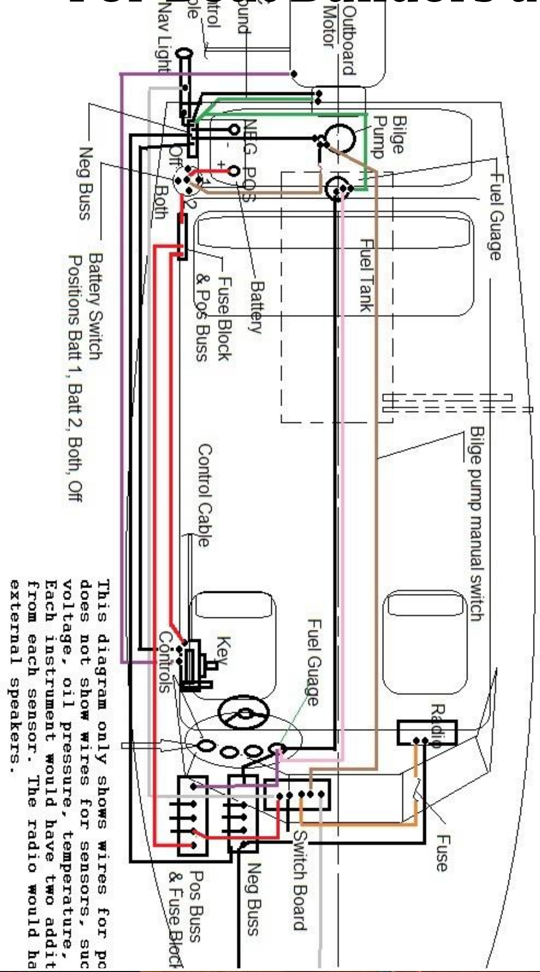
ELECTRICAL SYSTEMS

For Boat Builders and Owners



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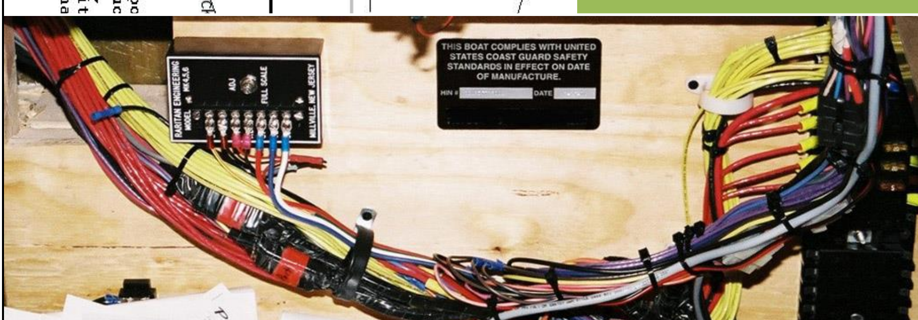

I am not a spokesperson for the US Coast Guard or ABYC or other authority. For an official interpretation of regulations or standards you must contact the US Coast Guard or other organization referenced.

This book is only intended to be an aide to the boat builder to learn about electricity and electrical requirements for recreational boats. It does not include all of the applicable rules or standards that are contained in the Code of Federal Regulations, TP1332 or the RCD, ABYC standards or ISO standards

It is the boat manufacturer's responsibility to ensure that their products comply with the regulations or laws in the country where they manufacture and/or sell their products. They should get copies of the laws or standards that apply to their products and become thoroughly familiar with their contents. This book can aide in doing that but boat manufacturers should consult with the US Coast Guard or the authority in their country to be sure that their products meet all of the regulations or standards that apply.

If you have any questions about the content of this book contact me at:
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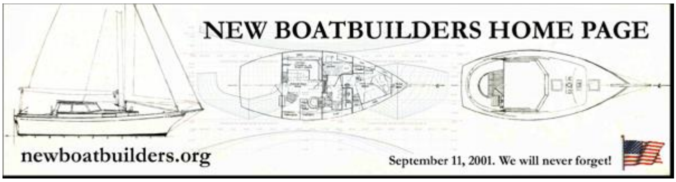

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Most important, I want to thank my wife for editing these pages. My grammar is as good as hers, so her help is invaluable.

Some editorial changes have been made to this document to improve readability. The order in which things appear may have been changed to make it flow better. But the content is the same as on the web pages.

I am also grateful to those who have e-mailed me asking questions and asking for assistance with the electrical systems on their boats. Any mistakes that may occur here are mine alone. If you find a mistake, or find that something is confusing or not easy to understand, please e-mail me at spinners110722@yahoo.com. All submissions will help to revise future editions.

This is an instruction on the basics of wiring. Electrical systems can be found in your house, your car, and your boat. Everything electrical is just an extension of the basics. Even your cell phone or your computer started out using fundamental electrical theory. But as systems become more extensive, and more complex, more and more care must be taken to make sure the basics are not violated. As can be seen in the illustration in Part 6, things can get very complex. But as long as you follow the basic rules everything should work correctly.

One thing that must be kept in mind when wiring a boat, or anything else for that matter, is that although the fundamental principles of electricity are the basis for any system, there may be several ways to achieve the same result. So if you see differences between what I describe here and other texts on electrical systems, it does not necessarily mean I or they are wrong. If the system complies with the basic fundamentals then it is correct. There may be several ways to wire a system to achieve the same result. A case in point is the section on transformers. An isolation transformer, or a polarization transformer, may be used to accomplish the same thing, even though they are wired slightly different.

Also, if you follow the industry standards you do not need to know a lot of formulas or do a lot of calculations to properly wire an electrical system. However, if the system begins to get complex it is best to hire a professional to help you design and install the electrical system. A simple error can have catastrophic affects. So it is important to make sure the system is correctly designed before you start installing

Disclaimer: I am not a spokesperson for the US Coast Guard or ABYC. Interpretations of regulations and standards given here are solely my interpretation. However, they are based on years of experience working for the Coast Guard Office of Boating Safety, Recreational Product Assurance Division, and participating in ABYC Project Technical Committees. For an official interpretation of regulations or standards you must contact the US Coast Guard, ABYC or other organization referenced.

Introduction

This guide was developed as part of my web site, **New Boat Builders Home Page**, to teach the basic elements of electrical systems to boat builders. If you want to learn more about electrical systems for boats, there is a list of references at the end of this document. The small boat builder needs to understand at least the basics of electrical systems. Most boat fires are electrical in origin and come from badly wired or badly maintained electrical systems. The boat builder should have at least enough knowledge to know when to hire a certified marine electrician or engineer to do the job.

The first part of this guide deals with basic electricity. The second part deals with the U. S. Federal Regulations for boats. A basic knowledge of electricity is necessary to understand The U. S. Federal Regulations.

Safety Considerations

Why are there so many requirements for fuel, electrical and ventilation on boats?

History and accident investigations have shown that one of the most devastating and damaging accidents that can happen on a boat is an explosion or fire. There is simply nowhere for you to go and it usually happens so suddenly that there is no reaction that can be made to prevent much of the damage and injuries which occur. So, over the years safety standards have been developed to prevent this.

Fires and explosions require three conditions before they can occur. The necessary conditions are called the **Fire Triangle**, and they are oxygen, a source of ignition and fuel. On boats the oxygen is obviously present, the source of ignition is usually the boats electrical system, and the fuel is generally gasoline. Do not be fooled though. Even though diesel is much less volatile than gasoline and fires occur much less frequently, diesel powered boats need to follow the same rules.

So, if one side of the fire triangle can be eliminated, then the explosion and fire can be prevented. Each of the standards dealing with the fuel systems, electrical systems, and ventilation, is designed to eliminate one of the sides of the fire triangle.

Ventilation: Fires and explosions occur within a very narrow range of conditions called the lower explosive limit (LEL) and upper explosive limit (UEL). This is the ratio of fuel to air. The range for gasoline is between a ratio of seven parts air to one part fuel vapor, and fourteen parts air to one part fuel vapor; seven (7) to one (1) to fourteen (14) to one (1). A ratio greater than fourteen to one is too lean to explode (too much oxygen) and less than seven to one is too rich to explode (too much fuel). This is why your car won't start when it's flooded; too much fuel. Ventilation is designed to keep the LEL way below fourteen to one so you never reach the lower explosive limit. Pour in lots of air and you should never reach that ratio. Big block engines especially need lots of air to breathe properly. So a well-designed ventilation system is very important.

Fuel: The fuel system standard is designed to do one thing. Stop leaks! The hose specified is to ensure that the hose will withstand the heat, humidity, and most importantly, the components of the fuel, without getting hard, or too soft, cracking or splitting. The hose is also designed to withstand fire for two and one half (2 ½) minutes so that should a fire occur, the hose doesn't just become a steady source of fuel for the fire. The fuel system fittings are designed to prevent leaks where they most frequently occur, at the fitting. Eliminate as many fittings as possible. Keep it simple!

Electrical: Last but not least, the electrical system has to be designed to eliminate sparks; sources of ignition! That is why there is an ignition protection requirement. But also, there is a need for over current protection, to eliminate the short circuit that causes the wire to get red hot and melt, setting off a fire. There are other safety considerations for electrical systems.

Shock hazard is a big consideration today. Twenty years ago most boats had a twelve (12) volt DC system. Few boats had 110 volt AC systems. They were generally only found on large yachts. Today it is very common to have extensive AC systems on even small cruisers in the twenty five and twenty six foot range, and on cruising sailboats in the thirty foot range. Larger yachts are installing 220 and 600 volt systems. Shock hazards are very real.

Also, even smaller boats are installing Lithium Battery Based systems. Some of these are 48 Volt DC or 60 Volt DC sytems. High voltage sytems can be truly dangerous.

Galvanic Corrosion: Galvanic corrosion is a very real problem on boats, particularly boats with both AC and DC systems. Even if your boat is well protected, the one next to you in the marina may not be. A poorly designed system can eat the stern drives right off your boat in a few days!

Here I am going to concentrate only on Electrical. But this seems to be the one that causes boat owners the most problems. Electrical fires are the single largest number of fires on boats. Hopefully if the system is in good working order and installed correctly many problems will be eliminated.

Also, here I will talk about the United States Code and the Federal regulations. However, the electrical standards in other countries are very similar. The International Organization for Standardization (ISO) has published standards for the world and these have been incorporated by the European Union in the Recreational Craft Directive (RCD). These are very similar to the US standards. Additionally, other countries, such as Canada and Australia, have similar standards. Almost all of these are based on or derived from the American Boat and Yacht Council Standards (ABYC), which is the boating industry standards organization in the USA. ABYC is also a member of ANSI, the American National Standards Institute and recognized worldwide as accepted industry standards for recreational boats.

Additionally, the Society of Automotive Engineers (SAE) and Underwriters Laboratories (UL) standards are incorporated into the US, ABYC and ISO standards. These are both internationally recognized standards societies that set the highest level of engineering standards for automobiles, boats, aircraft and many other devices.

There are a few differences between the USA, RCD, ISO and other standards. It is best to obtain a copy of the standards that apply in your country. Almost all of these are available on the internet from the government organization that is responsible for recreational boats.

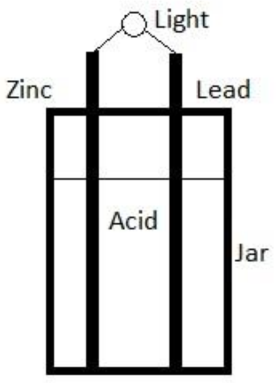
BASIC ELECTRICITY: Part 1

Electricity: I am going to try to keep this a simple as possible, not because I think you can't understand it. I assume that to master the art of boat building you have to be smart. I want to this to be simple, but complete enough to give you a basic understanding of how this electrical stuff works. This does not qualify you as an electrician. Electricians must take years of study and on the job training to pass certification exams. It will give you a basic understanding of what is going on and how simple circuits are wired. When I was much younger I worked on radars and computers on Coast Guard ships and when people asked us "how does it work?" we would say "magically, mystically, wonderfully, electronically". But it's actually a lot simpler than that. However, to some it still seems like magic.

So what is electricity? As we all learned in school the world is made up of atoms. Atoms are made up of electrons, protons and neutrons. What we are interested in, is the **electrons**, surrounding the nucleus of the atom. Electrons can be dislodged from their atom and attached to another atom giving it an excess of electrons. Excess electrons give an atom a negative charge. Atoms with not enough electrons have a positive charge. Through a chemical reaction or other force such as magnetism, electrons can be made to flow through a conductor from the negative to the positive and used as electricity. So electricity is really just a stream of electrons flowing through a conductor from point A to point B and back to where they came from. (A complete circuit.) This flow is called **current** and is measured in **amperes**.

All of us have experienced this either by getting a static discharge off of a door knob or other metal object, or by seeing nature's ultimate display of electricity, lightning. This is a simple exchange of electrons from one point to another. We use this every day in our homes, our cars, our cell phones, and every other electric or electronic device we use, but we give little thought to what is actually happening.

Basic Terminology:



In grade school most of us had a science teacher show us an experiment where a strip of lead with a wire attached and a strip of zinc with a wire attached, were put into a glass jar filled with acid. This is what is called a **voltaic cell, or battery.** The other ends of the wire were connected to a light, and lo and behold it lit up!

Battery History
https://en.wikipedia.org/wiki/History_of_the_battery

That is about as basic a battery as there is. What is happening here is not magic, just simple chemistry. The acid is an **electrolyte.** An electrolyte is a fluid that allows electrons to flow through it from one pole to another. Salt water is a pretty good electrolyte. Fresh water is not but will still conduct current and is actually more dangerous if current gets into the water. Dilute hydrochloric acid, used in most 12V lead-acid batteries is a very good conductor. (Here is a very technical definition of electrolyte. Especially, see the section on Electrochemistry.)
https://en.wikipedia.org/wiki/Electrolyte

When you put two dissimilar metals near each other in an electrolyte, one of the metals gives up electrons to the other metal. But this only happens if there is a complete circuit, which is the wire and the light. So the electrons flow from one plate to the other through the wire and the light, and back to the plates. This doesn't go on forever though. One plate will gradually disappear and soon there will be no more electron flow. Then the light goes out. Where does the material on the plate go? It gets deposited onto the other plate. Remember this, because this is crucial to how batteries work, and how galvanic corrosion works. In fact this is called the **Galvanic Process.** (See Galvanic Corrosion https://en.wikipedia.org/wiki/Galvanic_corrosion)

If we didn't have a light in the circuit, just a wire, electrons would still flow, but it would happen so fast that our primitive battery would be dead in no time at all, or the wire would get too hot and melt. This is called a **short circuit,** meaning the positive side of the battery is connected directly to the negative side. To prevent this we put in a load, something in the circuit that creates a resistance in the circuit. In this case the light is the **load.** It provides some **resistance** to the flow of electrons and slows down the process. Also the filament in the light gives off some of the energy of the electrons in the form of light and heat. Otherwise no work would get done by the electrons. So for electricity to do work there needs to be a load in the circuit. This can be lights, appliances, electronic equipment, or motors, all of which put the electrons to work.

The wire getting hot and melting is the basic principle behind a fuse. If too many electrons are flowing through the wire, a fuse is designed to get hot and melt at a predetermined amount of current flow. This breaks the circuit, or what is called an open circuit, and stops the current flow, the same way throwing a switch does. So, a fuse is a safety device to prevent the wire from getting too hot and maybe causing a fire. Note; the fuse is there to protect the wire, not the load. Fuses are designed to open at a specific amperage. If the current exceeds that amperage, then the fuse opens stopping current flow. A fuse can be used only once. If it "blows" it must be replaced.

Circuit breakers do the same thing as a fuse but can be reset and used again. How they do this is different than a fuse, but the important thing is they perform the same function; breaking (opening) the circuit and shutting off the power.

So now we know what current is. It is electron flow. The amount of **current is measured in Amperes**, or milliamperes. The symbol for Amperes is A, or for milliamperes, mA.

What drives this current is called voltage. **Voltage** is a measure of potential energy contained in the battery and is measured in volts. The symbol for volts is **V**.

The load is resistance to current flow and is measured in **ohms**, named after the guy who discovered that different loads create differing amounts of resistance. The symbol for this is either R or the Greek letter Omega (Ω). I will just use R.

Types of Electricity: AC and DC

Electricity comes in different flavors, **AC and DC**. No, that is not a rock group. **AC stands for alternating current**, which is what we all have in our houses, and most appliances run on AC, and is usually 120 volts, or 220 volts for some large appliances such as clothes dryers. Where does AC electricity come from? See https://www.saveonenergy.com/how-electricity-works/

DC stands for Direct Current and is usually low voltage such as 6 volts or 12 volts. Many of the small electronic devices we commonly use, such as cell phones, calculators, and IPods all run on DC. Your car also uses DC and most small boats use only DC. However, as the boats get bigger they may use both AC and DC, until you get into the ship sized yachts that use only AC. First though, I will deal with DC because it is simpler to explain and what most small boats use.

Direct current comes primarily from batteries. You can get it by converting AC to DC but for now I will stick with batteries. The simplest batteries are single cells such as the D cells used in flashlights, or AA and AAA cells used in most small electronic devices. (Today many devices use lithium batteries but I will get to that later) A long time ago, someone discovered that any single cell battery, no matter how big, puts out about 1.2 volts. By improving the chemistry during the centuries, it has been upped to about 2 volts. The larger you make a cell, the longer it will last, and the more current you will get out of it (amperes) but you still won't get any more than about 2 volts.

So how do we get typical lead-acid cells to be 12 V and 6 V batteries? These are lead-acid type batteries and have about two (2.0) volts per cell, compared to the 1.5 volts of most flashlight-type cells. If you tie a lot of these cells together in **series** (I'll explain series in a minute) they add up. So three cells combines to be six volts, and 6 cells adds up to 12 volts. So actually that 12 V battery in your car or boat is really six cells (count the vent caps) wired together to make twelve volts. These cells are all inside one case, so it looks to be one battery.

Series means battery cells that are connected together thus: The positive pole on the first cell is wired to the negative on the second, and the negative on the first is wired to the positive on the second, and so on until you have the voltage you need. See the diagram below.

Parallel means just the opposite. All the positive poles are connected to each other and all the negative poles are connected to each other. This still only gives you about two (2.0) volts per cell, but it increases the amount of current. This is commonly done in boats and recreational vehicles to make a large battery bank to power all the DC equipment on board. Two or more twelve volt batteries will be connected in parallel to increase the current, to run more equipment, or to run your equipment for a longer time.

However, if you have something that runs on 24 volts or 48 volts, you can connect 12 volt batteries in series to get the desired volts. In series you add the voltages. In parallel you add up the amperages.

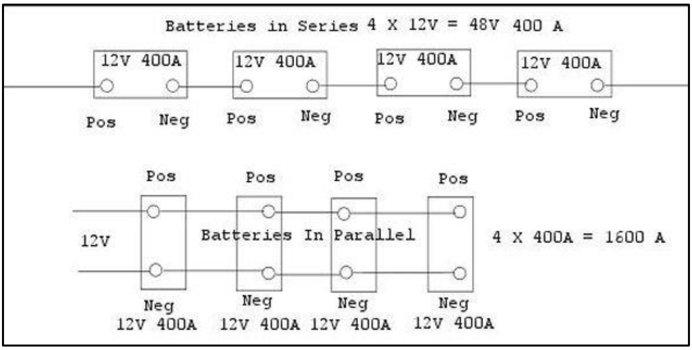


Fig. 1 Batteries in Series and Parallel

See the Figure on the next page, that shows three batteries. The two on the left are deep cycle batteries and are the "house batteries" that run most of the equipment on board, and are wired in parallel. The battery on the right is the starting battery and not connected to the two deep cycle house batteries. However, in this instance there is a switch which allows the house batteries, in an emergency, to be used to start the engine or the generator.

Fig. 2: Deep Cycle Batteries on the left, starting battery on the right.

So, why DC? DC has certain advantages. It comes in convenient sized packages; for example, your typical automotive batteries. Also, DC does not present the big shock hazard that AC does until you get over 50 volts. Plus that, most equipment used on small boats is designed specifically to run on DC. You don't need a large generator to produce DC, and you can easily recharge the batteries from an alternator on your engine, or with a charger from shore power, and you can keep them charged with simple solar chargers.

Why is it called direct current? Because **DC current flows in only one direction,** as opposed to AC, which flows both directions. For low power devices, DC is more than adequate to supply your power needs. See Wikipedia on Direct Current https://en.wikipedia.org/wiki/Direct_current

So, what about AC? It's called **Alternating Current because the current flow switches direction every 1/120th second**, meaning it takes 1/60 of a second to go through a complete cycle, or 60 cycles per second, now called **Hertz** after the inventor, and shown as **Hz.** See Wikipedia on Alternating current. https://en.wikipedia.org/wiki/Alternating_current

Alternating current's biggest advantage is that it can be easily transformed to higher or lower voltages with a **transformer.** To send lots of power a long distance, a high voltage up to hundreds of thousands of volts is used ("High Tension" lines). The current is much less, so the voltage drop is much less. Some of the newest long-distance lines now use DC, as new methods of converting DC up and down in voltage have been developed.

Someone discovered that electrical equipment such as AC motors run best at between 50 and 60 cycles. We in America chose to use 60, the rest of the world opted for 50. Also, most of the world outside the US uses 220 volts instead of the 120 we usually use. So if you go anywhere else, to run your US electrical equipment, you need an adapter that changes 220 volts to 120 volts. In most cases the difference between 50 and 60 Hz is not a problem. That's why when you go to Europe and take your laptop computer or a shaver, hair drier, or curling iron, you need appliances that have a switch for 120V to 220V, or a separate converter. Recently though many laptop chargers and small appliances will run from 120 or 220V and 50 or 60 Hz. Read the small print on the back of your charger!

AC can be changed easily to DC of various voltages as well, by power supply devices that change the voltage and rectify AC to DC.

See Wikipedia on Electrical Wiring https://en.wikipedia.org/wiki/Electrical_wiring

Wikipedia Electrical Wiring in North America
https://en.wikipedia.org/wiki/Electrical_wiring_in_North_America

Wikipedia Electrical Wiring (UK)
https://en.wikipedia.org/wiki/Electrical_wiring_in_the_United_Kingdom

Also **AC can be transformed**, that is changed easily to another voltage by use of a transformer, so you can have 120 volts AC, 220 or 440 AC, or whatever you need. It can be changed easily to DC as well, by a **converter**. Out on the power pole, the power in the lines coming into your neighborhood is around 10,000 volts AC. But the utility company mounts transformers on the poles to transform it to 120 volts AC, 220 or 440 AC so you can use it in your house, or on your boat.

Why AC on a boat? As boats get bigger the owners want the convenience of appliances that run off of AC. Probably number one is air conditioning. There are 12 V air conditioners but AC ones are more available and more powerful. Also, house type appliances such as large screen TV's, VCR's, computers, refrigerators, etc., all run on AC. So AC has come aboard our boats and is here to stay. It is also appearing on smaller and smaller boats every year as the market gets more competitive.