2 + \dots + V_n}{R_1 + R_2 + \dots + R_n}$$

Example using values from figure 9-5:

$$I = \frac{12V + 12V}{1.2\Omega + 2.0\Omega} = \frac{24V}{3.2\Omega} = 7.5A$$

### Parallel Connection of Loads

If a circuit path divides into two or more paths and loads are placed in each path then the loads are said to be connected in *parallel*. Figure 9-6 shows the same two resistances as before now connected in parallel.

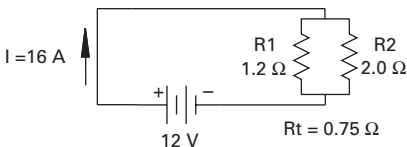


FIGURE 9-6: Loads Connected in Parallel

Although only two loads are shown, any number may be connected in parallel which is usually the case in boat circuitry. For example, several cabin lights are connected in parallel in one circuit.

As one might intuitively expect, two resistances connected in parallel will have less resistance to current flow than the lowest resistance connected. The equation for combining multiple parallel resistances into an equivalent or total resistance is:

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}}$$

EQUATION 9-4: Combining Parallel Resistances

There are a couple of ways to calculate the current flowing in the main circuit, as well as through the two branches. One alternative is calculate the combined resistance  $R_t$  and then use Ohm's law to solve for the main circuit current.

Here's the example for that approach:

$$R_t = \frac{1}{\frac{1}{1.2\Omega} + \frac{1}{2.0\Omega}} = \frac{1}{0.8333\Omega + 0.5\Omega} = \frac{1}{1.3333\Omega} = 0.75\Omega$$

$$I = \frac{V}{R_t} = \frac{12V}{0.75\Omega} = 16A$$

The other alternative is to figure the current through each branch of the parallel circuit and then add the currents together. The voltage across the top and bottom of the parallel branches is 12 volts, so this same voltage can be applied to each load to find the current through each branch.

$$I_1 = \frac{V}{R_1} = \frac{12V}{1.2\Omega} = 10A$$

$$I_2 = \frac{V}{R_2} = \frac{12V}{2.0\Omega} = 6A$$

$$I = I_1 + I_2 = 10A + 6A = 16A$$

### Parallel Connection of Voltage Sources

Figure 9-7 shows two batteries of equal voltage connected in parallel. Although the parallel connection of batteries is topographically the same as the parallel connection of the loads we just considered, the calculations are quite different. First, the batteries on each branch of a parallel circuit must be of equal voltage, since any difference will result in the higher voltage battery trying to charge the lower voltage battery, which is not a good thing.

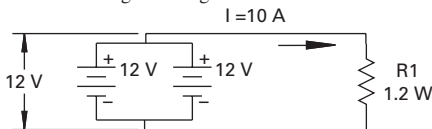
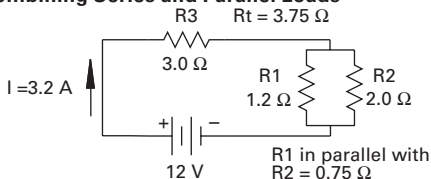


FIGURE 9-7: Voltage Sources Connected in Parallel

Second, the combined voltage is simply the same as the single battery voltage. So, the voltage applied to the resistance is 12 volts, just like in figure 9-2 on page 503, and the current is the same at 10 amps. By connecting two batteries in parallel, we are doubling the capacity or length of time the batteries will operate on a charge, while leaving current flow the same as with a single battery. Even if we connect 10 batteries in parallel, the current flow will still remain the same, but the batteries will last 10 times as long.

**Combining Series and Parallel Loads***FIGURE 9-8: Combining Series and Parallel Loads*

To calculate combined circuits, first combine the parallel resistances into equivalent resistances. In this case R1 and R2 were combined to  $R = 0.75 \Omega$  using equation 9-4 from the previous page.

Now the series resistances can be added up. In the example, we add  $3.0 \Omega + 0.75 \Omega$  to get  $3.75 \Omega$ .

With Ohm's law, the current is calculated as

$$I = V / R = 12 \text{ V} / 3.75 \Omega = 3.2 \text{ A.}$$

Once the current is known, the voltage drop over each resistance can be calculated.

$$\text{Over } R3 \text{ } V = I \times R = 3.2 \text{ A} \times 3.0 \Omega = 9.6 \text{ V.}$$

$$\text{Over } R1 \mid R2 \text{ } V = I \times R = 3.2 \text{ A} \times 0.75 \Omega = 2.4 \text{ V.}$$

The sum of the voltage drops  $9.6 \text{ V} + 2.4 \text{ V} = 12 \text{ V}$  should match the battery voltage of  $12 \text{ V}$ , and it does.

**ELECTRICAL POWER AND HORSEPOWER**

When electricity flows through a load, either heat is generated or mechanical work is performed. The power used in any electrical device is calculated as the voltage drop across the device times the current flow through the device and is termed the *watt* (W).

$$P = V \times I = \frac{V^2}{R} = I^2 \times R$$

Where: P = Power in watts  
V = Voltage drop in volts  
I = Current in amperes

*EQUATION 9-5: Calculation of Electrical Power in Watts*

The light bulb discussed earlier draws  $0.83 \text{ A}$  with a voltage drop of  $120 \text{ V}$  so the power used by the bulb is:

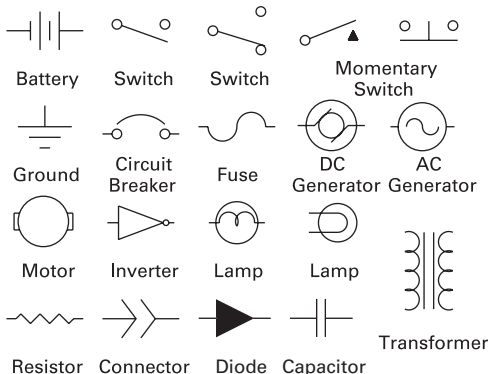
$$P = 120 \text{ V} \times 0.83 \text{ A} = 100 \text{ W}$$

**Kilowatts (kW)** is the electrical (and metric) equivalent of horsepower and 1 kilowatt is equal to 1000 watts.

To convert from kilowatts to horsepower multiply by 1.341. To convert from horsepower to watts multiply by 0.7457 (0.75 is a good approximation and is easier to remember).

Example: To power a generator that produces 10 kW requires a  $10 \text{ kW} \times 1.341 \text{ hp/kW} = 13.4 \text{ hp}$  diesel engine, assuming no losses.

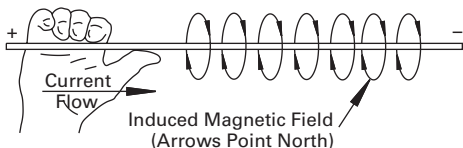
### **ELECTRICAL DIAGRAM SYMBOLS**



*FIGURE 9-9: Commonly Used Electrical Symbols*

### **ELECTROMAGNETISM AND BASIC ELECTRICAL DEVICES**

#### **Electromagnetic Force**



*FIGURE 9-10: Magnetic Field Around a Current Carrying Wire*

A current passing through a wire induces a magnetic field around the wire. Figure 9-10 shows how the field circles the wire.

If the right hand is held around the wire with the thumb pointing in the direction of current flow (from + to -), then the fingers point in the north direction of the induced field.

If the wire is formed into a circle, the magnetic field will still surround the wire but will be concentrated in the center of the circle. If the wire is formed into a helix (many circles) like that shown in figure 9-11, we have constructed a solenoid. The magnetic field is concentrated in the center of the solenoid and is weaker on the outside.

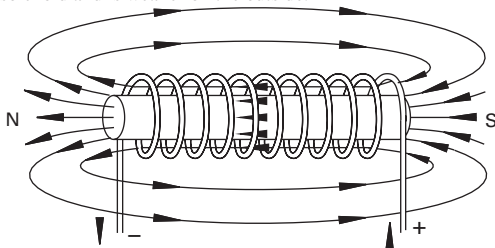


FIGURE 9-11: Solenoid

If an iron bar (*core*) is fixed in the center, as shown, the magnetic field will be strengthened several hundred fold, and as long as current flows we will have the equivalent of a bar magnet known as an *electromagnet*, with a north pole at one end and south pole at the other.

### Electric Relay

The solenoid principle is used in electrical *relays* where a small electric control current is applied to the solenoid to close a contact, to complete a circuit that carries much higher current than the control circuit. A relay can be used to control high current devices, such as a starter motor, to alleviate running large diameter cables from the starter to the bridge and back. The relay is basically a switch that is controlled electrically by a solenoid.

### Solenoids

The more common use of the term *solenoid* is to describe an electromechanical device based on the principal of the solenoid described above. If the iron core in figure 9-11 is

free to slide back and forth, and we move the core partly out one end and then apply current to the coil, the core will be drawn back to the center position with considerable force. This phenomenon is used in the devices we commonly call solenoids and are used to operate such things as solenoid valves or doorbell chimes. Of particular interest to the boater is the solenoid used in the starter to engage the flywheel when starting the engine on the boat. Solenoids are also used to actuate the electronic fuel injectors used in some diesel engines.

### Electric Motors

Anyone who has played with a couple of magnets knows that like poles repel and opposite poles attract. North repels north, south repels south, and north and south attract.

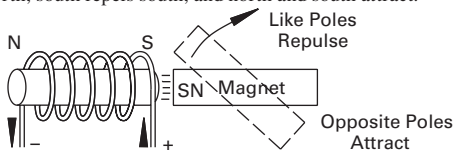


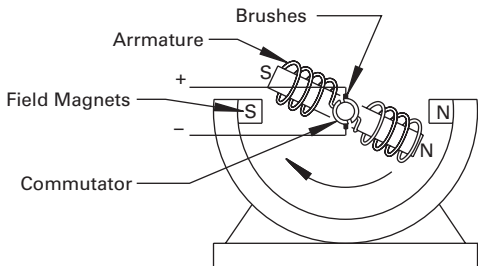
FIGURE 9-12: Magnetic Repulsion and Attraction.

In figure 9-12 we have an electromagnet fixed in place and a regular bar magnet near it that is free to move. If the electromagnet is energized with the south pole of the magnet near the south pole of the electromagnet it will push the magnet away. Conversely, if the electromagnet is energized with the north pole of the magnet near the south pole of the electromagnet it will pull the magnet toward itself.

Of course, if the magnet is fixed in place and the electromagnet is free to move, then it is the electromagnet that will be pushed away or pulled toward the magnet.

Figure 9-13 shows a schematic of a simple DC motor with a rotating electromagnet (*armature*). Power is supplied via stationary *brushes* that contact the *commutator*, which is a copper slip ring attached to the rotating shaft. The armature windings connect to the commutator.

The figure shows the north pole of the armature being repulsed by the north field magnet, and likewise the south poles, which propels the armature clockwise. As the armature rotates further clockwise, its north pole approaches the south field magnet and the mutual attraction reinforces the clockwise rotation.



*FIGURE 9-13: A Simple DC Electric Motor*

But once the armature north passes the south field magnet, the two opposites will still be attracting, which acts to impede continued rotation. The solution to this problem is to split the commutator into segments so that the polarity of the armature can be reversed as the north and south poles pass each other. This way the north pole of the armature changes to a south pole as it passes the south field magnet and the repulsion acts to continue clockwise rotation.

Keep in mind this is just an illustration to explain basic concepts. A real electric motor won't look much like our illustration. For example, in most motors, electromagnets are used instead of permanent field magnets and also there will be more poles. In addition, the field can be the rotating part in the center while the armature is stationary on the outside.

In an AC motor the reversing back and forth of the armature field is taken care of by the fact that the current is alternating back and forth already. When the motor is running at the correct speed, the changing of N-S orientation is synchronized with the passing of the field poles. Because of this, the AC motor usually runs at a constant speed that is some multiple of 60 cycles. Common AC electric motor speeds are 1800 and 3600 RPM.

### **Induced Voltage**

If an electrical conductor is moved within a magnetic field (or a magnetic field is moved past a conductor), a voltage is induced, which causes a current to flow if the circuit is closed. Stated differently, a change in the strength of a magnetic field near a conductor will induce a voltage in the

conductor. If the conductor is part of a closed circuit, induced voltage will cause a current to flow.

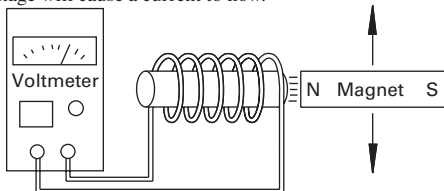


FIGURE 9-14: Induced Voltage

In figure 9-14 we have the same coil around an iron core as before, except now we connect it to a volt meter instead of a battery. As the permanent magnet is moved back and forth as shown, a voltage will be indicated on the voltmeter, with the highest voltage being induced as the permanent magnet pole passes the centerline of the coil. If the movement is stopped, the voltage drops to zero.

### Generators and Alternators

At this point you might be thinking that we can make a generator much like the motor in figure 9-13, and you would be correct. The principal is much the same except now we are applying an external force to rotate the shaft and armature past field magnets to induce a voltage, and the current produced is taken off the armature with the brushes. A generator such as this with a rotating armature is usually called just that—a generator.

A generator with the field magnets rotating within stationary current-producing windings (the *stator*) is usually termed an *alternator*.

A generator can produce either DC or AC, depending how the commutator is set up. Since on an alternator the current is taken off the stationary windings around the circumference of the generator, a commutator can't be used and the alternator can only produce alternating current (maybe that's why it's called an alternator).

In a 12-volt car or boat electrical system, the alternator AC output is *rectified* into DC using a system of *diodes*, which are electric devices similar to transistors that only allow electricity to pass in one direction. Here's an analogy: A diode is to electricity as a check valve is to water.

In a generator or alternator, the field magnets are electromagnets powered by direct current that usually is rectified current supplied from the armature or stator output. The output of the generator can be controlled by metering the amount of current allowed through the field windings with a voltage regulator. If too much current is flowing, the voltage regulator will decrease the field strength by decreasing the current to the field windings, and just the opposite if too little current is flowing. In some cases, the voltage regulator is installed in or on the alternator and in other cases as a separate unit.

### Transformers

Consider two windings around the same core as shown in figure 9-15. The winding connected to a power source is called the **primary** winding and the other winding connected to a load (voltmeter in this case) is called the **secondary** winding.

When the switch is closed with a DC power source, the primary coil produces a magnetic field in the core and as

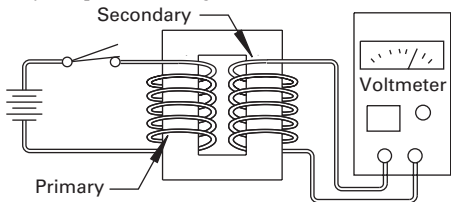


FIGURE 9-15: A Simple Transformer

the field is increasing in strength, a voltage is induced in the secondary coil and there will be a momentary reading on the voltmeter. Once the field has reached full strength and is no longer increasing, the induced voltage falls back to zero.

If, instead of direct current, alternating current is applied to the primary, the magnetic field will be constantly increasing or decreasing at the frequency of the applied current. As one might expect, the cycling magnetic field induces alternating current in the secondary windings at the same frequency.

If the number of windings in the primary and secondary are the same, the voltage and current induced in the secondary, will be the same as in the primary; however, if there are twice as many windings in the secondary, the voltage in the secondary will be doubled and the current halved.

Conversely, if there are half the windings in the secondary, the voltage will be halved and the current doubled.

This, of course, is why a **transformer** is called a transformer; it can transform voltage and current up or down to any desired ratio.

Some other things to note about transformers:

- The fact that only alternating current can be transformed is a major reason for our everyday use of AC power instead of DC power.
- A transformer will not allow DC to pass. This is of considerable interest when connecting to shorepower, which is discussed later.
- A transformer can be around 97 to 99 percent efficient, so there is a small power loss in the form of heat.
- The windings won't actually be configured as shown in figure 9-15, rather they might be wound one over the other or interleaved in layers to increase efficiency.
- The windings can be tapped at various points on either or both the primary and secondary, to provide several input and output voltage choices for a given transformer. For example, 120 VAC shorepower could be transformed up to 240 VAC if the transformer has the appropriate taps.
- A transformer cannot transform frequency; 60 Hz in will produce 60 Hz out. In Europe the power is 220 V, 50 Hz. A transformer can convert the power from 220 V to 110 V but not to 60 Hz. Some electrical devices will work at 50 Hz and others won't or will be damaged. Check before plugging in to a different frequency.

### Inverters

On a boat, inverters are used to transform 12 VDC to 120 VAC. An **inverter** uses solid state electronics to first convert the DC input to AC, then uses a transformer to increase the voltage.

## ELECTRICAL CABLING

### INTRODUCTION

#### Conductors and Insulators

A **conductor** is material that has very low resistance to the flow of electricity. An **insulator** is material that has very high resistance to the flow of electricity. Copper is a conductor that has very low resistance along with other properties that make it the best choice for electrical wiring in boats. Essentially, there's no choice: The regulations specify that conductors used in boats must be made of copper and that's that.

## Boat Cable

Electrical cables used in boats encounter an environment far more severe than that of a house or even a car. In the marine environment, the cable must be able to withstand constant flexing and vibration, high ambient temperatures, and exposure to oil, fuel, and saltwater.

U.S. federal regulations specify that *each conductor must be insulated, stranded copper*. The regulations go on to specify the type of insulation allowed, based on such factors as operating voltage and temperature.

Stranded cable is specified because solid copper cable will harden and break from constant flexing. Stranded cable is available as types 2 and 3 where type 3 contains more strands than type 2 and is therefore more flexible. Type 3 cable is used where vibration is excessive, as on engines and generator sets.

Better quality boat cable has been *tinned*, where each conductor has a thin coating of tin applied. Tinned cable is not a requirement but is highly recommended, because it provides much better protection from corrosion.

Rather than hunting around to find cable that meets all the requirements, the best approach is to just go to a reputable marine supply store and acquire marine electrical cable there. *Do not use automobile or house wire or cable for boat wiring!*

## Cable Connections

Most problems with wiring occur at connections and rarely in the cables themselves. Electrical cables should be terminated with crimp type connectors, rather than soldered. Note that *U shape connectors should not be used* unless they are the locking or flanged type shown. *Wire nuts should not be used. Set screws should not be used* unless they are the indirect bearing type. *Wire should not be secured directly to a bolt or screw*. See figure 9-16 on the next page for examples of acceptable connectors.

Like cable, the connectors should be specifically for marine use and the best way to ensure this is to buy them from a trustworthy marine supply. The connectors come in different sizes to match different wire sizes. To do a proper crimp, a good ratcheting crimper that matches the type of connector should be used, especially if you're an amateur. Also cables should be stripped to the correct length using a good wire stripper, *not* a pocket knife.



FIGURE 9-16: Cable Terminals and Connectors

Use nylon insulated rather than PVC-insulated connectors, since nylon withstands crimping better, or use connectors with heat-shrink sealed insulation.

Double crimp connectors are available from companies, such as Ancor, that have a second crimp that crimps onto the insulation to give a better grip. Good ratcheting crimping tools cost anywhere from \$50 to \$140, but they are well worth it if you are doing more than a couple of connections. Test crimps by trying to pull the wire out of the connector.

Solder should not be used as the sole means of connecting cable, because constant flexing can cause the soldered connection to break; however, there are differences of opinion as to whether solder should be used on crimped connectors. The argument for using solder is that it seals the end of the wire against moisture. The argument against is that if too much solder is applied it will flow up the wire and solidify it, thus making it susceptible to failure from flexing. A better alternative to soldering is probably to use the heat-shrink sealed connectors although they cost almost three times as much.

If you do decide to solder, you must use rosin rather than acid flux and use a good grade of solder with about 50 percent tin to 50 percent lead.

### **AC Terminations and Connections**

For safety reasons all AC terminations must be enclosed in an electrical box, much as they are in house wiring.

### **Color Coding**

The ABYC has set standards that stipulate specific wire colors for specific circuits, which makes it easier to trace those circuits and lessen the chance of error. Unless you are totally rewiring your boat, you probably want to stick with the generally accepted practice for general wiring, since it will be impractical to keep all those colors of wire on hand.

For DC 12-volt wiring the convention is:

Positive	Red
Negative	Yellow (not black)
Ground	Green

For AC wiring the convention is:

Hot wire (120 V or 240 V)	Black
Second hot wire (240 V only)	Red
Neutral (120 V or 240 V)	White
Ground (120 V or 240 V)	Green or bare

In the past black was used for negative conductors in DC wiring, which is also the color used for the hot conductor in AC circuits. This creates the possibility for confusion between the two and for this reason yellow is now used rather than black. You may find black DC negative return conductors in older boats.

**Duplex** (2 conductor) wire for DC use, sold at marine supply stores, follows this convention and will contain a red and a yellow conductor.

**Triplex** wire (3 conductor) wire for AC use, also available at marine supply stores, follows this convention too and will contain black, white, and green conductors. Note that although this color standard is the same as for house wiring, stranded type 2 or 3 marine cable must be used in boats.

## **Cable Routing**

AC cabling should be bundled separately from DC cabling and all cables should be supported every foot or so or continuously with tray or conduit. If conduit must be used it should have drain holes at any low spots.

The regulations state that *each conductor or group of conductors that passes through a bulkhead, structural member, junction box, or other rigid surface must be protected from abrasion*. Generally, any means that will accomplish this is acceptable. Grommets, bushings, caulking, hose, etc., are all ways to do this. Cable grip devices designed specifically for the purpose are available too.

If at all possible, avoid running cable through the bilge. If the cable has to be run through the bilge ensure it is above water at all points and try to avoid having any connections in the bilge. If there are any connections in the bilge they must be completely sealed.

Route cables well away from moving parts and exhaust systems. To avoid the possibility of cables falling onto an engine or exhaust system, don't run cables above them.

Take the time now to label both ends of every cable you run. A couple of years from now, when you're trying to debug some weird electrical problem, you'll thank yourself for doing it. Labels for this purpose are usually available from any electrical parts supplier or marine supply store. If you are doing a lot of work, labeling systems from Dymo or Brother work quite well and produce waterproof labels. In *Boat-owner's Mechanical and Electrical Manual*, Nigel Calder suggests the use of transparent heat shrink tubing over the labels to prevent their working loose, which sure seems like a good idea if you've gone to the trouble of putting the labels on in the first place.

## **Cable Sizing**

### **Wire Gauge**

Wire must be sufficiently large that the resistance of the wire is small compared to the load. Resistance of wire is proportional to its length and inversely proportional to its cross-sectional area.

Wire is sized by *gauge*, where larger gauge numbers correspond to smaller wire diameters. There are differing standards for wire gauge, the two most prevalent in North America being *American Wire Gauge (AWG)* and *Society of Automotive Engineers (SAE)* with wire of the same gauge

number in SAE having a slightly smaller diameter than wire of the same gauge number in AWG. In the United States, the regulations state that AWG gauge wire must be used for 50 volt and above systems, and either AWG or SAE may be used below 50 volts.

The gauge system was devised so that a decrease of three gauge numbers (e.g., 15 to 12) results in an approximate doubling of cross-sectional area, which corresponds to a doubling of current carrying capacity. It's also handy to know that a decrease of two gauge numbers will result in approximately 1.6 times or 60 percent more current carrying capacity. So going from 14 to 12 gauge will add 60 percent to

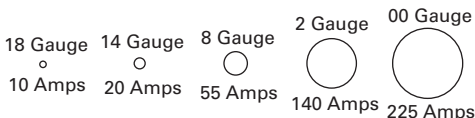


FIGURE 9-17: Actual Wire Sizes (Scaled to Actual Size)

allowable current. Figure 9-17 shows some typical wire sizes taken from table 9-1 on the next page and current carrying capacity (ampacity) at 60 degrees Celsius taken from table 9-2 on page 522.

### The Circular Mil

The cross-sectional area of wire is usually specified as circular mils rather than square inches or millimeters. A *mil* is

$$CM = D^2 \times 10^6 = D^2 \times 1,000,000$$

Where: CM = Circular Mils

D = Diameter in inches

### EQUATION 9-6: Calculation of Circular Mils

1/1000 of 1 inch or 0.001 inches. A *circular mil* (CM) is the area of a circle that has a diameter of 1 mil (0.001 in). With some manipulation we arrive at equation 9-6 for calculating circular mils from diameter:

In equation 9-6 use 1550 instead of 1,000,000 if you have the diameter in millimeters.

The use of the circular mil for measuring cross-sectional area eliminates the need to use pi or divide the diameter by 2 to get radius when doing area calculations.

**Standard Wire Sizes**

Table 9-1 lists standard wire sizes along with their cross-sectional areas and resistance per unit length.

Wire	Diameter		X-Section Area (Circular Mils)		Resistance @ 20° C (AWG)	
	AWG		AWG	SAE	$\Omega$ / 1000 ft	$\Omega$ / km
Gauge	in	mm	CM	CM		
18	0.0403	1.024	1620	1537	6.3850	20.9428
16	0.0508	1.290	2580	2336	4.0160	13.1725
14	0.0641	1.628	4110	3702	2.5250	8.2820
12	0.0808	2.052	6530	5833	1.5880	5.2086
10	0.1019	2.588	10380	9343	0.9989	3.2764
8	0.1285	3.264	16510	14810	0.6282	2.0605
6	0.1620	4.115	26240	24538	0.3951	1.2959
4	0.2043	5.189	41740	37360	0.2485	0.8151
2	0.2576	6.543	66360	62450	0.1563	0.5127
1	0.2893	7.348	83690	77790	0.1239	0.4064
0	0.3249	8.252	105600	98980	0.0983	0.3224
00	0.3648	9.266	133100	125100	0.0779	0.2555
000	0.4096	10.404	167800	158600	0.0618	0.2027
0000	0.4600	11.684	211600	205500	0.0490	0.1607

TABLE 9-1: Standard Wire Sizes and Specifications

**Current Carrying Capacity Limited by Wire Heating**

The first step in selecting a conductor size is to determine the continuous or steady state current that it will carry without overheating. Note that surges higher than continuous for short periods of time are allowed. The most common example of current surge occurs during the starting of an electric motor.

The top half of table 9-2 on page 522 contains the allowable amperages for no more than two conductors bundled, as specified in *U.S. 33 CFR 183.425*. Note: The top half of table 9-2 and the factors for use in engine spaces and correction factors for the number of current carrying conductors are the same as in tables in *U.S. 33 CFR 183.425*, in *ABYC standards* and in *Transport Canada Standards for Small Vessels*.

To use the table first enter the table in the column with the conductor insulation temperature rating of the cable you propose to use. This rating should be printed on the cable. Then proceed down the column until an amperage is reached that is greater than or equal to the desired continuous current and read the wire gauge from the left-hand column. This is the *minimum* diameter wire that may be used to carry that amperage.

Halfway down the table is a line that gives factors for inside engine spaces. These factors are provided as part of the regulations and they correct the amperages in the top table if the conductor is to be in an engine space. To spare you the calculation, the corrected values are provided in the bottom half of the table.

The regulation goes on to specify bundling correction factors for more than two conductors in a cable carrying 50 volts or more as follows:

- 3 conductors 0.70
- 4 to 6 conductors 0.60
- 7 to 24 conductors 0.50
- 25 or more conductors 0.40

For example, if you have a cable with five conductors operating at 120 volts, the allowable amperage in table 9-2 must be further corrected downward by multiplying by 0.60.

The four tables 9-3 through 9-6 on pages 523 to 526 have calculated the allowable amperages for each of the four correction factors so you can go directly to the appropriate table and directly determine your conductor size without having to perform the correction calculation.

A couple more things from the regulations to note:

- No conductors are to be smaller than 18 AWG if bundled with other conductors, and no smaller than 16 AWG if it is a single conductor.
- The regulations exempt from these rules such things as navigation equipment, electronic circuitry with currents less than 1 amp, high voltage ignition circuitry, and cranking motor conductors.

Example:

Assume we have an appliance that draws 30 amps at 12 volts. We will run 2 conductors together, inside the engine room. The cable we wish to use is rated 105 degrees Celsius.

Use table 9-2 for no more than 2 conductors. Enter the bottom half of the table for engine room spaces, find the column for 105 degrees Celsius and read down the column to find the first amperage greater than 30 amps which is 38.3 amps. In the right most column read the required wire gauge of 12 AWG.

<b>No more than 2 conductors bundled, any voltage</b>							
<b>Wire Size AWG</b>	<b>Temperature rating of conductor insulation</b>						
	<b>60° C</b>	<b>75° C</b>	<b>80° C</b>	<b>90° C</b>	<b>105° C</b>	<b>125° C</b>	<b>200° C</b>
	<b>140° F</b>	<b>167° F</b>	<b>176° F</b>	<b>194° F</b>	<b>221° F</b>	<b>257° F</b>	<b>392° F</b>
<b>Allowable Amperage of Conductors Outside Engine Spaces at Ambient 30° C (86° F)</b>							
18	10	10	15	20	20	25	25
16	15	15	20	25	25	30	35
14	20	20	25	30	35	40	45
12	25	25	35	40	45	50	55
10	40	40	50	55	60	70	70
8	55	65	70	70	80	90	100
6	80	95	100	100	120	125	135
4	105	125	130	135	160	170	180
3	120	145	150	155	180	195	210
2	140	170	175	180	210	225	240
1	165	195	210	210	245	265	280
0	195	230	245	245	285	305	325
00	225	265	285	285	330	355	370
000	260	310	330	330	385	410	430
0000	300	360	385	385	445	475	510
<b>Factor for Inside Engine Spaces</b>							
	<b>0.6</b>	<b>0.8</b>	<b>0.8</b>	<b>0.8</b>	<b>0.9</b>	<b>0.9</b>	<b>1.0</b>
<b>Allowable Amperage of Conductors Inside Engine Spaces at Ambient 50° C (122° F)</b>							
18	5.8	7.5	11.7	16.4	17.0	22.3	25
16	8.7	11.3	15.6	20.5	21.3	26.7	35
14	11.6	15.0	19.5	24.6	29.8	35.6	45
12	14.5	18.8	27.3	32.8	38.3	44.5	55
10	23.2	30.0	39.0	45.1	51.0	62.3	70
8	31.9	48.8	54.6	57.4	68.0	80.1	100
6	46.4	71.3	78.0	82.0	102.0	111.3	135
4	60.9	93.8	101.4	110.7	136.0	151.3	180
3	69.6	108.8	117.0	127.1	153.0	173.6	210
2	81.2	127.5	136.5	147.6	178.5	200.3	240
1	95.7	146.3	163.8	172.2	208.3	235.8	280
0	113.1	172.5	191.1	200.9	242.3	271.4	325
00	130.5	198.8	222.3	233.7	280.5	315.9	370
000	150.8	232.5	257.4	270.6	327.3	364.9	430
0000	174.0	270.0	300.3	315.7	378.3	422.8	510
Table derived from data per 33 CFR 183.425							

TABLE 9-2: Allowable Amperage, Two or Less Conductors.

<b>3 Conductors Bundled, &gt; 50 V -Factor 0.70</b>							
<b>Wire Size AWG</b>	<b>Temperature rating of conductor insulation</b>						
	<b>60° C</b>	<b>75° C</b>	<b>80° C</b>	<b>90° C</b>	<b>105° C</b>	<b>125° C</b>	<b>200° C</b>
	<b>140° F</b>	<b>167° F</b>	<b>176° F</b>	<b>194° F</b>	<b>221° F</b>	<b>257° F</b>	<b>392° F</b>
<b>Allowable Amperage of Conductors Outside Engine Spaces at Ambient 30° C (86° F)</b>							
18	7.0	7.0	10.5	14.0	14.0	17.5	17.5
16	10.5	10.5	14.0	17.5	17.5	21.0	24.5
14	14.0	14.0	17.5	21.0	24.5	28.0	31.5
12	17.5	17.5	24.5	28.0	31.5	35.0	38.5
10	28.0	28.0	35.0	38.5	42.0	49.0	49.0
8	38.5	45.5	49.0	49.0	56.0	63.0	70.0
6	56.0	66.5	70.0	70.0	84.0	87.5	94.5
4	73.5	87.5	91.0	94.5	112.0	119.0	126.0
3	84.0	101.5	105.0	108.5	126.0	136.5	147.0
2	98.0	119.0	122.5	126.0	147.0	157.5	168.0
1	115.5	136.5	147.0	147.0	171.5	185.5	196.0
0	136.5	161.0	171.5	171.5	199.5	213.5	227.5
00	157.5	185.5	199.5	199.5	231.0	248.5	259.0
000	182.0	217.0	231.0	231.0	269.5	287.0	301.0
0000	210.0	252.0	269.5	269.5	311.5	332.5	357.0
<b>Factor for Inside Engine Spaces</b>							
	<b>0.6</b>	<b>0.8</b>	<b>0.8</b>	<b>0.8</b>	<b>0.9</b>	<b>0.9</b>	<b>1.0</b>
<b>Allowable Amperage of Conductors Inside Engine Spaces at Ambient 50° C (122° F)</b>							
18	4.1	5.3	8.2	11.5	11.9	15.6	17.5
16	6.1	7.9	10.9	14.4	14.9	18.7	24.5
14	8.1	10.5	13.7	17.2	20.8	24.9	31.5
12	10.2	13.1	19.1	23.0	26.8	31.2	38.5
10	16.2	21.0	27.3	31.6	35.7	43.6	49.0
8	22.3	34.1	38.2	40.2	47.6	56.1	70.0
6	32.5	49.9	54.6	57.4	71.4	77.9	94.5
4	42.6	65.6	71.0	77.5	95.2	105.9	126.0
3	48.7	76.1	81.9	89.0	107.1	121.5	147.0
2	56.8	89.2	95.5	103.3	125.0	140.2	168.0
1	67.0	102.4	114.7	120.5	145.8	165.1	196.0
0	79.2	120.8	133.8	140.6	169.6	190.0	227.5
00	91.3	139.1	155.6	163.6	196.3	221.2	259.0
000	105.6	162.8	180.2	189.4	229.1	255.4	301.0
0000	121.8	189.0	210.2	221.0	264.8	295.9	357.0

Table derived from data per 33 CFR 183.425

TABLE 9-3: Allowable Amperage, Three Conductors.

<b>4 to 6 Conductors are Bundled, &gt; 50 V - Factor 0.60</b>							
<b>Wire Size AWG</b>	<b>Temperature rating of conductor insulation</b>						
	<b>60° C</b>	<b>75° C</b>	<b>80° C</b>	<b>90° C</b>	<b>105° C</b>	<b>125° C</b>	<b>200° C</b>
	<b>140° F</b>	<b>167° F</b>	<b>176° F</b>	<b>194° F</b>	<b>221° F</b>	<b>257° F</b>	<b>392° F</b>
<b>Allowable Amperage of Conductors Outside Engine Spaces at Ambient 30° C (86° F)</b>							
18	6.0	6.0	9.0	12.0	12.0	15.0	15.0
16	9.0	9.0	12.0	15.0	15.0	18.0	21.0
14	12.0	12.0	15.0	18.0	21.0	24.0	27.0
12	15.0	15.0	21.0	24.0	27.0	30.0	33.0
10	24.0	24.0	30.0	33.0	36.0	42.0	42.0
8	33.0	39.0	42.0	42.0	48.0	54.0	60.0
6	48.0	57.0	60.0	60.0	72.0	75.0	81.0
4	63.0	75.0	78.0	81.0	96.0	102.0	108.0
3	72.0	87.0	90.0	93.0	108.0	117.0	126.0
2	84.0	102.0	105.0	108.0	126.0	135.0	144.0
1	99.0	117.0	126.0	126.0	147.0	159.0	168.0
0	117.0	138.0	147.0	147.0	171.0	183.0	195.0
00	135.0	159.0	171.0	171.0	198.0	213.0	222.0
000	156.0	186.0	198.0	198.0	231.0	246.0	258.0
0000	180.0	216.0	231.0	231.0	267.0	285.0	306.0
<b>Factor for Inside Engine Spaces</b>							
	<b>0.6</b>	<b>0.8</b>	<b>0.8</b>	<b>0.8</b>	<b>0.9</b>	<b>0.9</b>	<b>1.0</b>
<b>Allowable Amperage of Conductors Inside Engine Spaces at Ambient 50° C (122° F)</b>							
18	3.5	4.5	7.0	9.8	10.2	13.4	15.0
16	5.2	6.8	9.4	12.3	12.8	16.0	21.0
14	7.0	9.0	11.7	14.8	17.8	21.4	27.0
12	8.7	11.3	16.4	19.7	22.9	26.7	33.0
10	13.9	18.0	23.4	27.1	30.6	37.4	42.0
8	19.1	29.3	32.8	34.4	40.8	48.1	60.0
6	27.8	42.8	46.8	49.2	61.2	66.8	81.0
4	36.5	56.3	60.8	66.4	81.6	90.8	108.0
3	41.8	65.3	70.2	76.3	91.8	104.1	126.0
2	48.7	76.5	81.9	88.6	107.1	120.2	144.0
1	57.4	87.8	98.3	103.3	125.0	141.5	168.0
0	67.9	103.5	114.7	120.5	145.3	162.9	195.0
00	78.3	119.3	133.4	140.2	168.3	189.6	222.0
000	90.5	139.5	154.4	162.4	196.3	218.9	258.0
0000	104.4	162.0	180.2	189.4	226.9	253.7	306.0
Table derived from data per 33 CFR 183.425							

TABLE 9-4: Allowable Amperage, four to six Conductors

<b>7 to 24 Conductors are Bundled, &gt; 50 V - Factor 0.50</b>							
<b>Wire Size AWG</b>	<b>Temperature rating of conductor insulation</b>						
	<b>60° C 140° F</b>	<b>75° C 167° F</b>	<b>80° C 176° F</b>	<b>90° C 194° F</b>	<b>105° C 221° F</b>	<b>125° C 257° F</b>	<b>200° C 392° F</b>
<b>Allowable Amperage of Conductors Outside Engine Spaces at Ambient 30° C (86° F)</b>							
18	5.0	5.0	7.5	10.0	10.0	12.5	12.5
16	7.5	7.5	10.0	12.5	12.5	15.0	17.5
14	10.0	10.0	12.5	15.0	17.5	20.0	22.5
12	12.5	12.5	17.5	20.0	22.5	25.0	27.5
10	20.0	20.0	25.0	27.5	30.0	35.0	35.0
8	27.5	32.5	35.0	35.0	40.0	45.0	50.0
6	40.0	47.5	50.0	50.0	60.0	62.5	67.5
4	52.5	62.5	65.0	67.5	80.0	85.0	90.0
3	60.0	72.5	75.0	77.5	90.0	97.5	105.0
2	70.0	85.0	87.5	90.0	105.0	112.5	120.0
1	82.5	97.5	105.0	105.0	122.5	132.5	140.0
0	97.5	115.0	122.5	122.5	142.5	152.5	162.5
00	112.5	132.5	142.5	142.5	165.0	177.5	185.0
000	130.0	155.0	165.0	165.0	192.5	205.0	215.0
0000	150.0	180.0	192.5	192.5	222.5	237.5	255.0
<b>Factor for Inside Engine Spaces</b>							
	<b>0.6</b>	<b>0.8</b>	<b>0.8</b>	<b>0.8</b>	<b>0.9</b>	<b>0.9</b>	<b>1.0</b>
<b>Allowable Amperage of Conductors Inside Engine Spaces at Ambient 50° C (122° F)</b>							
18	2.9	3.8	5.9	8.2	8.5	11.1	12.5
16	4.4	5.6	7.8	10.3	10.6	13.4	17.5
14	5.8	7.5	9.8	12.3	14.9	17.8	22.5
12	7.3	9.4	13.7	16.4	19.1	22.3	27.5
10	11.6	15.0	19.5	22.5	25.5	31.2	35.0
8	16.0	24.4	27.3	28.7	34.0	40.0	50.0
6	23.2	35.6	39.0	41.0	51.0	55.6	67.5
4	30.4	46.9	50.7	55.3	68.0	75.7	90.0
3	34.8	54.4	58.5	63.5	76.5	86.8	105.0
2	40.6	63.8	68.3	73.8	89.3	100.1	120.0
1	47.8	73.1	81.9	86.1	104.1	117.9	140.0
0	56.5	86.3	95.5	100.4	121.1	135.7	162.5
00	65.3	99.4	111.2	116.8	140.3	158.0	185.0
000	75.4	116.3	128.7	135.3	163.6	182.4	215.0
0000	87.0	135.0	150.2	157.8	189.1	211.4	255.0

Table derived from data per 33 CFR 183.425

TABLE 9-5: Allowable Amperage, seven to 24 Conductors

<b>25 or More Conductors are Bundled, &gt; 50 V - Factor 0.40</b>							
<b>Wire Size AWG</b>	<b>Temperature rating of conductor insulation</b>						
	<b>60° C</b>	<b>75° C</b>	<b>80° C</b>	<b>90° C</b>	<b>105° C</b>	<b>125° C</b>	<b>200° C</b>
	<b>140° F</b>	<b>167° F</b>	<b>176° F</b>	<b>194° F</b>	<b>221° F</b>	<b>257° F</b>	<b>392° F</b>
<b>Allowable Amperage of Conductors Outside Engine Spaces at Ambient 30° C (86° F)</b>							
18	4.0	4.0	6.0	8.0	8.0	10.0	10.0
16	6.0	6.0	8.0	10.0	10.0	12.0	14.0
14	8.0	8.0	10.0	12.0	14.0	16.0	18.0
12	10.0	10.0	14.0	16.0	18.0	20.0	22.0
10	16.0	16.0	20.0	22.0	24.0	28.0	28.0
8	22.0	26.0	28.0	28.0	32.0	36.0	40.0
6	32.0	38.0	40.0	40.0	48.0	50.0	54.0
4	42.0	50.0	52.0	54.0	64.0	68.0	72.0
3	48.0	58.0	60.0	62.0	72.0	78.0	84.0
2	56.0	68.0	70.0	72.0	84.0	90.0	96.0
1	66.0	78.0	84.0	84.0	98.0	106.0	112.0
0	78.0	92.0	98.0	98.0	114.0	122.0	130.0
00	90.0	106.0	114.0	114.0	132.0	142.0	148.0
000	104.0	124.0	132.0	132.0	154.0	164.0	172.0
0000	120.0	144.0	154.0	154.0	178.0	190.0	204.0
<b>Factor for Inside Engine Spaces</b>							
	<b>0.6</b>	<b>0.8</b>	<b>0.8</b>	<b>0.8</b>	<b>0.9</b>	<b>0.9</b>	<b>1.0</b>
<b>Allowable Amperage of Conductors Inside Engine Spaces at Ambient 50° C (122° F)</b>							
18	2.3	3.0	4.7	6.6	6.8	8.9	10.0
16	3.5	4.5	6.2	8.2	8.5	10.7	14.0
14	4.6	6.0	7.8	9.8	11.9	14.2	18.0
12	5.8	7.5	10.9	13.1	15.3	17.8	22.0
10	9.3	12.0	15.6	18.0	20.4	24.9	28.0
8	12.8	19.5	21.8	23.0	27.2	32.0	40.0
6	18.6	28.5	31.2	32.8	40.8	44.5	54.0
4	24.4	37.5	40.6	44.3	54.4	60.5	72.0
3	27.8	43.5	46.8	50.8	61.2	69.4	84.0
2	32.5	51.0	54.6	59.0	71.4	80.1	96.0
1	38.3	58.5	65.5	68.9	83.3	94.3	112.0
0	45.2	69.0	76.4	80.4	96.9	108.6	130.0
00	52.2	79.5	88.9	93.5	112.2	126.4	148.0
000	60.3	93.0	103.0	108.2	130.9	146.0	172.0
0000	69.6	108.0	120.1	126.3	151.3	169.1	204.0
Table derived from data per 33 CFR 183.425							

TABLE 9-6: Allowable Amperage 25 or More Conductors

***Effect of Voltage Drop on Conductor Sizing***

Having determined a conductor size adequate to carry the specified current, we must also determine the size of conductor to keep voltage drop over its length to less than a specified amount (usually 3 percent or 10 percent). The final conductor size is the larger (smallest gauge number) of the two determinations.

Many electrical devices will work fine with a 10 percent voltage drop but others, particularly some electric motors and some electronic equipment, will suffer. It is preferable to wire for a 3 percent maximum drop wherever possible, and only use the 10 percent maximum drop where absolutely necessary in situations with very high current draw, such as operating bow thrusters or a windlass (assuming they have motors that can tolerate the lower voltage).

Equation 9-7 relates voltage drop to length and cross-sectional area of a conductor.

$$V = I \times \left( \frac{K \times L}{A} \right) \quad (1) \quad \text{or rearranged} \quad A = \frac{K \times L \times I}{V} \quad (2)$$

Where: V = Voltage drop across the length of conductor (volts)

I = Current flow (amperes)

L = Length of conductor (feet or meters)

A = Cross sectional area of conductor (circular mils)

K = Constant relating resistance to length and area of conductor

= 10.75 for L in feet

= 35.26 for L in meters

***EQUATION 9-7: Conductor Area for Voltage Drop and Length***

With equation 9-7(2) we can determine the area in circular mils (CM) that corresponds to a given length (L) of conductor and current (I). The constant K varies with temperature and for boat calculations K = 10.75 is the standard used by the ABYC and Transport Canada).

Example:

Assume we have an appliance that draws 30 amps at 12 volts. The distance from the source to the appliance is 12 feet. We want to limit the voltage drop to 3 percent.

Total conductor length out to appliance and back  $L = 12 \times 2 = 24$  feet. Allowed voltage drop  $= 3\% \times 12 \text{ V} = 0.36 \text{ V}$

$$A = (K \times L \times I) / V = (10.75 \times 24 \text{ ft} \times 30 \text{ A}) / 0.36 \text{ V} = 21,500 \text{ CM}$$

So we need a cable of at least 21,500 circular mils area. From table 9-1 on page 520 we find the smallest conductor with an area larger than 21,500 CM is a 6 gauge conductor with an area of 26400 CM which is the cable we would select.

Tables 9-7 through 9-9 are provided on the following pages, calculated from equation 9-7, for determining the wire gauge to carry a specified current over a specified distance, at voltage drops of either 3 percent or 10 percent. So you have the option of calculating wire gauge using the formula or using the tables.

To use the tables:

1. First pick the appropriate table for the operating voltage and percent voltage drop.
2. Then enter the table in the first column and go down until you reach the first round trip distance that is greater than your required round trip distance.
3. Then move to the right across that line until amperage is found that is greater than or equal to your required amperage. If there is no amperage found in the line greater than your required amperage, then you only have to consider current carrying capacity, as per table 9-2.
4. Move up that column to the top of the table to read the size of conductor required.

Example:

Repeating the example we just solved by the equation method, use table 9-8 for 3 percent drop and 12 volts. In the Round Trip Distance column, the line with 25 feet is the first line greater than the 24 foot length of the conductor.

Moving to the right across the line, 35 A is the first amperage greater than our design amperage of 30 A.

This is in the 6 gauge column so our answer is 6 gauge.

Checking table 9-2 on page 522; at 105 degrees Celsius our conductor has a permissible amperage of 120 A so 6 gauge is okay and is our final answer

Some other things to note about these tables

- For 6 V circuits, multiply the amperages in the 12-volt tables by 0.5 and for 24 V circuits, multiply the amperages by 2.0.
- 120 V tables are given, but most of the time the current carrying capacity rather than voltage drop will be what determines the conductor size.

3% Voltage Drop - 110 Volts - K=10.75 - 1 of 2									
Round Trip Distance		AWG Wire Gauge							
ft	m	18	16	14	12	10	8	6	
		Amperage							
21	6.4	24							
23	7.0	22	34						
25	7.6	20	32						
27	8.2	18	29						
29	8.8	17	27	44					
31	9.4	16	26	41					
33	10.1	15	24	38					
36	11.0	14	22	35					
39	11.9	13	20	32	51				
42	12.8	12	19	30	48				
45	13.7	11	18	28	45				
49	14.9	10	16	26	41	65			
52	15.8	9.6	15	24	39	61	97		
57	17.4	8.7	14	22	35	56	89		
61	18.6	8.2	13	21	33	52	83	132	
66	20.1	7.5	12	19	30	48	77	122	
71	21.6	7.0	11	18	28	45	71	113	
76	23.2	6.5	10	17	26	42	67	106	
82	25.0	6.1	9.7	15	24	39	62	98	
89	27.1	5.6	8.9	14	23	36	57	91	
96	29.3	5.2	8.3	13	21	33	53	84	
103	31.4	4.8	7.7	12	19	31	49	78	
111	33.8	4.5	7.1	11	18	29	46	73	
120	36.6	4.1	6.6	11	17	27	42	67	

3% Voltage Drop - 110 Volts - K=10.75 - 2 of 2									
Round Trip Distance		AWG Wire Gauge							
ft	m	4	2	1	0	00	000	0000	
		Amperage							
71	21.6	180							
76	23.2	169							
82	25.0	156							
89	27.1	144	229						
96	29.3	133	212	268					
103	31.4	124	198	249	315				
111	33.8	115	184	231	292	368			
120	36.6	107	170	214	270	340	429		

TABLE 9-7: Allowable Amperage for 3% Voltage Drop, 110 Volts, AWG 18 to AWG 0000 Gauge Cable

3% Voltage Drop - 12 Volts - K=10.75 - 1 of 2								
Round Trip Distance		AWG Wire Gauge						
ft	m	18	16	14	12	10	8	6
<b>Amperage</b>								
10	3.0	5.4	8.6	14	22	35	55	88
11	3.4	4.9	7.9	13	20	32	50	80
12	3.7	4.5	7.2	11	18	29	46	73
13	4.0	4.2	6.6	11	17	27	43	68
14	4.3	3.9	6.2	9.8	16	25	39	63
15	4.6	3.6	5.8	9.2	15	23	37	59
16	4.9	3.4	5.4	8.6	14	22	35	55
17	5.2	3.2	5.1	8.1	13	20	33	52
18	5.5	3.0	4.8	7.6	12	19	31	49
20	6.1	2.7	4.3	6.9	11	17	28	44
21	6.4	2.6	4.1	6.6	10	17	26	42
23	7.0	2.4	3.8	6.0	9.5	15	24	38
25	7.6	2.2	3.5	5.5	8.7	14	22	35
27	8.2	2.0	3.2	5.1	8.1	13	20	33
29	8.8	1.9	3.0	4.7	7.5	12	19	30
31	9.4	1.8	2.8	4.4	7.1	11	18	28
33	10.1	1.6	2.6	4.2	6.6	11	17	27
36	11.0	1.5	2.4	3.8	6.1	9.7	15	24
39	11.9	1.4	2.2	3.5	5.6	8.9	14	23
42	12.8	1.3	2.1	3.3	5.2	8.3	13	21
45	13.7	1.2	1.9	3.1	4.9	7.7	12	20
49	14.9	1.1	1.8	2.8	4.5	7.1	11	18
52	15.8	1.0	1.7	2.6	4.2	6.7	11	17
57	17.4	1.0	1.5	2.4	3.8	6.1	9.7	15
61	18.6	0.9	1.4	2.3	3.6	5.7	9.1	14
66	20.1	0.8	1.3	2.1	3.3	5.3	8.4	13
71	21.6	0.8	1.2	1.9	3.1	4.9	7.8	12
76	23.2	0.7	1.1	1.8	2.9	4.6	7.3	12
82	25.0	0.7	1.1	1.7	2.7	4.2	6.7	11
89	27.1	0.6	1.0	1.5	2.5	3.9	6.2	9.9
96	29.3	0.6	0.9	1.4	2.3	3.6	5.8	9.2
103	31.4	0.5	0.8	1.3	2.1	3.4	5.4	8.5
111	33.8	0.5	0.8	1.2	2.0	3.1	5.0	7.9
120	36.6	0.5	0.7	1.1	1.8	2.9	4.6	7.3

TABLE 9-8(1): Allowable Amperage for 3% Voltage Drop, 12 Volts, AWG 18 to AWG 6 Gauge Cable

3% Voltage Drop - 12 Volts - 2 of 2								
Round Trip Distance		AWG Wire Gauge						
ft	m	4	2	1	0	00	000	0000
Amperage								
10	3.0	140	222	280				
11	3.4	127	202	255	321			
12	3.7	116	185	234	295			
13	4.0	108	171	216	272	343		
14	4.3	100	159	200	253	318	401	506
15	4.6	93	148	187	236	297	375	472
16	4.9	87	139	175	221	279	351	443
17	5.2	82	131	165	208	262	331	417
18	5.5	78	123	156	196	248	312	394
20	6.1	70	111	140	177	223	281	354
21	6.4	67	106	133	168	212	268	337
23	7.0	61	97	122	154	194	244	308
25	7.6	56	89	112	141	178	225	283
27	8.2	52	82	104	131	165	208	262
29	8.8	48	77	97	122	154	194	244
31	9.4	45	72	90	114	144	181	229
33	10.1	42	67	85	107	135	170	215
36	11.0	39	62	78	98	124	156	197
39	11.9	36	57	72	91	114	144	182
42	12.8	33	53	67	84	106	134	169
45	13.7	31	49	62	79	99	125	157
49	14.9	29	45	57	72	91	115	145
52	15.8	27	43	54	68	86	108	136
57	17.4	25	39	49	62	78	99	124
61	18.6	23	36	46	58	73	92	116
66	20.1	21	34	42	54	68	85	107
71	21.6	20	31	39	50	63	79	100
76	23.2	18	29	37	47	59	74	93
82	25.0	17	27	34	43	54	69	86
89	27.1	16	25	31	40	50	63	80
96	29.3	15	23	29	37	46	59	74
103	31.4	14	22	27	34	43	55	69
111	33.8	13	20	25	32	40	51	64
120	36.6	12	19	23	29	37	47	59

TABLE 9-8(2): Allowable Amperage for 3% Voltage Drop, 12 Volts, AWG 4 to AWG 0000 Gauge Cable

10% Voltage Drop - 12 Volts - K=10.75 - 1 of 2								
Round Trip Distance		AWG Wire Gauge						
ft	m	18	16	14	12	10	8	6
		Amperage						
10	3.0	18	29					
11	3.4	16	26	42				
12	3.7	15	24	38				
13	4.0	14	22	35				
14	4.3	13	21	33	52			
15	4.6	12	19	31	49			
16	4.9	11	18	29	46			
17	5.2	11	17	27	43	68		
18	5.5	10	16	25	40	64		
20	6.1	9.0	14	23	36	58	92	
21	6.4	8.6	14	22	35	55	88	
23	7.0	7.9	13	20	32	50	80	127
25	7.6	7.2	12	18	29	46	74	117
27	8.2	6.7	11	17	27	43	68	108
29	8.8	6.2	9.9	16	25	40	64	101
31	9.4	5.8	9.3	15	24	37	59	94
33	10.1	5.5	8.7	14	22	35	56	89
36	11.0	5.0	8.0	13	20	32	51	81
39	11.9	4.6	7.4	12	19	30	47	75
42	12.8	4.3	6.9	11	17	28	44	70
45	13.7	4.0	6.4	10.2	16	26	41	65
49	14.9	3.7	5.9	9.4	15	24	38	60
52	15.8	3.5	5.5	8.8	14	22	35	56
57	17.4	3.2	5.1	8.0	13	20	32	51
61	18.6	3.0	4.7	7.5	12	19	30	48
66	20.1	2.7	4.4	7.0	11	18	28	44
71	21.6	2.5	4.1	6.5	10	16	26	41
76	23.2	2.4	3.8	6.0	9.6	15	24	39
82	25.0	2.2	3.5	5.6	8.9	14	22	36
89	27.1	2.0	3.2	5.2	8.2	13	21	33
96	29.3	1.9	3.0	4.8	7.6	12	19	31
103	31.4	1.8	2.8	4.5	7.1	11	18	28
111	33.8	1.6	2.6	4.1	6.6	10	17	26
120	36.6	1.5	2.4	3.8	6.1	9.7	15	24

TABLE 9-9(1): Allowable Amperage for 10% Voltage Drop, 12 Volts, AWG 18 to AWG 6 Gauge Cable

10% Voltage Drop - 12 Volts - 2 of 2								
Round Trip Distance		AWG Wire Gauge						
ft	m	4	2	1	0	00	000	0000
Amperage								
10	3.0							
11	3.4							
12	3.7							
13	4.0							
14	4.3							
15	4.6							
16	4.9							
17	5.2							
18	5.5							
20	6.1							
21	6.4							
23	7.0							
25	7.6							
27	8.2	173						
29	8.8	161						
31	9.4	150	239					
33	10.1	141	224					
36	11.0	129	206	260				
39	11.9	119	190	240	302			
42	12.8	111	176	222	281	354		
45	13.7	104	165	208	262	330	416	
49	14.9	95	151	191	241	303	382	482
52	15.8	90	142	180	227	286	360	454
57	17.4	82	130	164	207	261	329	414
61	18.6	76	121	153	193	244	307	387
66	20.1	71	112	142	179	225	284	358
71	21.6	66	104	132	166	209	264	333
76	23.2	61	97	123	155	195	246	311
82	25.0	57	90	114	144	181	228	288
89	27.1	52	83	105	132	167	210	265
96	29.3	49	77	97	123	155	195	246
103	31.4	45	72	91	114	144	182	229
111	33.8	42	67	84	106	134	169	213
120	36.6	39	62	78	98	124	156	197

TABLE 9-9(2): Allowable Amperage at 10% Voltage Drop, 12 Volts, AWG 4 to AWG 0000 Gauge Cable

## **DC ELECTRICAL SYSTEMS**

### ***DC GROUNDING AND CABLING***

#### **Grounding**

For our purposes, *ground* refers to an electrical connection to the surrounding earth or water with the express purpose of ensuring the connected part of the electrical circuit stays at the same electrical potential (voltage) as the surrounding earth or water.

One side of a power source, such as a battery, can be connected to ground to keep it at ground potential. In the case of a boat's DC system, this connection is from the negative side of the battery to the negative terminal of the engine block or the main boat ground bus, which provides a connection to the water outside the hull via the propeller shaft or a ground plate installed on the outer hull. This keeps the negative or return side of the system that is connected to the negative side of the battery at ground potential. This is a *negative ground* system.

#### **DC Cabling**

DC cabling is sized and connected as per the earlier topic on cabling.

A circuit doesn't always consist of wire; part of it can be any conductor such as earth, water, a metal framework, or even your body (not good). If a circuit uses a metal framework or chassis to complete the circuit back to the power source, it said to have a *ground return*. This is commonly used in automobiles but *is not used in boats* (not even metal boats). Exception: Electrical equipment on the engine block, such as starters and alternators, often but not always use the engine block itself as a negative ground return.

DC cabling on boats requires both a positive conductor and negative return conductor for each device on each circuit. Marine duplex cable used for DC cabling has a red conductor for positive and a yellow conductor for the negative return. On some older boats you may find black instead of yellow for the negative return conductor. The return conductor must be as large as the positive supply conductor; the use of duplex cable guarantees this.

The red conductor may or not connect to a switch, and then must connect to a circuit breaker or fuse on the DC distribution panel. The negative or yellow conductor is connected directly to a negative bus which in turn connects to the negative battery terminal. The negative side of DC circuits always

connects directly to the bus with no intervening switches, breakers, or fuses.

## BATTERIES

### Introduction

Batteries tend to be one of those things that receive little or no attention on the average recreational boat, which results in substantially shortened operating life and premature failure—usually at the worst possible time. Often batteries are bought and installed without any thought as to what they are to be used for and how much capacity is needed. The result is batteries mismatched to the application and often undersized for the actual loads encountered.

The type of battery used on boats is a *lead-acid* battery, so named because of the use of lead in the electrodes and acid in the electrolyte.

### How the Battery Charges and Discharges

Figure 9-18 shows a schematic representation of a lead-acid battery cell under charge. The *electrodes* are conductors for current that enters or leaves the electrolyte and the *electrolyte* is a conductive solution of acid.

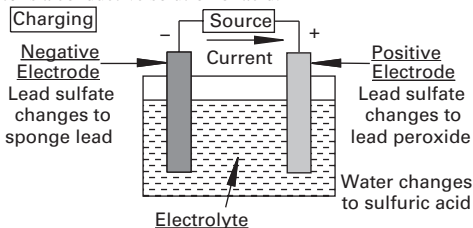


FIGURE 9-18: Charging a Lead-Acid Battery

When the charging current is applied the lead sulfate in the positive electrode changes to lead peroxide, the lead sulfate in the negative electrode changes to sponge lead, and water is changed to sulfuric acid. Note: Sponge lead is just lead that has a porous physical structure like a sponge.

As charging nears completion, hydrogen gas begins forming at the negative plate, and oxygen at the positive plate. This happens because there is too much charging current for the remaining lead sulfate and the excess current ionizes the water in the electrolyte. Ionizing refers to the separation of

water (H<sub>2</sub>O) into its constituent elements of hydrogen (H) and oxygen (O). This phenomenon is referred to as **gassing** or **venting**.

Concentrated sulfuric acid has a specific gravity of around 1.83, so the electrolyte in a charged cell with a higher acid concentration has a higher specific gravity than a discharged cell. Also as one might expect, a fully charged battery, not under load, will have a higher voltage across the electrodes. Table 9-10 shows specific gravities and no load voltages found in normal lead-acid batteries.

Condition	Discharged	Charged
Specific Gravity	1.12	1.7
Voltage 1 cell	1.8	2.1
Voltage 6 cells	11.7	12.7

TABLE 9-10: Lead-Acid Battery Specific Gravity and Voltage

Note: The condition of the electrodes is what determines the charge, and adding sulfuric acid to the battery doesn't increase the battery's charge; rather it just moves the range of discharged-charged specific gravities upward. Some batteries used in special applications use higher or lower ranges of specific gravity but these don't normally show up on recreational type boats.

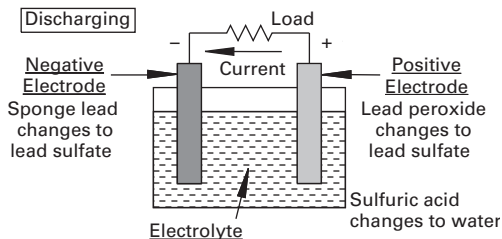


FIGURE 9-19: Discharging a Lead-Acid Battery

In figure 9-19 we see that discharging the battery is just the opposite process as charging, converting both electrodes back to lead sulfate.

## Battery Construction

The lead-acid battery has a number of cells connected together in series so that the voltage of the battery is 2.1 volts per cell times the number of cells. Thus a 12-volt battery will have six cells.

The cells are constructed of a hard plastic or rubber material and contain positive and negative electrodes that are in the form of flat plates interleaved with one another, such that every positive plate has a negative plate on either side. The plates are kept from touching each other by separators.

**Starting batteries** are designed to deliver a very high current for a short period of time and are the type found in automobiles and in boats for engine starting. They deliver higher current by having many thin plates that increase internal plate surface area, which permits higher current flow.

Some batteries are designed with fewer thicker plates that allow the battery to function longer, which effectively gives the battery greater capacity (i.e., more stored energy). These are known as a **deep-cycle battery**, and they are meant to deliver lower amperage over longer periods of time to a deeper discharge level than starting batteries.

## Battery Specifications and Ratings

There are several different measures used to describe battery characteristics.

The **20-hour rate** is the continuous amperage that the battery can supply for 20 hours at 80° Fahrenheit (27° C). An alternate way to state this: The 20-hour rate is the continuous current needed to fully discharge the battery over 20 hours.

The battery's capacity is measured in **amp-hours (Ah)** and is a measure of the energy the battery can be expected to deliver under standardized condition. The amp-hour rating is defined as the 20-hour rate (amps) times 20 hours. For example a battery that can supply 5 amps continuously over the 20-hour period is a  $5 \text{ A} \times 20 \text{ h} = 100 \text{ Ah}$  battery.

The amp-hour rating is the rating of interest for almost all applications except engine starting.

If a battery is discharged at a faster rate than the 20-hour rate, the amp-hours produced will be less than the rated amp-hours. Conversely, if the battery is discharged at a lower rate, then the amp-hours produced will be greater than the rated amp-hours. For example, if a battery with a 20-hour rate of 5 amps is discharged at 25 amps it will produce only around 70 percent of the rated amp-hours.

**Cold cranking amps (CCA)** is defined as the number of amps a battery can deliver for 30 seconds at 0 degrees Fahrenheit (-18 degrees C) with an ending voltage of at least 7.2 V while still cranking.

**Marine cranking amps (MCA)** is defined as the number of amps a battery can deliver for 30 seconds at 32 degrees Fahrenheit (0 degrees C) with an ending voltage of at least 7.2 V. MCA will always be higher than CCA.

CCA or MCA is the measure of most interest for engine starting applications.

The **reserve capacity** is the number of minutes a battery can be discharged at 25 amps at 0 degrees Fahrenheit (-18 degrees C) and maintain a voltage of at least 10.5 volts while still under discharge.

### **Battery Types**

There are three types of lead-acid batteries used in recreational boats, these being *wet-cell*, *gel*, and *absorbed glass mat (AGM)*.

#### **Wet-Cell Battery**

The flooded or wet-cell lead-acid battery is the conventional type that we are used to in our cars and uses a liquid sulfuric acid electrolyte. The wet-cell battery has vents at the top of each cell and may lose electrolyte during the venting process, which requires checking and topping up the electrolyte from time to time.

Wet-cell advantages:

- There is a lower initial cost.
- There is better deep-cycle performance.
- With proper maintenance and charging regimens, higher quality wet-cell cell batteries should achieve more than a thousand charge-discharge cycles.

Wet-cell disadvantages:

- Maintenance is required.
- Liquid battery acid can be spilled.
- Gases are released during charging.
- Quality varies considerable among different manufacturers. The expected number of charge-discharge cycles ranges anywhere from 500 to 2000 cycles.
- They have a high self-discharge rate—greater than 6 percent per month.
- Something most people don't realize is that if a wet-cell battery is left totally discharged for more than a couple

of weeks, the battery will sustain serious damage or fail completely.

### ***Gel-Cell Battery***

The gel-cell has the acid electrolyte in gel rather than liquid form and the cell is sealed although it has pressure release valves to vent any excess gas. The slightly higher internal pressure causes any vented oxygen and hydrogen to recombine into water which keeps the gel from drying out.

Gel-cell advantages:

- There is virtually no maintenance.
- It can't spill or leak.
- If charged correctly, there is no gas release.
- There is low self-discharge of around 3 percent per month.
- It is faster charging.

Gel-cell disadvantages:

- The charging process must be more closely controlled since too much gassing in the last part of the charging process will result in drying out the gel and ruining the battery.
- The maximum charging voltage of 14.2 volts may require specialized charging equipment.
- There is a higher initial cost.
- Too much gassing will ruin electrolyte.

### ***Absorbed Glass Mat Battery***

Absorbed glass mat (AGM) batteries have a glass mat separator tightly packed between the positive and negative plates. Just enough electrolyte is in these plates to activate the battery. The tight packing lowers internal resistance to allow higher starting currents in a battery that is also a deep-cycle battery. As with the gel-cell, the oxygen and hydrogen gases are recombined into water.

AGM advantages:

- It is maintenance free.
- It is shock and vibration resistant.
- There is little or no gas release under charge.
- It is good for both deep-cycle and starting.

AGM disadvantages:

- It has the highest initial cost.
- It is heavier than wet-cell type for same capacity.
- It requires very controlled charging cycle.
- Too much gassing will ruin electrolyte.

### Comparing Battery Costs

Batteries of each type were randomly selected from various vendors and the prices averaged for each type in table 9-11. Note that prices differed widely for various vendors and brands so just consider these as a rough comparison.

Type	Usage	Volts	\$ / Ah	CCA / \$
AGM	Deep-cycle	12	2.00	3.27
Gel	Deep-cycle	12	2.25	2.54
Wet-cell	Deep-cycle	12	1.18	4.23
Wet-cell	Deep-cycle—golf cart	6	0.83	3.96
Wet-cell	Starting	12	n/a	12.12

TABLE 9-11: Comparative Cost of Battery Types

Because of charging considerations (which we'll discuss further on) AGM, gel-cell and wet-cell batteries can't be mixed together. Once the decision on battery type is made, that should be the only type of battery on the boat, including the starting battery.

### Matching Batteries to the Application (Starting or Deep-Cycle)

Usually on a small boat like a runabout, only a starting battery is installed, and its only function is to start the engine, although it may run some very low power devices such as a bilge pump or radio from time to time. Obviously, a starting type battery makes the most sense, since a deep-cycle battery with enough cold cranking amps to start the engine would be excessively large and expensive. A quick look at table 9-11 shows how you get a lot more CCAs per dollar with a starting battery.

Many smaller boats are outfitted for fishing with an electric trolling motor that requires battery power while the main engine is stopped. Obviously you don't want to be discharging the starter battery to run that trolling motor or you may end up rowing those fish back to shore. The solution is to provide a second battery for powering the trolling motor, which allows the starting battery to be used exclusively for engine starting. The second battery should be a deep-cycle battery, which is suited to being deeply discharged as is likely in this situation.

In addition to deep-cycle and starting batteries, there are dual-purpose batteries designed to perform both functions. If a second battery is to be used as a back up starting battery, this could provide an argument for it being a *dual-purpose*

battery, if a deep-cycle battery can't provide the necessary CCAs.

When you trade in your runabout for a 30-foot express cruiser, you are most likely getting a boat with plenty of added house electrical loads, like cabin lights or a refrigerator. Many of these will be loads you expect to use when the engine is turned off, when you'll be relying entirely on the batteries (assuming you don't have an AC system with generator or a shorepower connection). If the starter battery is used to run these loads overnight, most likely the engine isn't going to start in the morning —the same situation as with the trolling motor.

Here's where you start thinking about a second battery or bank of batteries so you can save the starter battery for starting. This second bank (called *house batteries*) will be deep-cycle batteries since, starting batteries just aren't designed for continuous use and deep discharges.

Deep-cycle batteries say deep-cycle on the label and provide instructions for charging. Read the labels on those marine batteries at your local warehouse store to make sure you're getting what you really want; starting or deep-cycle.

On even larger boats, you start thinking about enough battery power to run an inverter that can provide AC power for appliances such as televisions and microwave ovens. Here the possibilities start to multiply. The usual and probably best approach is to have dedicated starting batteries and a separate bank of deep-cycle batteries, just like we did on the express cruiser.

An alternative is to go with two banks of house batteries and use one bank for engine starting and the other for the house power. This is acceptable, provided the total CCAs meet the requirements specified by the engine builder, even if it doesn't make a lot of economic sense.

Yet another plan is one starting bank and two house banks where use of the house banks alternates from one day to the next, the idea being that the batteries will last twice as long.

Nigel Calder makes a good detailed argument in his book that if you want to double the capacity like this, you would be better off to have all the batteries in one bank discharging them only half as much each time.

To summarize matching batteries to the application: *Use starting batteries for starting and deep-cycle batteries for everything else!*

## **Estimating Required Battery Capacity**

### ***Starter Battery Capacity***

Engine starting batteries are sized by cold cranking ampere (CCA) rating and not the ampere hour (Ah) rating. The engine manufacturer specifies the CCA requirement and you simply need to meet this requirement. If necessary, two or more batteries can be wired in parallel to increase the CCAs available.

### ***Actual Capacity Realized from House Batteries***

The number of times a battery can be expected to be completely charged and discharged is usually specified by the manufacturer and depending on the quality and type of battery can range anywhere from 300 to 1000 full cycles. The number of times a battery can be cycled has an inverse relationship to the percent it is discharged. Thus, a battery that is only partially discharged in each cycle can be cycled more times than a battery that is fully discharged each cycle. It is generally accepted that a 50 percent discharge gives the best balance between achieving useful capacity and useful battery life, and this number should be used to calculate expected capacity.

However, there is some controversy as to the amount of charging that has to take place. Some argue that it is unlikely that more than an 80 percent charge will be achieved during a day's run, so that's all you should plan for. Others argue that you must charge to 100 percent if you are to expect maximum battery life. If you use the 80 percent figure, you are now only getting  $80\% - 50\% = 30\%$  of the rated capacity.

The number that seems to have fairly general acceptance is 25 percent, so *figure on obtaining 25 percent of the battery's rated capacity in ampere-hours (Ah) each day.*

### ***Estimating Power Usage***

To estimate the required battery capacity, we must first estimate daily power usage. This is a reasonably straightforward process that involves listing all the power loads on the boat, along with their current draw and length of time they will be used each day. Multiplying the current (amps) by the time (hours) for each load yields the ampere-hours, which are then totaled up with all the other loads to give the total estimated daily power requirement in ampere-hours.

A form for estimating the boat's power requirement can be drawn up on a scratch pad (or spreadsheet) with column headings similar to the sample in table 9-12.

Equipment	Volts	Watts	Amps @ 12V	Hrs/ Day	Amp- Hrs
<i>Bilge Pump</i>	12	75	6.3	0.5	3
<i>Fan</i>	12	25	2.1	8	17
<i>Light</i>	12	25	2.1	4	8
<i>Microwave</i>	120	1500	125.0	0.2	25
<i>Hair Dryer</i>	120	1200	100.0	0.1	10
<i>Etc.</i>	...	...	...	...	...
<i>Total</i>					135

**TABLE 9-12: Example Ampere-Hour Tabulation**

An explanation of the columns is as follows:

- **Equipment**—This lists every piece of equipment that consumes electrical power on board.
- **Volts (12 or 120)**—Not necessary for this calculation, but it's useful information.
- **Watts**—The actual wattage from the equipment label.
- **Amps (12-volt basis)**—This is watts divided by 12 regardless of whether this item operates at 120 V or not. If you just have the amperage for a 120 V piece of equipment, then multiply the amperage by 10 to get the amperage on a 12 V basis.
- **Hours/day**—Estimated hours per day the item will operate.
- **Amp hours**—This is amps multiplied by hours/day. This is totaled at the bottom to get the final answer.

Our example totals up to 135 ampere-hours. Since batteries only supply 25 percent, or 1/4 of their capacity, multiply 135  $\times$  4 to get 540 amp-hours of battery capacity is needed for the house batteries.

Table 9-13 on the next page lists some typical equipment that might be found onboard and ranges of power requirements for each. This table could be used for a guesstimate, but the watts or amperes should be determined from the actual equipment labels or manuals.

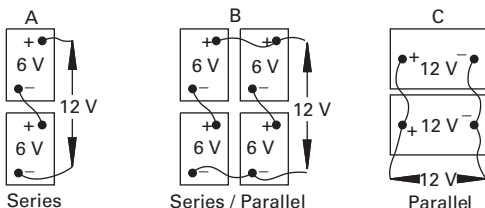
Equipment	Watts		Amps (12 V Basis)	
	From	To	From	To
Anchor Light	10	12	0.8	1.0
Anchor windlass	400	4000	33.3	333.3
Bilge blower	20	50	1.7	4.2
Bilge pump	50	500	4.2	41.7
Fan	10	200	0.8	16.7
Fresh water pump	50	100	4.2	8.3
Light	5		0.4	
Light	10		0.8	
Light	25		2.1	
Light	50		4.2	
Shower pump	50	100	4.2	8.3
Clothes dryer	4000	5000	333.3	416.7
Clothes washer	400	600	33.3	50.0
Water heater	700	2000	58.3	166.7
Air Conditioner	1000	2000	83.3	166.7
Electric drill	300	500	25.0	41.7
Hair Dryer	1000	1300	83.3	108.3
Color TV 10"	35	45	2.9	3.8
Color TV 19"	70	90	5.8	7.5
Computer	100	150	8.3	12.5
Satellite Receiver	15	30	1.3	2.5
Stereo	30	100	2.5	8.3
VCR	15	30	1.3	2.5
Blender	150	300	12.5	25.0
Coffeemaker (brew)	700	1300	58.3	108.3
Electric frypan	1000	1500	83.3	125.0
Icemaker	100	200	8.3	16.7
Microwave	500	1500	41.7	125.0
Refrigerator	50	500	4.2	41.7
Toaster	800	1200	66.7	100.0

Note: Amps on a 12 volt basis are watts divided by 12 regardless of operating voltage

TABLE 9-13: Typical Equipment Power Draw

### Battery Cabling

Assuming your boat has a 12-volt DC system, all 12-volt batteries will be wired in parallel, never in series. Six-volt golf cart batteries are often used for house batteries because they are cheap and have good deep-cycle characteristics. In a 12-volt system, two golf cart batteries must be wired in series to produce 12 volts.



**FIGURE 9-20: Battery Wiring Examples**

In figure 9-20, B would have twice the amp-hour capacity of A but voltage is the same at 12 volts. C shows two 12-volt batteries hooked together to double the capacity but leave the voltage at 12 volts.

### Battery Installation

According to 33 CFR 183.420, *a battery must not move more than one inch in any direction when a pulling force of 90 pounds or twice the battery weight, whichever is less, is applied through the center of gravity of the battery.* If batteries weighing 50 pounds and more are able to slide back and forth an inch in rough seas, eventually something is going to break. *The batteries should be fixed in place so as to be totally immobile in all directions including vertical.*

*The battery must be installed so that metal objects cannot come in contact with the ungrounded battery terminals.* This can be accomplished by covering the connection with an insulating boot or installing the battery in a covered battery box.

*Each metallic fuel line and fuel system component within 12 inches and above the horizontal plane of the battery top surface as installed must be shielded with dielectric material.* What the heck does that mean? Basically it means that any metal fuel system component that is above the battery and within 12 inches of the battery in any direction must be insulated. The purpose is to allow the battery to be installed or removed without the terminals contacting the metal and sparking. The author would like to suggest that it's going to be quite awkward to install or remove a heavy battery with an obstruction only 12 inches above it and that neither fuel lines nor anything else should be within 3 feet of the top of a battery.

*Each battery must not be directly above or below a fuel tank, fuel filter, or fitting in a fuel line.* This is pretty much self-explanatory. You don't want fuel leaking onto the battery, and you don't want to be servicing fuel lines that are below a battery.

*A vent system or other means must be provided to permit the discharge from the boat of hydrogen gas released by the battery.* Hydrogen gas is lighter than air and is highly explosive and will rise, so provision must be made to allow the gases to escape, particularly from pockets above the batteries.

*Each battery terminal must not depend on spring tension for its mechanical connection to the terminal.* This means the terminal must either clamp on to the battery post or be secured by a nut or bolt.

## **Battery Charging**

### ***Introduction***

Batteries on a boat are usually charged using the alternator attached to the main engine or with a battery charger powered by 120 VAC. The AC power for the charger is supplied either from a shore connection or an onboard generator. Other alternatives such as solar and wind power are used, particularly on cruising sailboats, to charge the batteries while underway without the engine running. Here discussion is limited to charging with alternators and AC chargers.

The alternator supplied with a gasoline or diesel boat engine is usually a small frame alternator designed to generate just enough power to charge a starting battery, and will not be capable of continuous operation at rated maximum output. Similarly, the voltage regulator supplied with the engine is designed for the same purpose and will be incapable of properly charging the deep-cycle house batteries we just discussed.

### ***Voltage Regulators and Battery Chargers***

Earlier we established that the output of the alternator can be controlled by metering the amount of current allowed through the field windings with a **voltage regulator**. We want a voltage regulator that will allow the alternator to charge the batteries as fast as possible, but without excessive gassing, and without overcharging them.

The same qualities are also desirable in an AC-powered battery charger, so both will be discussed at the same time.

Cheaper regulators, like the one that came on the boat engine and automobile type battery chargers, usually provide a **one**

*stage* charge that begins charging with a high current that drops rapidly so charging time is lengthened considerably. The dotted lines on figure 9-21 show how the voltage and current behave over the charging cycle with a single stage regulator or charger.

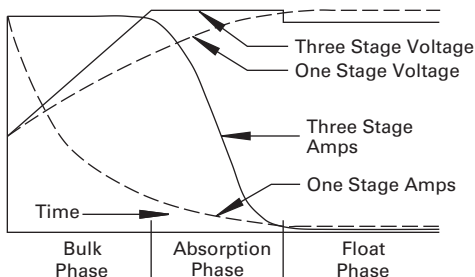


FIGURE 9-21: One and Three Stage Charging

The curves in figure 9-21 are not for any particular battery; rather they are just for illustrating the concept of three stage charging. Actual curves vary by battery model and manufacturer and also will be different for wet-cell, gel-cell, and AGM battery types.

A *three stage* charger or regulator manages the charging process in three separate stages or phases in order to charge the battery in the minimum amount of time but without excessive gassing or overcharging. The solid lines on figure 9-21 show how the voltage and current behave over the charging cycle with a three stage regulator or charger.

A battery is capable of accepting a current of approximately 25 to 40 percent of its amp-hour capacity rating until it reaches about 75 percent of full charge. Initial charging at this rate is termed the *bulk phase*. During the bulk phase the charging voltage is raised to maintain the constant current flow until the voltage reaches 14.4 volts for a wet-cell or 14.1 volts for a gel-cell.

Note that although the battery might accept current up to 40 percent of capacity, that is probably excessive and it would be advisable to limit bulk current to a maximum of 25 percent of capacity. Charging at somewhere from 15 to 25 percent of

capacity is a reasonable target. Fifteen percent gets you from 50 percent charged to 75 percent charged in a little under two hours.

At this point the battery begins excessive gassing if the high current flow is maintained, so the charging current must be lowered to prevent this. This is the *absorption phase* where the voltage is held constant at 14.4 V (for wet-cells) and the charging current falls off as the battery is further charged. Eventually, while still at the absorption voltage, the battery will only accept current of about 2 percent of capacity. At this point, the battery is considered fully charged and the voltage is then dropped to 13.3 volts (13.7 V for gel-cells) to maintain the charge in the float phase.

One can see in figure 9-21 the dramatic difference in current delivery from a one stage and three stage charging system. The single stage regulator or charger just isn't going to get the house batteries charged during an eight hour run. If a boat is going to be out for more than a couple of days and drawing power from the batteries every night, a three stage charging system isn't just a nice option, it's a necessity.

### **THE ALTERNATOR**

Now that the charging current has been established as somewhere in the range of 15 percent to 25 percent of battery bank capacity, the required alternator output can be determined.

An alternator heats up when producing and also will be running continuously in a hot engine space which will cause it to run even hotter. At higher temperatures, the output is reduced by as much as 20 to 25 percent, so this should be allowed for when sizing the alternator. If the desired charging rate is 20 percent of bank capacity, then the alternator size is  $125\% \times 20\% = 25\%$  of bank capacity.

Another item to consider is that alternator output decreases as RPMs decrease. For example, an alternator that produces 110 A at 6000 RPM will only produce 75 A at 2500 RPM. If you think a lot of charging will be done at anchor with the engine running at idle, then an even larger alternator is indicated. Be sure the regulator can control current delivery to the battery bank.

Alternators are available as small frame alternators, similar in size and mounting configuration to an automobile alternator, and as large frame alternators that operate at higher outputs. Small frame alternators can replace the existing alternator while large frame alternators may require addi-

tions or modifications to the engine to be mounted properly. Generally large frame alternators will run cooler and therefore will be more efficient. Small frame alternators are available in outputs up to about 160 A. To achieve more than that, you either need to install two alternators or install a large frame alternator.

If you replace an existing alternator, keep the old one as a spare. Another option is to keep the existing alternator in service to charge the starting battery and use the new high capacity alternator to charge the house bank.

One last consideration: The alternator uses horsepower produced by the main engine and this could be a significant consideration with a very small engine. A 160 amp alternator would draw around 3 horsepower from the engine.

## **AC SYSTEMS**

### **INTRODUCTION**

These days AC electrical systems are becoming more and more commonplace on smaller and smaller boats. The impetus driving this trend is the desire to have power microwave ovens, refrigerators, color televisions, kitchen appliances, power tools, and all the other comforts of home, onboard. Many of these items aren't available at all for 12 VDC operation or the ones that are available cost two or three times more than their 120-volt brethren, further fueling the move to AC.

In many cases, inverters are retrofitted to older boats that didn't have a 120 V system to start with, often with little or no regard for proper wiring or grounding—a dangerous practice, to say the least. One-hundred-twenty volts is 10 times greater than 12 volts, which means it can push 10 times the current through your body with sometimes fatal results. Add in the fact that saltwater is an excellent electrical conductor, and you have a greater chance of receiving a serious or even fatal shock than in your home.

At the beginning of this electrical chapter it was emphasized that *this book will in no way qualify anyone to carry out electrical work on their boat*, and this bears repeating. You should hire an electrician with actual marine electrical experience if you wish to have electrical work done on your boat, keeping in mind that even a journeyman electrician qualified to work on house or even industrial wiring is not automatically qualified to work on boat electrical systems. Again,

if you insist on being a do-it-yourselfer, obtain, read, and thoroughly understand one or more of the publications mentioned at the beginning of this electrical chapter. Purchase the appropriate standards from the ABYC and get a qualified person to coach you and inspect your work.

## AC CABLING AND CONNECTIONS

AC cabling is sized and connected as per the earlier topic on cabling.

### Polarity

As mentioned previously, triplex cable for marine AC wiring has three conductors as follows; black for hot, white for neutral, and green for ground. Four conductor cable for 240 VAC has an additional hot conductor with red insulation.

Correct polarity must be maintained throughout the AC system. When connecting to any electrical device or receptacle:

- The black hot conductor connects to the brass or copper colored terminal.
- The white conductor connects to the silver terminal.
- The ground connects to the ground terminal, usually marked with green.

Get one of these gizmos from your local hardware store for checking correct polarity of AC receptacles, then go ahead and check all the receptacles on your boat regardless of who did the wiring. It will only take five minutes and it could save you a lot of grief.



Figure 9-22 shows color pinouts for standard 3 prong 125 V wall receptacles. These are polarized receptacles designed to ensure that anything plugged into them will maintain correct polarity. Note the wider slot that ensures that a polarized plug with just two blades will only plug in with the correct

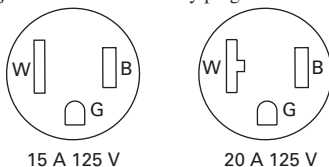


FIGURE 9-22: AC 125 V Receptacle Pinouts

orientation. These receptacles have the same design and polarity as the ones in your house (except they are marine grade) so everyday household appliances can be plugged into them safely.

In your house, the neutral and ground connectors are connected at the main junction box where the power comes into your house. On a boat, the neutral must only connect to ground at the power source and nowhere else. Make sure neutral is not connected to ground in any appliances onboard. To check this with an ohmmeter, the resistance from white (neutral) to green (ground) should be infinity.

Receptacles for household use are not suitable for marine use and are definitely not designed to connect to stranded wire, so all 125 V receptacles onboard should be of a type approved for marine use. They might seem ridiculously expensive at more than 20 bucks a pop, but if you own a boat you are already painfully aware that everything for boats costs a lot more, so hopefully you've already learned to live with it.

### **Ground Fault Circuit Interrupters**

A ground fault circuit interrupter is a circuit breaker that can detect current leakage to ground and trip when it does so. The operating principle is to trip if the return current is less than the supply current—the difference is assumed to be leaking to ground. This usually provides reasonable protection from electric shocks.

Receptacles located in deck areas, galleys, heads, and machinery spaces are supposed to have ground fault circuit interruption (GFCI) installed. Consider installing GFCI for all AC circuits on the boat. A GFCI receptacle must be the first one installed in a series to protect all the downstream receptacles.

### **Distribution Panel**

All AC circuits originate from individual breakers installed on the AC distribution panel. Double pole breakers that open both the hot and neutral circuits are preferred, but single pole breakers on just the hot black conductors are acceptable if the system is properly polarized throughout.

The neutral white wire is connected to a neutral bus and the green ground wire is connected to an AC ground bus. Neutral and ground must not be connected here (like they are in your house). It bears repeating that *neutral and ground are only connected together at one place and that is at the*

power source, be it ashore at the marina, or at your onboard generator or inverter.

### **AC Grounding**

The ground conductor circuits must not be able to be disconnected in any way and must not have any installed breakers, fuses, or switches.

The AC ground from AC distribution panels is connected to a single AC ground bus, which in turn is connected to the negative engine terminal or the boat main ground bus. This effectively grounds the AC ground to the surrounding water either through the propeller shaft or an external grounding plate.

If this AC electrical system ground connection is somehow disconnected, you may someday find yourself or your first mate performing a rather unpleasant role that is much better performed by said ground connection. *Severing the AC ground connection in the hope of eliminating stray dockside currents or for any other reason is downright dangerous and should not be done!* You cannot rely only on shorepower ground for protection.

## **AC SOURCES**

### **Introduction**

There are three ways to provide AC electricity to a boat:

1. Plug into a source ashore using a shorepower cable.
2. Generate power onboard using a diesel or gas powered generator.
3. Use an inverter to convert 12 VDC current to 120 VAC current.

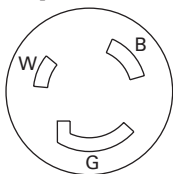
Wiring must be such that individual circuits can only be connected to one of these sources at a time, although it's possible to use more than one these power sources at a time, as long as no individual circuits can be connected to more than one power source. In other words, some circuits may be powered by source 1, while other circuits are powered by source 2, and yet others by source 3, as long as the wiring is such that no circuit can be connected to more than one source at a time.

Any power source must have sufficient capacity to power all the circuits that can be connected to it. For example, if the inverter is capable of powering several circuits, not including the air conditioning system, then the wiring must be such that the inverter cannot be connected to the air conditioning system.

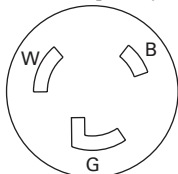
## Shorepower

### *Shorepower Receptacles*

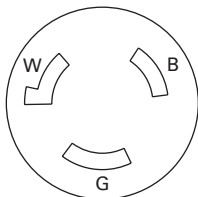
Today most marinas provide some kind of shorepower although the voltage and current vary. Typical hookups are: 120 volt/20 amps, 120 volt/30 amps, 120 volt/50 amps and 240 volt/50 amps. The standard locking receptacles used for dock outlets are shown in figure 9-23 along with the conductor color pinouts used to maintain correct polarity.



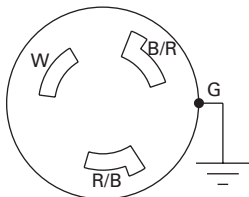
20 A 125 V Locking



30 A 125 V Locking



50 A 125 V Locking



50 A 250 V Locking

**FIGURE 9-23: Shorepower Receptacle Pinouts**

Note how the 250 V receptacle shows B/R and R/B on two of the prongs. This just means that the B/R prong can be connected to either black or red and the R/B prong must be connected to the other color (i.e., if the B/R prong is connected to red then the R/B prong must be connected to black).

Knowing the pinout, it's easy to check for correct polarity before plugging in.

With 125 V receptacles:

- W to G should read 0 V. If W to G is around 120 V then polarity has been reversed. If W to G is greater than 0 V

but less than 100 V then polarity isn't necessarily reversed but there's a problem somewhere.

- W to B should read approximately 120 V.

With 250 V receptacles:

- W to G should read 0 V. If W to G is around 120 V then polarity has been reversed. If W to G is greater than 0 V but less than 100 V, then polarity isn't necessarily reversed but there's a problem somewhere.
- B to R should read about 240 V.
- B to W about 120 V.
- R to W about 120 V.

Anything else and there's a problem. Note that voltage can vary quite a bit. Expect voltages dockside to range from 105 V to 125 V or 210 V to 250 V.

If you detect reverse polarity in a dock outlet you should:

- Not plug in. Having a hot neutral in your boat is dangerous and may also introduce AC currents into the water around your boat, which can be lethal to a nearby swimmer.
- Immediately notify marina management and ask that the wiring be fixed, since this is dangerous not only to you, but to the next boater who comes along and unknowingly plugs into the faulty receptacle.

### ***Hooking Up to Shorepower***

Cables for connecting your boat to shorepower are available at marine supply stores and must be rated for marine use. The dock receptacle is female and the boat receptacle is male.

The sequence for hooking up to shorepower is:

1. Turn the boat's shore power switch to off. If there's a breaker on the dockside outlet, switch it off too.
2. Plug in the boat end of the shorepower cable first. This is to ensure you don't drop a "hot" cable into the water.
3. Plug in to the shore outlet.
4. Check your polarity indicator on your main panel. If it's on then polarity is wrong and you stop here. If it is off continue.
5. Turn the boat's shore power switch to on.

To disconnect:

1. Turn the boat's shore power switch to off.
2. Disconnect from the shore outlet first.
3. Disconnect the boat end of the cable.

### ***The Shorepower Circuit***

The circuit diagram in figure 9-24 is for a shorepower hookup, and it shows the essential parts of the connection.

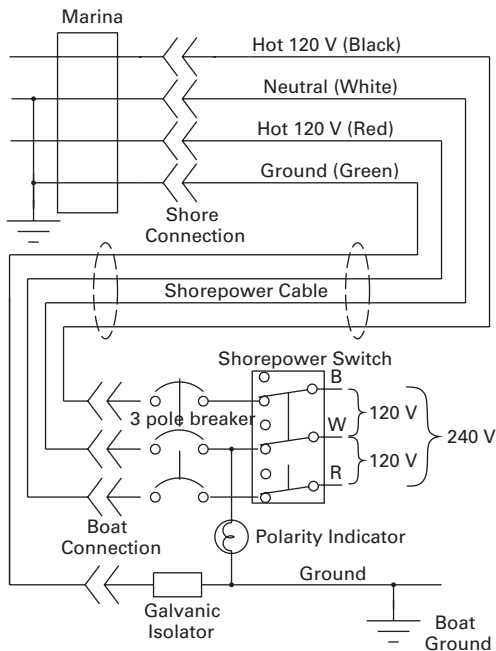


FIGURE 9-24: Shorepower Circuit 240 V

Things to note about this hookup:

- Neutral is connected to ground only at the source, in this case the marina.
- Polarity is maintained throughout.
- A 3 pole breaker that breaks all three current carrying conductors is required near the shorepower inlet.
- The galvanic isolator prevents stray currents from flowing through the ground wire.
- There are no breakers or switches in the ground conductors.
- The AC ground (green) is grounded inside the boat.

- A 120 V supply circuit is similar to the 240 V circuit shown in figure 9-24 but without the red conductor.

### ***AC Leakage Danger***

With this setup, if there is AC current leaking aboard the boat, it will normally return to shore via the ground conductor as it should. However, if there is high resistance somewhere in the ground connection to the marina, the current, seeking the path of least resistance, flows out through the boat's ground and returns to the marina source through the water and perhaps through neighboring boats. This can be quite dangerous for anyone in the water, so keep that in mind next time you think about letting your kids swim at the marina. Note: There have been several deaths caused by stray currents paralyzing swimmers around boats in marinas. In at least one case, an individual who jumped in to rescue another also died.

### ***Galvanic Isolator***

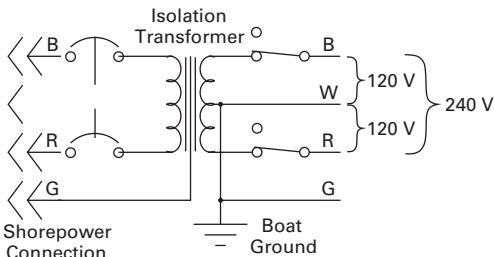
Stray currents entering the boat through the ground conductor can cause serious corrosion problems in a very short period of time if they are not stopped. The ***galvanic isolator*** is designed to stop these stray currents by only allowing currents to flow only in the presence of a voltage greater than 1 volt. Stray current is usually at a voltage less than 1 volt and therefore won't pass the isolator, but higher voltage current from grounding of live conductors or equipment will pass.

Note that the galvanic isolator does not eliminate the danger of AC leakage mentioned above. A galvanic isolator may not be found on some older boats; however, most new boats will have one if they are constructed to ABYC standards. Some galvanic isolators can be problematic since they won't give any indication of failure, leaving the boat unprotected. Models are available with an integrated monitor that indicates whether or not the unit is working properly.

Cost of a galvanic isolator is from about \$150 for a 30-amp unit with no monitor, to around \$350 for a 50-amp unit with monitor. The incremental cost of the integrated monitor is about \$100.

### ***Isolation Transformer***

A much better alternative to the galvanic isolator is an ***isolation transformer***, which severs the ground connection to the marina completely, leaving no possibility of stray currents from that source.



**FIGURE 9-25:** *Isolation Transformer*

The shorepower ground ends at the transformer. The secondary of the transformer acts as an independent source, and therefore the neutral is attached to boat ground there. Since the two windings are not electrically connected, no stray current can pass the isolation transformer.

For 240-volt input only the red and black conductors need be attached to the primary. The secondary is tapped in the center to provide two separate 120-volt circuits.

This arrangement keeps the neutral at ground potential and at the same time provides a return path for AC leakage, through the ground conductor back to the secondary. This way no AC leakage currents will leave the boat as they always seek to return to their source. An added bonus is that your boat will not be able to act as a ground return for the boat next to you, since you are not connected to shorepower ground.

Another advantage of an isolation transformer is that reverse polarity on the shorepower side of a 120-volt transformer doesn't matter, since the secondary sets its own polarity by attaching neutral to ground.

It's pretty clear that this is the way to go especially if your boat spends a lot of time plugged in at the marina. The only problem is, it's not cheap and it's relatively heavy. Figure on about \$1000 for a 30-amp unit and around \$2000 for a 50-amp unit. A 50-amp transformer capable of voltage boosting goes for approximately \$4000 and weighs over 200 pounds.

### **Inverter**

A boat *inverter* is designed to convert (invert) electricity from 12-volt DC to 120-volt AC. The general idea behind inverter use is to charge the house batteries from the alterna-

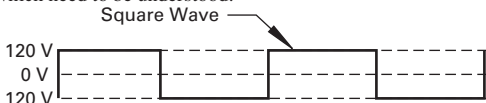
tor during the day while the main engine is running, and then produce AC with the inverter drawing from the batteries while the engine is off in the evening.

Portable Inverters are available in sizes ranging from about 100 watts to 500 watts. The smaller size would be suitable for running a laptop computer and the larger size might power small hand tools. Just keep in mind that a 500 watt draw on the 12-volt batteries is  $500\text{-W} / 12\text{ V} = 40$  amps so the larger portable models will have to connect directly to the batteries rather than just plug into a cigarette lighter.

Permanent mount inverters that double as battery chargers are quite common since the internal transformer can be used to transform voltage up or down. Combining the two functions like this in an inverter/charger saves both space and money, although installation should be done by a professional.

### *Inverter Output Wave Forms*

Earlier, AC was described as current that changes direction back and forth, at its frequency of 60 hertz (60 times per second). Actually, AC comes in a couple of different flavors, which need to be understood.

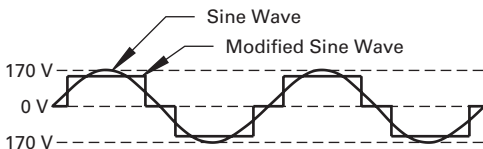


**FIGURE 9-26:** *Square Wave AC*

Figure 9-26 shows how we might imagine what AC looks like. Voltage would alternate back and forth from +120 V to -120 V as the current changes direction 60 times per second and the average absolute value of voltage would be 120 V. This is the current waveform that would be produced by a very simple inverter.

The power delivered by the public utility system or a generator actually takes the form of a sine wave and looks more like the waveform in figure 9-27.

Here, the voltage increases smoothly to a peak value of approximately 170 volts and then smoothly down to a reversed 170 volts at 60 cycles per second. The average or **root mean square (RMS)** voltage will be 120 V as it was for the square wave voltage above. We don't need to know why all this is so, we just need to know that electrical devices are designed to



**FIGURE 9-27:** *Sine Wave and Modified Sine Wave AC*

work with the sine wave form of AC and that some devices just don't work well with square wave current.

Marine inverters are available that produce either *true sine wave (TSW)* or *modified sine wave (MSW)* output. The modified sine wave attempts to approximate the sine wave through a series of steps as shown in figure 9-27. The modified sine wave is better than the square wave, but not as desirable as a true sine wave. Electronics such as television sets and stereo systems tend to be quite sensitive to the waveform and will work best with TSW. Microwave ovens may not work very efficiently with MSW but they should work. Heat-producing appliances, such as light bulbs, toasters, and electric frying pans, don't care about the wave form at all.

As you might expect, a TSW inverter costs more than a MSW inverter. Browsing through a marine equipment catalog, I found 2000-watt TSW inverter/chargers priced around \$1600 to \$1800 and a 2000-watt MSW inverter/charger at about \$1300.

### ***Inverter Size***

Inverters are sized by watts, so wattages for all the 120-volt loads on the inverter need to be tabulated. Keep in mind that some of the loads will be continuous and some higher loads will be for relatively short periods. For example, starting an electric motor usually requires a power surge more than double the running wattage. Other examples of short period loads include a microwave oven or a hair dryer. It is important to distinguish between the two because inverters have both a continuous and peak rating.

Inverters are available up to 2000 or even 3000 watts (5000 W or 8000 W surge) capacity. Figure 3000 watts is about equivalent to 110 V shorepower of 3000 W/ 110 V  $\cong$  30 amps. Without even allowing for efficiency losses this will translate to more than a 300 amp draw on the house batteries! Just running a 1000 watt microwave for five minutes

will draw  $1000 \text{ W} / 12 \text{ V} = 83$  amps (again not allowing for inefficiency).

It should be apparent by now that the inverter is not going to be the real challenge; rather it's going to be the size of the house battery bank and getting it fully charged each day. Running a medium size refrigerator overnight is going to be pushing it. And don't even think about trying to run air-conditioning from an inverter. Actually, you can do it, but you'll need an awful lot of batteries.

### **Generator**

Once power needs go much beyond 2000 watts, the inverter just doesn't cut it and a generator becomes the only real option when you're away from the dock. Unfortunately it's not a cheap option. A standalone diesel powered generating system will likely be the single most expensive item on the boat after the main engine.

A boat generating system consists of an armature or alternator type generator driven by a dedicated diesel engine. The generator produces 120 VAC or 240 VAC power directly and may also have a battery charging alternator attached.

The output wave form is sinusoidal (which is the preferred form) and can be produced at a frequency of 50 or 60 hertz. The output frequency depends on the engine RPM and 60 hertz power is usually produced at 1200, 1800, or 3600 RPM. The slower turning engine is the quietest, but is larger and heavier. 1800 RPM is probably the best compromise between noise and size. Also keep in mind that the 3600 RPM engine will have a shorter operating life.

The generators' diesel engine cooling and exhaust systems will usually be of the same type as the main engine systems, however they should be entirely separate from the main engine cooling and exhaust systems. In particular, the generator wet exhaust should never be run into the main engine wet exhaust system because water can be forced back into the main engine cylinders.

As with the main engine cooling system, avoid raw water cooling in favor of a closed circuit cooling system.

The system should be sized so the generator will run at 40 to 70 percent of full power when it is running. If running for extended periods at less than 40 percent is anticipated, consider installing two smaller size generators.

## **Combining the Inverter and Generator**

The main objection to onboard generating systems is the noise and exhaust they produce. Often nearby boaters will find either or both of these objectionable, particularly if the system is left on all night.

Unless there's a need to keep the air conditioning running all night, a system that combines both an inverter and generator might be the best alternative. The generator is used in the early evening when using equipment that draws lots of power such as microwaves, clothes washers and dryers, electric skillets, hair dryers and curling irons, etc. Then the inverter is used just to keep the refrigerator, lights, and television going through the night.

## **BONDING AND CORROSION**

### ***BONDING***

*Bonding* refers to the electrical connection of all metal frames and hardware on the boat to a common ground that is connected electrically to the surrounding water, so as to maintain the voltage potential of everything connected to the bonding system at the ground potential of the surrounding water.

The items to be connected include such diverse metal items as, fuel and water tanks, seacocks, propeller shafts, etc. Electrical equipment enclosures that are not otherwise grounded should also be connected to the bonding system. This should include all DC equipment enclosures since there is no grounding conductor in DC cabling (even though the negative return conductor is ultimately connected to ground).

Any of the aforementioned metal pieces of equipment or hardware has the potential to become electrically charged by contact with something like a loose or bare wire, so that they leak stray currents, or even worse, shock someone who comes in contact with them. Bonding prevents this possibility by providing any spurious currents a low resistance path to ground.

The physical installation of a bonding system consists of a long copper bus that runs the length of the boat, with each piece of equipment connected to this bus. A copper bar or copper pipe is usually used for this purpose and connections to it are made by drilling, tapping, and installing screws. The bonding system is grounded to the engine negative (ground) terminal for grounding through the propeller shaft or the

boat's main ground bus, which is grounded either through the propeller shaft or to a ground plate on the outside of the hull. Through-hulls, such as seacocks and the propeller shaft, may or may not be connected to the bonding system. Reasons for bonding or not bonding are discussed later in the topic on corrosion.

## **GROUNDING**

A circuit doesn't always consist of wire; part of it can be any conductor such as earth, water, a metal framework, or even your body (not good). If a circuit uses a metal framework or chassis to complete the circuit back to the power source, it is said to have a ground return. As mentioned previously this is commonly used in automobiles but not in boats—except on the engine block.

For our purposes, ground refers to the potential of the surrounding earth or water.

A wire that connects to a power source can be also connected to ground to keep it at the same potential (voltage) as ground. In the case of a boat this connection is to the surrounding water and the wire or conductor that is connected to ground is said to be grounded. In 12-volt DC systems it is the negative side of the battery that is grounded. Grounding is extremely important in boats and is also discussed in the sections on 12-volt and 120-volt systems.

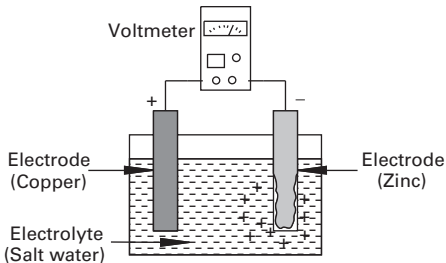
The DC ground, AC ground, and bonding system must all be connected to the engine negative terminal or to the main ground bus that is connected to the engine negative terminal.

## **GALVANIC CORROSION**

### **Galvanic Series**

Figure 9-28 shows an experiment that anyone can set up and perform at home. Suspend two different metals in a saline solution and connect the two together with a wire and a voltmeter as shown. The voltmeter will read a voltage. In this case with one electrode of zinc and the other of copper a voltage of about 0.6 V should register on the voltmeter. I did this and registered a reading of approximately 0.8 V.

What's happening here? The zinc and copper have differing electrical voltage potentials, which induce a current flow if the two metals are connected and immersed in an electrolyte. This device we constructed for the experiment is known as a *voltaic cell* and is a specific example of the fact that two metals of differing potential will have a current flow between



**FIGURE 9-28:** *Demonstration of Galvanic Potential Using a Voltaic Cell*

them if they are connected and immersed in an electrolyte. Note that if the two electrodes are of the same metal, there is no voltage difference and therefore no current flow.

If the cell is left connected and a current continues to flow, it will eventually become evident that the zinc is being eaten away, and if left long enough the zinc will completely disappear. This process is known as **galvanic corrosion**. There is a chemical reaction involved that explains why this is happening, but here all we need know is that when two different metals are joined and immersed in an electrolyte such as water, the metal with the lower voltage potential will corrode away.

Note that the two different metals don't have to be joined by a wire as in our experiment; they just have to be in contact with one another while immersed in the electrolyte, in order to produce the same effect. The strength of this reaction is far more pronounced in saltwater, since saltwater is a much better electrolyte than fresh water,

Table 9-14 lists some common metals ranked in descending order of their voltage potential so that metals at the top of the list have more positive voltage and metals near the bottom more negative voltage relative to each other. This ranking is known as a **Galvanic Series**. The values in the right-hand column are the galvanic potential (voltage) and are averaged from four different tables (No two tables match but they are all close).

The metals at the top of the list are termed **cathodic** or **more noble** while metals further down the list are termed **anodic**

	Alloy	Volts
Anodic = Less Noble = More Active << ----->> Cathodic or More Noble = Least Active	Graphite	0.3
	Platinum	0.2
	Titanium	0.0
	18-8-3 stainless steel, type 316 (passive)	-0.0
	18-8 stainless steel, type 304 (passive)	-0.1
	Monel	-0.1
	Silver	-0.1
	Nickel (passive)	-0.2
	Inconel (passive)	-0.2
	Silver solder	-0.2
	70-30 cupro-nickel	-0.2
	Lead	-0.2
	400 series stainless steels (passive)	-0.3
	Bronze Type M and G	-0.3
	Manganese bronze	-0.3
	Silicon bronze	-0.3
	Admiralty brass	-0.3
	Tin	-0.3
	Red brass	-0.3
	Aluminum bronze	-0.3
	Naval brass	-0.4
	Yellow brass	-0.4
	Copper	-0.4
	Inconel (active)	-0.4
	18-8-3 stainless steel, type 316 (active)	-0.4
	400 series stainless steels (active)	-0.4
18-8 stainless steel, type 304 (active)	-0.5	
13 percent chromium stainless steel, type 410 (active)	-0.5	
Mild steel	-0.6	
Cast iron	-0.6	
Cadmium	-0.7	
Aluminum alloys	-0.8	
Zinc	-1.0	
Magnesium	-1.6	

TABLE 9-14: The Galvanic Series

or *less noble*. Since the least noble metal is the one with the most negative voltage potential, it is the least noble metal that will corrode when the two metals are joined in an electrolyte. The less noble metals are more active and more susceptible to corrosion.

To get an idea of the potentials involved, the difference in voltage potential from platinum at the top of the list to zinc near the bottom of the list is approximately  $-1.8$  volts. That is to say, zinc is negative 1.8 volts relative to platinum and current flow through the connection will be from the platinum (+) to the zinc (-). Another example would be zinc at 1.3 V less than copper.

In general, metals far apart on the series can be expected to produce more galvanic corrosion and metals close together very little galvanic corrosion.

### **Galvanic Corrosion on Boats**

For example, if an aluminum propeller is mounted on a stainless steel shaft and immersed in seawater, the aluminum prop will experience galvanic corrosion since aluminum is further down the table than stainless steel.

This of course, is not good; we need to find a way to stop the galvanic corrosion of the propeller. It turns out that if three, rather than two, metals are linked together in our galvanic cell, only the least noble of the three metals experiences galvanic corrosion and the two more noble metals don't corrode and are protected (at least until the less noble metal has completely corroded away). This applies to any number of metals connected together; only the least noble metal will experience galvanic corrosion.

This explains the zincs we see mounted on propeller shafts, rudders, hulls, etc. They are near the bottom of the galvanic series and being lower down than the steels, bronzes, and aluminums, serve to protect by sacrificing themselves, thus the term *sacrificial zincs* or *anodes*. Zincs must be inspected and replaced periodically, since they corrode, and they must never be painted if they are to function as intended.

Something to note: Galvanic corrosion occurs without the presence of electricity from any external source; it is entirely self-generated by the action between dissimilar metals connected together in an electrolyte. It can be experienced just as easily on a sail boat with no installed electrical systems, as on a fully electrified powerboat.

If all metal through-hulls are bonded together with an internal bonding circuit then galvanic currents can develop between these through-hulls. For example, a bronze seacock forward on the hull that is bonded (connected) internally to a steel propeller shaft aft can induce galvanic corrosion of the steel shaft (assuming no zincs on the shaft).

Galvanic corrosion can even occur between differing metals on neighboring boats if the boats are connected electrically to each other, such as via a shorepower cable grounding wire.

### **Internal Corrosion**

Almost all metals used on boats are an alloy of two or more metals. Stainless steel, brass, bronze, and sometimes aluminum are all alloys. These metals can be susceptible to internal galvanic currents in the presence of seawater, which leads to galvanic corrosion of the least noble metal in the alloy.

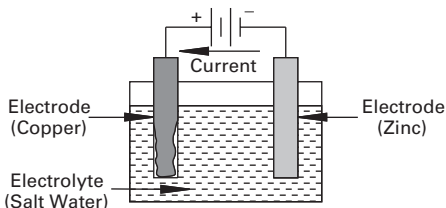
Brass is a case in point. Brass is very "shippy." You find nicely polished brass fittings all over the place onboard ships and yachts, so you might conclude that brass is a good metal for use in a marine environment. In fact, brass is copper alloyed with up to 40 percent zinc, so if brass fittings are used below the waterline the zinc is going to corrode away just like the sacrificial zinc anodes we just talked about in a process called *dezincification*. The remaining copper will crumble and fail and well, there goes your seacock, leaving a 2-inch hole in the bottom of your boat. *Never use brass valves or fittings below the waterline.* Always use marine grade bronze.

Another somewhat different example is stainless steel. Stainless steel is alloyed with metals such as nickel and chromium, and develops an oxidized layer that actually requires the presence of oxygen to stay intact. When stainless is deprived of oxygen, corrosion begins and it's not so stainless anymore. Where this causes the most problem is in crevices such as the space around a stainless bolt in a hole, under deck fittings, or around a propeller shaft, where this is little or no oxygen available. When you see rust stains coming from stainless steel fittings like this, you are seeing evidence of *crevice corrosion*. When stainless steel experiencing crevice corrosion it is said to be *active* and is much lower in the galvanic series than stainless steel in a *passive* state.

Much the same process occurs with aluminum. Whereas aluminum will work fine as hull material, it suffers from crevice corrosion when used for fuel tanks with no breathing space around them or that sit on a damp surface.

**STRAY CURRENT CORROSION****Corrosion of Electrodes by Applied Electrical Current**

Figure 9-29 shows the same voltaic cell as figure 9-28 on page 563, but the voltmeter has been replaced by a battery with its positive terminal connected to the copper (+) electrode.



**FIGURE 9-29:** *Electrical Current Induced Corrosion*

In this case, the battery is working against galvanic potential, and if the battery voltage is sufficient to overcome the galvanic potential difference between the two electrodes, a current will flow in the reverse direction to the galvanic current and cause the copper electrode to corrode, even though it is more noble and has a higher galvanic potential than the zinc.

This little experiment demonstrates that:

- A metal electrode can be corroded by an applied current.
- Corrosion from applied electric currents is independent of and in fact can operate in the reverse direction of galvanic corrosion.
- The corrosion occurs in the electrode that has the current flowing out of it (i.e., the electrode on the positive side of the electrical source).

A couple of other things to know about corrosion from applied electric current:

- The positive and negative metal electrodes can be either the same metal or different metals. The corrosion occurs regardless.
- Corrosion from stray currents can occur at much higher rates than galvanic corrosion due to the higher voltages and currents involved.
- If the positively charged electrode that is being made to corrode consists of more than one metal connected together, the least noble metal will corrode first.

## **Stray Electrical Currents in Boats**

Stray current corrosion has grown from being a relatively unknown phenomenon 40 years ago to a significant problem today. This is because of the proliferation of electrical hardware and systems on boats, along with the almost universal use of shorepower at all marinas.

Stray currents are usually generated by faulty electrical wiring and equipment both within and without the boat, and act like the applied electric currents described above that cause corrosion to the metal parts (the electrodes) immersed in the surrounding water (the electrolyte). Stray current generation inside the boat is usually caused by leaks to ground from such things as frayed insulation, saltwater, or salt bridges between positive terminations and ground, or current leaks into bilge water. Undersized wiring can create unbalanced potentials in grounding systems, which also can lead to generation of stray currents.

Sources of stray current outside the boat include faulty marina wiring and faulty wiring in your neighbor's boat. Stray currents can affect your boat even if you aren't connected to shorepower, in that they can enter your boat via a metal through-hull and exit elsewhere via a metal through-hull if they are bonded together.

In general, stray currents are much stronger than galvanic currents and will therefore cause corrosion to proceed at a much faster rate.

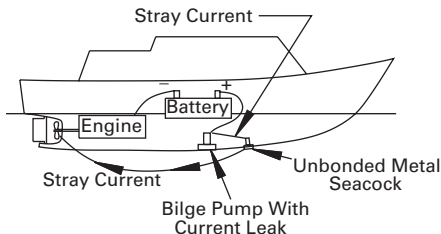
As noted above, if two or more metals are joined as part of the same corroding electrode, the least noble metal will corrode first so those zincs do provide some measure of protection. Keep in mind, though, that strong stray current may cause loss of zincs in a matter of hours instead of the months you would expect from galvanic corrosion. Once the zincs are gone, expect the next metal down the series to follow the zincs.

## ***BONDING VERSUS NONBONDING OF THROUGH-HULLS***

### **Unbonded Through-Hulls**

Bonding all through-hulls together electrically helps protect them from corrosion due to current leakages inside the boat, since the bonding system provides a path of least resistance for the current to return to the source.

Figure 9-30 shows what can happen when a metal through-hull is not bonded. A stray current leakage has developed



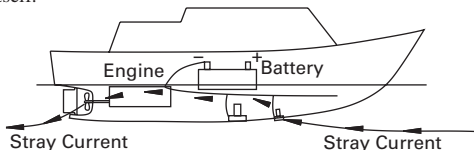
*FIGURE 9-30: Internal Stray Current Leakage From an Unbonded Through-Hull*

from a bilge pump located near a nonbonded seacock. The stray current flows out through the seacock, through the saltwater (electrolyte) to the propeller shaft, which is the path of least resistance back to the source. The result: The seacock is going to corrode.

If the seacock had been bonded, the current would find its way directly back to the source through the bonding system and the seacock corrosion prevented. This is the primary argument for bonding all metal parts that are in contact with seawater.

### Bonded Through-Hulls

Unfortunately, there's also a downside to bonding all the metal through-hulls together. The bonding system provides a path of least resistance for external stray currents either from your neighbor's boat or leakage from the shorepower system itself.



*FIGURE 9-31: External Stray Currents Through Bonded Through-Hulls*

Figure 9-31 gives an example of this case. A stray current seeking to return to its source follows a path, in through the seacock, through the bonding system, back to the engine, and out through propeller. In this case, the propeller will

corrode, unless there's a zinc installed, in which case the zinc will corrode first. If the seacock had not been attached to the bonding system, there would have been no low resistance path through the boat and the current would have followed an external path through the water.

### **Bond or Unbond?**

In my research, I haven't found any opinions strongly favoring either bonding or not bonding metal through-hulls. Readers are usually presented with similar information to that given here and left to decide for themselves. But here are some ideas.

If your boat's electrical system is in excellent condition with adequate size conductors and all electrical devices have a dedicated ground return conductor, then you might consider unbonding your through-hulls. If your boat spends a lot of time around marinas where you would expect to find lots of external stray currents, then you might also consider unbonding through-hulls.

Conversely, if you've bought an older boat with questionable wiring, then the wise thing would probably be to bond all the through-hulls. Of course, it would be even wiser not to buy that boat in the first place.

If the boat spends most of its time at sea, and is rarely near other boats and shorepower, then bonding is probably the better way to go.

### **LIGHTNING PROTECTION**

There is plenty of literature on the subject of lightning protection for small boats, both in book form and on the internet. Google *lightning protection small boats*, and you'll turn up plenty of information on the subject. One excellent site that turns up near the top is <http://www.thomson.ece.ufl.edu/lightning/>. This is a University of Florida website authored by Dr. Ewen M. Thomson that provides up-to-date common sense information on lightning protection, as well as links to other sites and to papers on the subject.

Here, I just want to touch on the subject enough to get you to appreciate that you should take this subject seriously and do a little more research on it. There's not enough information here to allow you to design and install a lightning protection system; the idea is to just understand the basic concepts involved.

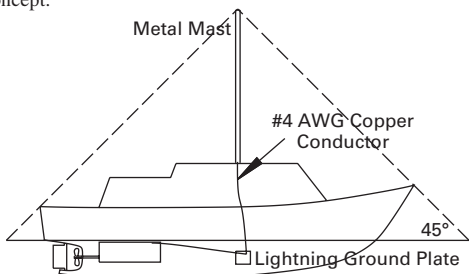
In general, boats of aluminum or steel construction are less likely to be seriously damaged by a lightning strike since

the metal hull provides a path to ground. That doesn't mean a metal boat is invulnerable to lightning damage, however; masts, stays, antennas, electric, and electronic gear are all susceptible. So are people on the outside of the boat.

A fiberglass boat hit by lightning normally sustains far more serious damage than a metal-hulled boat. Lightning can travel down a metal mast, straight down through the center of the boat, and out through a hole that it blasts in the bottom of the hull. If it finds the bonding system it can pass through it to all grounded through-hulls and may end up melting those out. If you're on deck anywhere near a stay and holding on to the tiller, you yourself become an excellent path to ground.

### The Protection System

The basic design of a small craft lightning protection system is fairly simple in principle. It consists basically of a #4 AWG copper conductor or its equivalent leading from the top of a mast of adequate height, down as straight a path as possible, through the boat to a grounding plate of at least 1 square foot affixed to the outside of the hull. The mast must be high enough to provide a cone or zone of protection that extends downward and outward at a 45-degree angle that encompasses the entire boat. Figure 9-32 illustrates the basic concept.



*FIGURE 9-32: Elements of a Lightning Protection System*

This system is not attached to the boat's grounding system inside the boat, but the grounding system may connect to the external lightning grounding plate. With the protective system in place, the lightning has a path to ground that doesn't necessitate blowing holes in your hull. More important, if all the stays and metal objects on deck are tied in to the system,

some measure of protection is provided to personnel who don't have sense enough to get below when there's lightning around.

There are several guidelines published as to minimum turning radius of the main down conductor, minimum size of copper strands, acceptable connections, proximity to other equipment, methods of isolating electronic equipment, etc. The three books mentioned at the beginning of this chapter, the ABYC, and Dr. Thomson's website all provide detailed installation related information and requirements.

### **Is Lightning Protection a Good Idea?**

As we've seen, a lightning protection does not prevent lightning strikes; rather it provides a relatively safe path through your boat for the strike to reach ground. There are those who say that installation of a lightning protection system increases the chances of being struck by lightning. Virtually all the experts dispute this, stating there is no reason for this to be so and no statistical evidence to support this view.

In the very first sentence on his website, Dr. Thomson states, "The only benefit of not protecting a yacht from lightning is saving the cost of the protection system."

I hope this discussion will persuade you to analyze further the whole issue of lightning protection on your boat, particularly if you do your boating on the East Coast or Florida (where most lightning strikes occur).

## **CHECKLIST**

<b>BASIC ELECTRICAL TOOLKIT</b>	
Spare fuses (if your boat uses them)	<input type="checkbox"/>
Screwdrivers -slotted	<input type="checkbox"/>
Screwdrivers -phillips	<input type="checkbox"/>
Needlenose pliers	<input type="checkbox"/>
Linemans pliers	<input type="checkbox"/>
Wire stripper	<input type="checkbox"/>
Crimping tool	<input type="checkbox"/>
Selection of marine grade crimping terminals	<input type="checkbox"/>
Electrical tape	<input type="checkbox"/>
Heat shrink tubing	<input type="checkbox"/>
Multimeter	<input type="checkbox"/>
Spare wire in various sizes (marine grade)	<input type="checkbox"/>
Battery testing hydrometer	<input type="checkbox"/>
110 V receptacle polarity tester	<input type="checkbox"/>
Battery terminal puller	<input type="checkbox"/>
Soldering iron and rosin core solder	<input type="checkbox"/>