By: Peter McDowell

Electricity 101

Introduction

Electricity can be difficult to understand, and is very easy to misunderstand through uneducated observation. Misinformation about it is rampant. I have seen some horrendous explanations of it in amateur publications and online. Somebody once said that if you can't explain something in simple, easy to understand terms, to someone who knows nothing about it, then you really don't understand it yourself. There are some very good books written about electricity. There are also some very good online sources, amateur hobby discussion boards, not so much. I had an interesting discussion with a fellow at the Gravenhurst boat show in 2010. He was talking about the reason you are supposed to ground spark plug wires when turning over a motor without the spark plugs connected. When I told him his story was a very common mis-belief, he said an engineer told him about it and nothing would ever change his mind. Life is too short to waste trying to convince people like that so I let it go. I did a little online research afterwards and found about 24 main branches of engineering. Including all the sub categories the total was 79. Just because someone is an engineer doesn't make them an electrical engineer. Some people's minds are closed and no amount of evidence will convince them. Trying to do so is a waste of life. It took me many years to figure that out. Interestingly, while perusing the Professors library at school I came across a book titled "Electrical engineering for all Engineers." This article is written for the open minded who genuinely want to understand basic electricity and how ignition systems work.

I teach electrical apprentices at George Brown College's Casa Loma campus. I can see the castle from the intermediate shop window. Over their approximately 5 year apprenticeship the students go to school for three sessions called Basic, Intermediate and Advanced. They take Theory, Shop, Instrumentation, Electronics, Electrical Code and Blue Print reading. For theory, in Basic, they learn about Direct Current, Ohm's Law, Current, Voltage and Resistance, also Kirchoff's current and voltage laws. In Intermediate theory they learn about Alternating Current, Reactance, Impedance, Capacitance, Inductance, Power Factor and Motor theory. In Advanced theory they learn all of those as applied to three phase AC. I'm going to write a series of articles following along the same lines, leading (hopefully) to an understanding of how the ignition systems in our old outboards actually work. We won't talk about three phase; it's not required to understand ignition systems. We will talk about AC, including Peak, RMS, Average and Instantaneous values of a sine wave. Along the way I will dispel as many myths as I can. I have also built a demonstration unit to bring to meets.

What is Electricity?

So what is electricity? What you and I think of as electricity is part of what physicists call "Electromagnetism". It is one of the major forces that shape our world. They call it that because electricity and magnetism are part of the same force, not two separate forces. When you have current in a conductor a magnetic field forms in the space around the conductor. This is how clamp-on ammeters work. They read the magnetic field strength, which is directly proportional to the current in the conductor. When you have relative motion between a magnetic field and a conductor you get a potential difference (voltage) formed across the conductor and if the path is closed you will get current. This is how generators and alternators work. The term "Relative Motion" is used because it doesn't matter if you have a stationary magnetic field and a moving conductor, or a moving magnetic field and a stationary conductor. All that matters is that they are moving relative to each other. So magnetism causes flow of charges, (current) and flow of charges, (current) causes magnetism. As an interesting side note, this relative motion between a magnetic field and a conductor is one of the things that led Einstein to his theory of "Relativity". (Google "moving magnet and conductor problem")

Electricity is all about charges, positive and negative charges. Everything on this planet is full of charges, everything. Metals, plastics, wood, stone, you, your bones, hair and flesh, everything. Most of the time, the positive and negative charges are in balance. There are the same numbers of positive and negative charges on an object, so the overall charge is neutral. The positive and negative charges cancel each other out. The charges are still there, only their effect is cancelled out. Electrons are the negative charges. Protons in the nucleus of atoms are the positive charges. In many materials the charges are very tightly bound up and do not easily become mobile. These materials are called insulators. Materials in which the charges are easily made to move are called conductors. Materials like stone and wood are insulators. Metals are conductors. As with most things in life there are always grey areas. A third class of materials are called "semi conductors", which includes Silicon and Germanium. When certain other elements, called "impurities" are added to these we get Diodes, Transistors, SCR's and Triacs. They are called semi conductors because they can be made to conduct sometimes and not at others.

You could say electricity is the study of the separation of, and or movement of, charges. What physicists call "Electrostatics" is the separation of charges. You are probably more familiar with the term "Static Electricity". Electrodynamics is the study of charges in motion. What many call "Current Electricity." The two are not entirely separate fields of study. In electrostatics, to become separated the charges had to move in the first place. So Electrodynamics is the study of charges that are constantly moving and electrostatics is that study of charges that move only part of the time.

There is some symmetry between electricity and magnetism. For example in magnetism, opposite magnetic poles attract each other and like poles repel each other. This is how a compass works. One end is attracted to the geographic north pole and one to the geographic south pole. In electricity opposite charges attract each other and like charges repel each other. When you rub a balloon on your head it sticks to the wall or ceiling because of the electric field between opposite electric charges. A magnetic field forms between magnetic poles. An electric field forms between electric charges. There are asymmetries also. With electric charges you have mono poles, an electron is a bundle of negative charge and a proton is a bundle of positive charge. However for magnetism there are no magnetic mono poles. Magnets always appear as "Dipoles", with a north pole and a south pole. If you take a bar magnet and cut it in half you don't end up with a north pole and a south pole. You end up with two magnets each of which has a north pole and a south pole. I read somewhere that some physicists believe that magnetic mono poles are theoretically possible but to date none have been discovered or created.

Probably everyone reading this has experienced walking across a carpet and receiving a shock as you reached for a door knob. It may not have occurred to you how many similarities there are between that and lightning during a thunderstorm. When you walk across the carpet you lost electrons to the carpet. When you reached for the door knob the electrons transferred back to you. During a thunderstorm charges become separated between the clouds and the earth. The mechanism that causes the separation is still not known with certainty. There are several theories. That the charges do become separated is not in doubt. When the electric field between the separated charges reaches a certain point a lightning bolt results. When you reach for the door knob a small spark results. The obvious difference is the level of power. The average lightning bolt is about 30,000 Amps. The spark between you and the door knob is probably about 30 micro amps. Micro is 10 to the power of -6. The lightning bolt is many orders of magnitude larger.

Myth #1, How fast is Electricity?

Before we go any further, let's talk about one of the most common myths about electricity – its speed. You've all probably heard it, "electrons travel through the wires at the speed of light." There are several good analogies to illustrate why this is not so.

The speed of sound is 768MPH through dry air at 68 deg F. Imagine that you and I are standing 6ft apart at an outboard meet. We are face to face and I say "Hi George, how's it going?" The temperature is 68 deg F and the air is dry. The sound energy is traveling at 768MPH. There are 5,280 ft in a mile. Therefore, 768mph x 5,280ft = 4,055,040 ft/hr. 4,055,040 ft/hr divided by 60 = 67,584 ft/min. 67,584 ft/min divided by 60 = 1126.4 ft/sec. Since you and I are only 6' apart, it will take 6ft/1126.4 seconds or .0053sec, which is 5.3milli seconds, to cover the distance between us. Air is the medium through which sound travels at 768 MPH, but the air itself is not traveling at 768 MPH. Keeping in mind that a category 5 hurricane is anything with sustained wind speeds of 156 MPH or greater, if the air was coming out of my mouth at 768 MPH, which is about 5 times the speed of the lower end of a category 5 hurricane, you would certainly be knocked off your feet. You of course are not because the air is **NOT** traveling at 768 MPH. The analogy fits very nicely with electricity. Air is the medium through which the sound energy travels. The sound energy is moving at 768 MPH, the air, not so much. The electric charges in the wires are the medium through which the electrical energy travels, the electrical energy is moving at the speed of light, the charges, again, not so much.

Another analogy commonly used in electrical text books is to think of a long hollow tube that is several miles long and circular so that it starts and ends a few feet apart. The tube is completely filled with ping pong balls. You push in a new ball in one end of the tube and instantly another ball pops out of the other end. We know that the ball didn't race through the tube at the speed of light and pop out the other end. The tube was already full of balls and each individual ball only moved one ball diameter, the speed of each individual ball was very slow, not even close to the speed of light. (This is of course an imaginary tube that has no internal friction. In a real setup like this you would not be able to apply enough force to overcome the friction of all the balls against the walls of the tube). Electrical wires are very much like this, they are already filled with charges. All the charges in the circuit move at the same time, just like the ping pong balls in the above example. This is why the light comes on the instant you flick the switch, and why so many casual observers get the mistaken impression that the charges are moving at the speed of light.

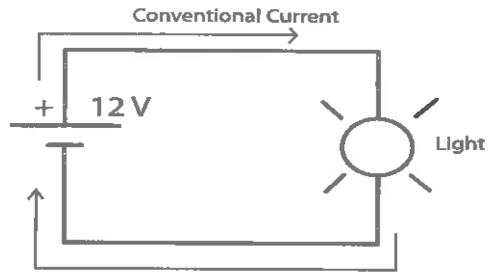
Finally if you really think carefully about it, common sense should tell you that the electrons cannot move through the wires at the speed of light. The speed of light is 186,282 miles per second, in a vacuum, like the vacuum of space. That is not the speed of light in all mediums. It has a slower speed in air, even slower in water or glass, or the fibers of a fiber optic cable (lookup "refractive index"). So does it make sense to you that electrns move through something as dense as a copper wire at the same speed as light moves in a vacuum? It shouldn't. My feeling is that most people don't take the time to really think it through.

The speed of charges varies with the current and the diameter of the wire. With a current of 3 Amps and a diameter of 1 mm the average drift velocity of an electron is .00029m/s or about 1 m/hr. Turtles move faster than that. I'm sure several guys are saying, you are wrong, everybody knows that electrons move through wires at the speed of light. Many people believe it to be so, **but that does not make it so**. Belief does not equal reality. Remember, at one time, everyone "**KNEW**" that the earth was flat, and everyone "**KNEW**" that the sun and planets revolved around the earth. Neither was ever true. Amazingly, the flat earth society still exists, though judging by their website even they no longer take themselves seriously.

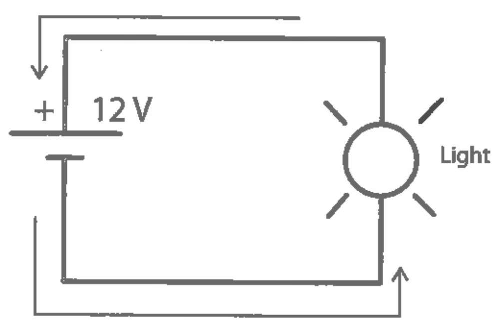
Which way does "Electricity" flow?

(Conventional current Vs. Electron flow)

Many years ago, in the time of Faraday, Franklin, Ohm and Ampere etc, it was decided that current came out of the positive terminal of the battery and went through the load and then back into the negative terminal. This was believed to be true for a long time and became known as "Conventional" current. I read somewhere many years ago that it was current in an electrolyte (a conducting liquid) that led them to believe that this was the correct direction for the movement of charge carriers. You may or may not have noticed that I have avoided using the term "flow of current". Since the definition of current is one coulomb of charge passing any point in a circuit in is like saying flow of flow, it is sloppy terminology. Everyone will understand what you mean but it is technically incorrect. It is correct to talk about flow of charge carriers but not flow of current. So conventional current is a flow of charge carriers from positive to negative. See diagram below.

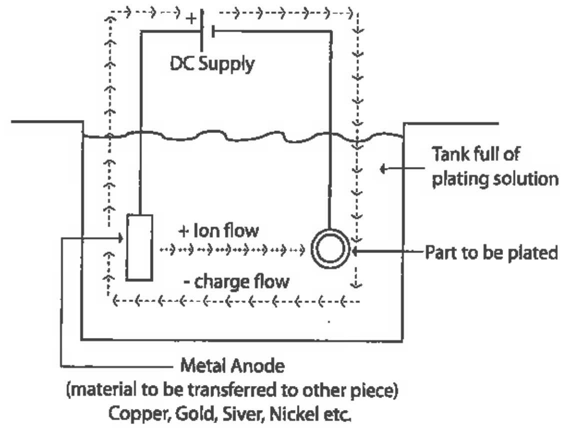


With further investigation into electricity, better testing methods and equipment, we now know that in metallic conductors the only moving charges are electrons. Electrons come out of the negative terminal of the battery, go through the load and back into the positive terminal. This is referred to as "Electron flow". It is exactly the opposite of conventional current. Most modern text books on electricity say right on the front cover, "Electron flow theory" or "Conventional Current theory". It might seem that this is a large problem but it's not. Ohm's law and Kirchoff's laws all still hold true, just the direction of the charge carriers is different. Current still equals Voltage/Resistance. See below for electron flow diagram.

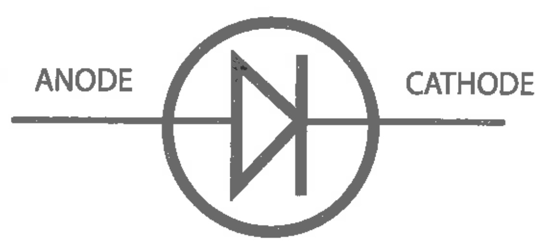


Electron Flow

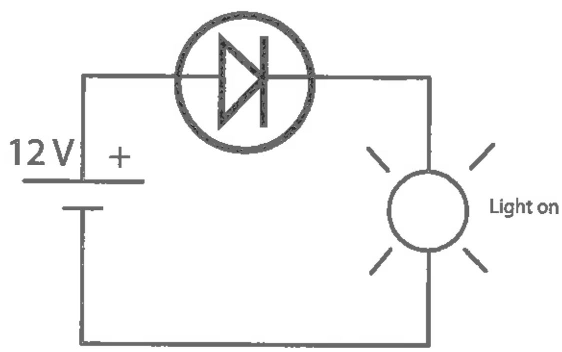
In metallic conductors the only moving charges are the electrons. In electrolytes (conducting liquids) both negative charges and positive ions move. Examples are batteries and electroplating tanks, see diagram below. In lightning we also get movement of both negative charges and positive ions.



The area where the direction of charge movement does cause some confusion is semi-conductors. These devices were created at a time when conventional current was believed to be correct. The semi-conductor symbols all have arrows in them that indicate the direction charge carriers must move in order to turn the device on, or in which they will flow when the device is turned on. This makes the arrows all backwards in relation to electron flow, but it's too late and we can't go back and change them, if you work with these devices you just have to understand that. The simplest of the semi-conductors is the rectifier diode, usually just called a diode. See picture below.

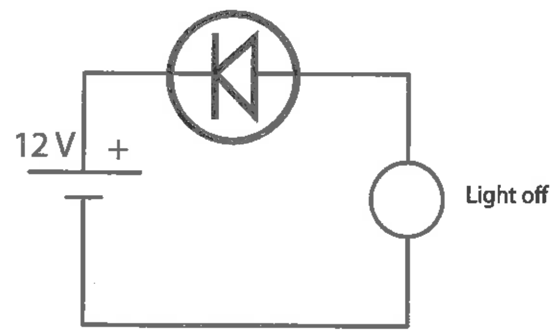


The diode will conduct if the Anode is positive with respect to the Cathode, if the Cathode is positive with respect to the Anode the diode will not conduct. It is basically an on-off switch, or one way valve. Looking at the figure below, the anode is positive and the diode will conduct (called "forward biased"), so the light is turned on.



Forward biased diode

In the next picture the connection of the diode is reversed and the cathode is positive. This diode is reverse biased and will not conduct, the light is turned off.



Reverse biased diode

End of part 1.

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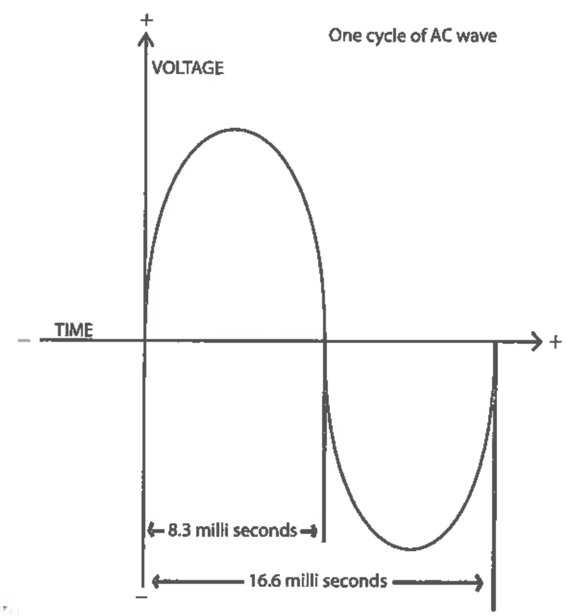
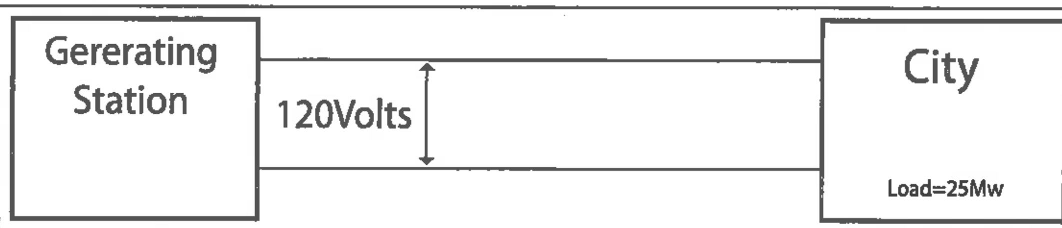
Electricity 101 – Part 2

(Part 1 in the March 2012 Newsletter)

Electricity comes in two main flavors, AC and DC. In DC (Direct Current) the charges are always moving in the same direction. In AC (Alternating Current) the charges constantly change direction. In North America, the frequency of our AC supply is 60 Hz, or 60 cycles per



The above picture is of a single cycle of AC. Since there are 60 cycles in one second, the time for one cycle is 1 second/60 =.0166 seconds, or 16.6mS. A half cycle is 8.3mS. The charges flow in one direction for 8.3mS and



then switch direction for the next 8.3mS etc etc. The direction of flow for the charges changes every 8.3mS. Since the charge carriers actually move very slowly, (it depends on the level of current and the diameter of the wire) in an AC system the charges just sit in one place and vibrate back and forth.

We like AC because it can easily and efficiently be produced by rotating machines. It's because it is produced by rotating machines that the AC sine wave looks like it does. The rotating part (armature) of every generator on the planet produces AC. If you want the output of the generator to be DC you have to add a commutator to the armature. Whenever you transmit power over a distance you lose some of that power - it dissipates in the transmission lines. Given two identical setups, one with AC and one with DC, the DC will have a smaller "Line Loss" than the AC setup. I'm not sure of the exact numbers, just that the loss is less with DC.

Electrical power distribution & AC

So why do we use AC almost exclusively worldwide for the distribution of electrical power? Around 1882 Edison was heavily invested in and pushing DC. Westinghouse and Tesla realized that for the large scale distribution of power to be economical AC was the obvious choice (as I will explain below).

Edison instigated some very nasty shenanigans to try to promote DC. He even had an elephant electrocuted with AC to prove how dangerous it was. The truth is high voltage is dangerous, it matters very little if it's AC or DC. The elephant could just as easily have been killed with DC; Tesla and Westinghouse just had a little more class than Edison. The confrontation between the two sides was called "The War of Currents" (you can Google it), in the press of the day.

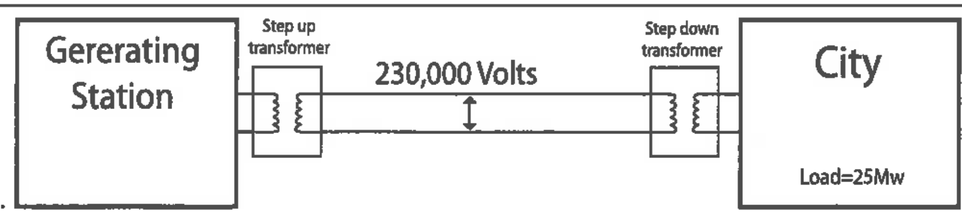
Let's look at how to send power to an imaginary city.

So here is our city with an electrical load of 25MW. (25 million watts) On August 1st 2006, Ontario set a record for electrical load of 27,005MW, or just over 27 Billion watts. So our imaginary city is about 1/1000th of the size of the largest ever provincial load. We are going to feed our imaginary city with single phase (one pair of wires) at 120 Volts. Since Power=Current X Voltage, the formula can be re-arranged so that we get Current = Power/Voltage. So 25,000,000W/120V = 208,333 Amps. That's a lot of current. The largest cable made is 2,000Kcmil (Kcmil = thousand circular mills). It means the cross sectional area of the cable is equivalent to 2 million circular mills. A mil is .001 inches, or 1/1000th of an inch diameter. A 2,000Kcmil cable is good for 1700 Amps. So 208,333Amps/1700 = 122.5 so we are going to need 123 cables for each of our wires. The copper in each 2000kcmil cable is about 1.6" in diameter.

Obviously the towers to hold the cables would be many and closely spaced along with needing to be built much stronger than existing towers are today. So add up the cost of that many cables, the number and size of the towers, and try to imagine what it would cost to run 1000 miles of cables.

Enter the transformer. Tesla and Westinghouse realized that if they used AC and transformers they could step up the voltage to a much higher level and transmit the same amount of power at a much lower current. Lower current = smaller wires. A step up transformer is used to take the power at whatever voltage it is generated and step it up to 230,000 Volts. At the other end, the voltage is stepped back down to 120 Volts. Let's redo the math. For our new setup, Current =25,000,000W/230,000V = 108.69 Amps. Much better, now a single #4 cable can replace the bundle of 123 - 2,000 Kcmil cables. The copper in a #4 cable is about 1/4" in diameter. So now a single cable 1/4" in diameter replaces 123 cables each of which was 1.6" in diameter. That represents a huge savings in the cost of cables and towers. The towers don't need to be as strong and you need less of them.

At the time the "War of Currents" was going on there was no economical way to step DC up and down. Your business or residence would have had to be within a mile or two of the generating station. Hundreds of thousands of generating stations all over North America would have been needed - and guess who would have profited from that? Right, Mr. Edison as he held all the patents and stood to receive all the royalties.



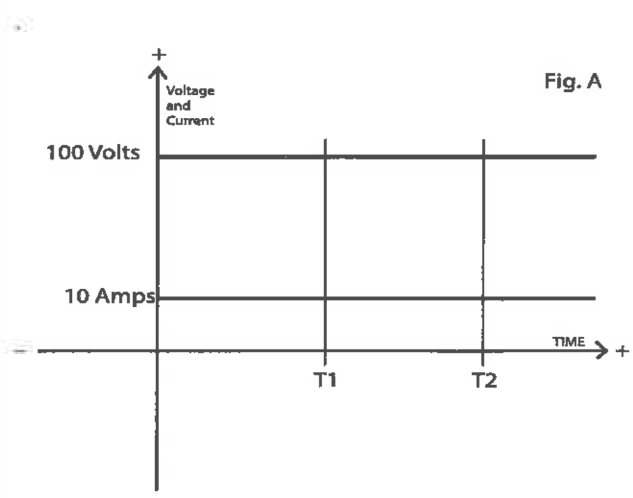
This is of course an over simplification of things but the principles are the same. There would not be one large transformer stepping down the 230KV to 120V. Local distribution would be 27,600V and 13,800V. Commercially, power enters buildings at these lower voltages and is stepped down to 600V and distributed that way throughout the building and then stepped down to 208V/120V within the building. The power running down most residential streets is probably in the neighborhood of 5,000V. It is stepped down to 240V from there for household use.

How electricity is measured

Everyone knows that the voltage at a standard receptacle in your house or business is 120 volts, Right? That's not the completely correct. It's 120 volts RMS. RMS means Root of the Mean Square. If you measured the voltage at that standard receptacle with an oscilloscope you would see that it is about 169 volts. If you have access to a scope, DO NOT attempt to measure the voltage at a receptacle unless you know the proper way to do it. If done incorrectly you can cause a dead short and it could blow up in your face.

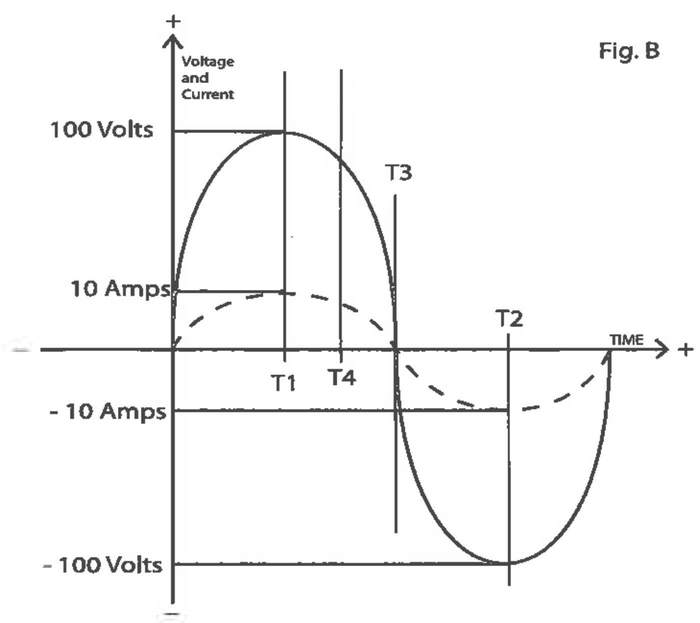
Why do we measure AC Voltage and Current in RMS Volts and RMS Amps? The reason is power.

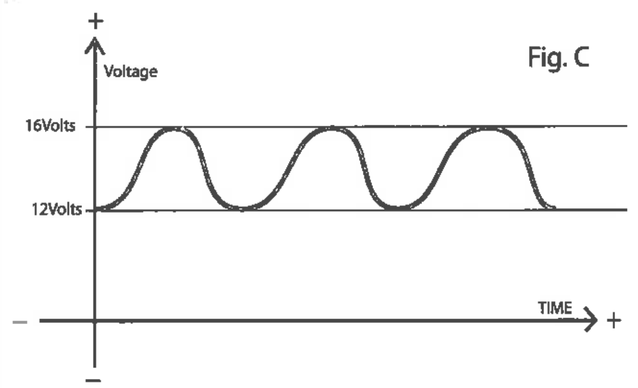
Look at Figure A below. In this circuit the supplied voltage is 100 Volts DC and the current is 10 Amps.



Since power is I x V, looking at T1, 10A x 100V = 1000Watts. At T2 power is also 10A x 100V = 1000Watts. It is apparent that since both the voltage and current are unchanging, the power at any time in this circuit is 1000Watts. Since the instantaneous power is always 1000Watts the average power over time will also be 1000Watts.

Now look at Figure B on the next page. We have an AC source voltage with a peak value of 100 Volts and the peak value of current is 10 Amps. The same levels as we had in Figure A with the DC source.





At T1, power = 10 A x 100 V = 1000Watts. At T2, power = -10A x -100V = 1000Watts. For those who have forgotten their high school math, a negative times a negative equals a positive. At T3, power = 0A x 0V = 0 Watts. At T4 power = 8 A x 80 V = 640Watts (approximately). So for an AC waveform with the same peak values of voltage and current as a DC circuit, you can see that the instantaneous power is not always 1000Watts as it was with the DC circuit. Obviously averaged over time the value would be less than 1000Watts. How much less? About 30% less. You cannot use the peak values of a sine wave in power calculations. The RMS value of sine waves is used in power calculations; it is how much work the circuit can do. Vrms = Vpeak x .7071. Your household voltage has a peak value of 169.7Volts and an RMS value of 120Volts. An RMS value of 120V means this circuit can do the same work as a DC source of 120V. So an AC source of 169V peak can do the same work as a DC source of 120V. It is called the "Effective" value. Some people call it the average value but it's not. The average value of a sine wave is .63 of the peak value, RMS is .7071 of peak.

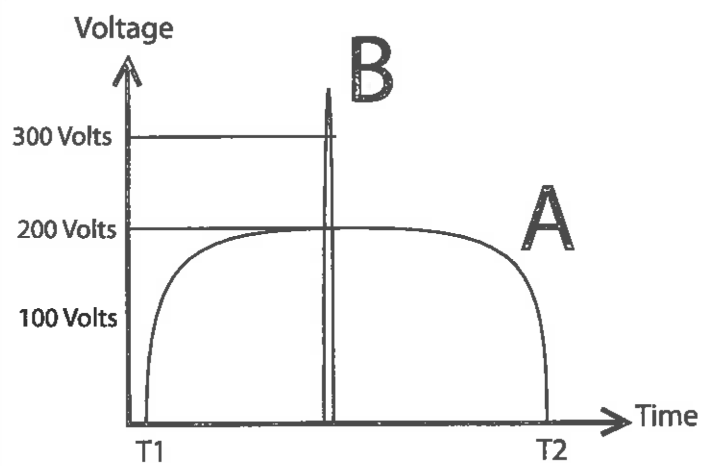
RMS means <u>R</u>oot of the <u>M</u>ean <u>S</u>quare. Mathematically, a large number of points on one half of the sine wave are Squared, the Mean is taken (math speak for average) and then the square root of the average is taken. Hence Root of the Mean Square. Any meter that says AC Volts or AC Amps on a scale is calibrated to read in RMS Volts and RMS Amps. It doesn't say that, but if you are qualified to use the meter you are supposed to understand that. Looking at Figure C we have a DC Voltage fluctuating between 16V and 12V.

It looks like AC but since it always stays on the + side of the vertical axis it is DC. The charges are always flowing in the same direction, just not always at the same rate. As with the sine wave, we can't use the peak value for power calculations. For a fluctuating DC source the "Effective" value is it's average. DC meters are calibrated to read average. A DC meter connected to the above signal would read 14Volts.

To summarize: meter scales that say AC Volts or AC Amps, read in RMS Volts and RMS Amps. Meter scales that say DC Volts or DC Amps read in average Volts and average Amps. They are called collectively "Averaging Meters". You may have seen a meter that says "True RMS" on it. For a "symmetrical" sine wave the RMS value is the peak x .7071. If the sine wave becomes distorted the RMS value changes. Standard meters simply take the peak reading and multiply by .7071 and display the result. That is sufficiently accurate for most situations. However, depending on the degree of distortion of the sine wave, it can be off by an unacceptable degree. That's why the "True RMS" meter was built. It has a microprocessor that calculates the true RMS value of the waveform. It is of course more expensive but necessary in some situations.

There are also "Peak" reading meters. They say it right on the front of the meter, "Peak Reading Meter". I have a peak reading voltmeter and a peak reading kilovolt meter. The peak reading voltmeter is for working on the primary side of the ignition coil and the peak reading kilovolt meter is for working on the secondary (spark plug) side of the ignition coil. In almost all areas of the electrical and electronics industry we want to know the power available in a circuit. That is why meters read in RMS for AC and average for DC. The only exception I'm aware of is ignition systems. There may be others, I'm just not aware of them. Because of the nature of ignition systems, and the transformer (ignition coil) in particular, and the fact that the output voltage is the input voltage x the turns ratio of the transformer (I will go into this in greater detail in one of the following articles) the higher the input voltage, the higher the output voltage and the "hotter" the spark. A hot spark (higher voltage) gives us better combustion. More power on the input does not necessarily lead to a higher output; it's a higher peak that's important.

Looking at the following diagram, compare waveform A with waveform B. You can see that A has a peak value of about 200Volts and B has a peak value of 350Volts. Averaged over the time period from T1 to T2, you can see that the average value for A would be something less than 200. Without measuring and calculating lets say it's approximately 175Volts. If you look at waveform B, you can see that even though it's peak is 350 it's zero most of the time and averaged over the same time period would probably be about 20Volts.



About ten years ago, I was at a local marina visiting a friend who was the head mechanic there. They were a Mercury dealer. The motor he was working on had ignition trouble. He had the service manual out and it said he required a "DVA" to service the ignition. He asked me if I knew what that was. I didn't. I did a little research and discovered that "DVA" means Direct Voltage Adapter. It is not industry standard terminology, Mercury made it up (knowing them it's not really surprising is it?). It is a Peak reading adapter. Rather than buying separate peak meters as OMC dealers had to do, Mercury made an adapter that plugged into a standard meter and converted it to peak reading.

Several years ago, this question came up on John's Old Mercury Website discussion board. "What is a DVA?" One guy piped in with the most incredible answer (I'm trying very hard to be nice). I printed it out and used to read it to my classes as a warning about the kind of crap you will come across on the internet. We always had a good laugh. Unfortunately I've since lost it. The gist of what he said was something like, "the electrons are moving at the speed of light through the wires (it just won't go away) and need to be displayed in real time". I fetched my hip waders and responded to his answer. I should have known better. I'm not sure if he really believed what he said was true or would just never admit to being wrong because of pride. I never responded to his response, there was no point.

Peter McDowell