Basics of Electrics (without Math)

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Understanding the basics of electronics is essential to electric powered aircraft, cars and robots. Having this understanding will allow you to experiment with your motor, gears, prop, wheels and battery to maximize the performance. This discussion on the fundamentals of volts, amps, ohms and watts will hopefully be presented in a fun and intuitive way. Often the math used to teach the fundamentals of electricity, tends to turn off most people to the point where they skip over the material. That is a shame because the concepts of electricity are really not that hard to understand.

In the real world **electricity behaves very much like water flowing down a garden hose**. Yes it's that simple! We have all had experience with how water flows down a hose which makes relating to electricity much more intuitive.

So then, what is a Volt?

Let's start with this magical word "VOLT". What the heck is it? Well, at the core of electricity is this tiny little thing called an electron. They can move around freely in metal objects called conductors. When you manage to move lots of extra electrons into a piece of metal, the electrons get a little cramped. For now, forget how they get cramped in the first place. (Hint; it is usually due to a chemical reaction or moving magnets and coils of wire.) Since electrons all have the same negative charge, they tend to repel each other. This is very similar to a bunch of tiny magnets with all the South polls facing each other. The more electrons you cram together the more they want to repel each other and the greater the pressure they force upon each other. This pressure is measured in units called ***volts***.

But wait, you may ask, how can water help us understand volts? Well that is simple, volts is like water under pressure. More volts, more pressure! Say you have this big tall 10,000 gallon tank of water on top of a house, the higher you fill it, the more the tank weighs, and the more pressure is available at the bottom of the tank. The weight of the water makes the water want to get out of the tank. More water and weight gives the water more pressure.

With water, we measure pressure in terms of its weight in pounds per square inch or PSI. With electricity we measure the pressure in terms of Volts. So the terms PSI and Volts are units of measurement for water and electricity respectively.

So the answer to the question "what is a volt?" can simply be answered like this: Volts in a battery is like water pressure in a tank. The more pressure (volts) you have, the easier you will be able to get it to move through even the smallest hose (wire). But let's not get too far ahead yet. So far, in understanding volts, nothing is moving yet. We haven't turned on the faucet. That comes next when we look at….. Amps!

OK Volts are easy to understand, so then, what is an Amp?

If a volt is the *pressure* of electricity, then the ampere (amp for short) is the *flow* of electricity. It is no wonder they also call it current! Electricity flows through a wire in much the same way that current flow down a river. But for the sake of our discussion we are going to talk about how water flows down a hose. It is easier and more meaningful to equate a garden hose to a piece of wire.

Let's get back to our tank and let's place a shut off valve at the bottom of the tank so that we can let water out and empty it all the way if we want to. Connected to the shut of valve will be a hose. (I promised you it was coming didn't I?) The hose will simply dump the water into the ground. Later we will need to pump the water back up into the tank, but more about that later. The shut off valve on the tank acts like a switch. It either stops the water current from flowing or it allows it to pass. An electrical switch does the same thing to the flow of electrons. When the switch is on, we have current flowing when we shut it off, we have no current. That was too simple, wasn't it?

Ok, so when are you going to get to what an amp is? Well, here it is. The rate of water that flows down a hose is similar to the rate of electrons that flows down a wire. We might measure the flow in a garden hose in terms of gallons per hour or ounces per minute. However we measure current in terms of electrons per second. Actually one amp is technically defined as 62,420,000,000 electrons going past a point of wire per second. (Give or take a few!) I told you they were tiny didn't I? More amps mean more electrons per second. Fewer amps mean less flow. So how do you get more amps you might ask?

Well, there are two ways. First, if you have more volts (remember pressure) you will provide more motivation for the little electrons to scoot down the wire in a hurry. This is just like putting more water into our holding tank, giving us more weigh, and therefore giving us more pressure. The flow of water or the amps of current will be greater with more water pressure or voltage.

The second way to get more current with water, without increasing the pressure, is simply to get a bigger hose. This is one reason why bigger wires can carry more current. Put a fire hose and a bigger valve on the water tank and more gallons per minute will flow.

Now here is an interesting concept. Put a faucet on that water tank and now you can reduce how many gallons per hour will flow even though you may still have a big fire hose. This is why the size of wire you have can limit the maximum current you can deliver. Yes, you can use a pair of automotive jumper cables to power a cell phone but people may think that is quite a waste of wire. Jump starting a car requires many - many amps of current so that is why the wires are big for that application.

The bigger the wires are, the greater the ability they will have to a high flow of current. And just like forcing water down a long skinny hose, lots of PSI (pressure) at the tank side can turn into very little PSI dribbling out the end. A skinny wire can restrict flow and reduce the apparent pressure. That is why in high current applications we want as big a wire as practical.

So getting back to the faucet, we now have this way of reducing the flow of current by simply turning down a knob. As we all know, a faucet merely makes the opening for the water current smaller and smaller offering more resistance until it is fully shut off. Turning a faucet completely off is the ultimate resistance.

So what is the analogy to this faucet resistance in terms of electricity? Well, this one is easy, the scientific electronics term is called (drum roll please)…………. resistance, yes resistance! Resistance to electricity flowing is measured in a unit called Ohm. (No, not the chant that you do in your yoga class.) An ohm is a term that you have to understand when you start talking about amps. Why? Because Ohms and amps are inversely related! So what the heck does that mean? Simply that when you have ***more*** Ohms (resistance) you have ***less*** Amps (current flow) This is like when you turn down a faucet! Also, when you have ***less*** Ohms (resistance) you get ***more*** amps. This is like opening up the faucet and/or using a big fire hose! This whole discussion, of course, assumes that the volts (pressure) remain constant.

OK so we now know that Ohms and Amps affect each other in opposite directions. On the other hand if you leave Ohms the same and you change the volts (pressure) up and down, you will find that more volts (pressure) means more amps (current flow) and less volts (pressure) means less amps (current flow).

Now if for some reason the discussion above was confusing to you in any way, it is simply because we are using new words to describe principles that you no doubt already understand. Take the time to re-read the paragraph above until you get it. It's not really hard to understand, plus you will have mastered the fundamentals of electricity when it becomes clear to you.

Quick Review:

Volt = unit of measurement of electrical pressure.
Amp = unit of measurement of the rate of electrical current flow in a conductor.
Ohm = unit of measurement of a conductors ability to resist current flow.

> *Want a little tiny bit of math? (Its just easy multiplication and division but you can skip over this if you want)*
>
> *Volts are equal to # of Amps multiplied by the # of Ohms*
> *Amps are equal to # of Volts divided by # of Ohms*
> *Ohms are equal to # of Volts divided by # of Amps*

The above formulas collectively are called "Ohms Law" and they describe the basics of all electricity and electronics.

OK, I understand Volts, Ohms and Amps, so what's a Watt?

The short answer is that the Watt is a unit of work done over time. More watts, then more work is getting done quickly, less watts means less work. OK so how does this relate to water? Think of it this way, Say you had that 10,000 gallon container filled with water and you had a wide open valve going to a fire hose and you decided to have some fun and point the hose at all your buddies standing 5 ft in front of you. I bet that you could knock them all over in no time and make a big mess at the same time. Now suppose you only had 100 gallons of water and a small garden hose. Well the results would not be as spectacular.

I surely doubt you could knock them over with the stream of water from a garden hose and after a few minutes of aggravating them, you would be dropping that hose and running away from some wet and angry friends. The same is true with electricity. Lots of volts and amps with little ohms mean a lot of watts worth of power. Low volts and low amps with high ohms mean much less power. Increasing either volts or amps while leaving the ohms the same will increase watts. Here is a point of reference to help you gauge how much work a watt of electrical power is worth. It takes 745.699 watts to equal one horsepower. Say WATT? That means that a 100 watt bulb is actually a little over 1/8 horsepower.

OK, so watts represents power (work over time) and to get lots of watts you need lots of volts AND lots of amps. This is an important concept to understand when it pertains to the performance of your electric airplane, car, robot or even your power tools. Carefully juggling the right voltage and current for a given motor and its load, without burning your motor controller, wires or batteries is the goal. It's a balancing act.

If your kit has pre-selected all the parts for you, then someone else has done all the engineering for you. The bad part is that you are now stuck with the performance that "they " want you to have. What fun is that? In the immortal words of comedian Tim Allen, all we really want to do is to have "more power!" (Grunt grunt) don't we? So you can begin to see that these concepts are important to understand when we want to tailor the performance of our models or, just like Tim, not having a good understanding may have you end up with smoke or explosions. More on tailoring power after we learn about how they secretly rate the power of batteries.

Want a little tiny bit more math?

Watts are equal to # of Volts times the # of Amps or,
" " " " # of Amps times # of Amps times # of Ohms, or
" " " " # of Volts times # of Volts divided by # of Ohms

In a commercial wattmeter, volts and amps are measured and simply multiplied automatically for you.

Batteries!!! They aren't rated in AMPS or Watts; they are rated in mAh, what is that?

Well they are actually rated in amps (sort of) that's what the "A" in mAh is for. Well, mAh stands for milliamp hours. A milliamp is simply one thousandth of an Amp. It seems silly to say 1000 milliamps when you really mean 1 amp but this is exactly how most batteries are usually numbered. (I don't know why so please don't ask!)

The ***hour*** part of the milliamp hour rating is simply that, its how many milliamps a fully charged battery can provide for a solid one hour. *At least that is the theoretical meaning!* So a 1000 mAh battery should provide (in theory) 1000 milliamps steadily for exactly one hour. So what if you change the load resistance (electric faucet) so that it only draws 500 milliamps? Well, that battery would supply 500 milliamps now for 2 hours since it is flowing out only half as much as before. Think of those trillion trillions of electrons coming out half as fast. It will take twice as long to get them all out.

It works the other way too. If you draw 2000 milliamp rate out of the 1000 mAh battery then you would exhaust the battery at twice its rated capacity! (Sometimes called 2C...more on that later...) That's twice as fast! That means that you would have a dead battery in only half an hour!

So the milliamp hour number is simply a measure of capacity or size. It's just like comparing a 10,000 gallon water tank to a 500 gallon tank! You know that the 10,000 gallon tank will last longer dumping out at the same rate.

So you now have some practical information here. You can see why a 2000 mAh pack will fly your plane or power your robot twice as long as a 1000 mah battery. Here is another interesting bit of information. When you parallel two similar batteries (typically done with Lithium batteries by connecting plus to plus and minus to minus) they each help each other handle the load so that you now have double the capacity. So two 1000 mah batteries in parallel act like one big 2000 mah battery. Three similar batteries in parallel are triple and so on… Usually this is done for cost, availability, redundancy or space reasons. Note that paralleling a battery doesn't increase the voltage. The voltage remains the same. It is just like having two water storage tanks side by side and combining them to flow from a single faucet. The faucet will run twice as long but the pressure will be the same as with one tank.

Now suppose you stacked one big water tank on top of the other and connected them together. The weight of the water would be double so the pressure would double. This is the same with batteries. If you hook two batteries up in series, (plus to minus) the voltage will double. Three will triple and so on.

This is why many times you will see people add another cell in series to get more power out of a motor, instead of changing the load on the motor to increase the current. (Remember watts?) In general it is easier to generate more power by increasing voltage because you will not need to increase the wire size to carry more current. Also don't forget that motors have wires inside them too. When the current goes up, the wires in the motors can get too hot and melt! More on this later, I promise!

What does a max *DISCHARGE* rate of 12C mean?

Well, when we learned what it means to have a battery rated at 1000 mah, we were simply talking about its capacity. The letter C is simply used as a shorthand notation of the batteries capacity. The number 12 in front of it means that we multiply the capacity by 12 and that is the most current we should ever demand from this battery. So a 1000 mah battery rated at 12C can safely produce 12,000 ma or 12 Amps without burning up the battery.

What most people don't realize is that it also means that running at 12C you will exhaust the battery in 5 minutes or less! The reason it may be less is because total capacity is usually better at lower discharge rates and that is where battery manufacturers rate their cells. At these higher rates heat and other losses reduce the available capacity.

Staying under the rated capacity is important. Just like motors and wires burn up when we run too much current through them, batteries are the same way. The discharge rate should not be exceeded or we can end up ruining the battery. Sometimes the battery manufacturer may cut you a little slack and tell you that you can pull more current (say 20C) for 15 seconds at a time. This is because the real killer is the heat generated by the current and the internal resistance (more on internal resistance later). If you exceed the current for just a little while, and you give the battery a chance to cool down then no permanent damage results. When it comes to rechargeable batteries, the reality is that the harder you are on a battery, the quicker it will deteriorate. Experience has shown that the more you push the batteries, in terms of max power, the less charge and discharge cycles you will get.

What does a max *CHARGING* rate of 1C mean?

Well just as in the discharge rate, charging is described in terms of the batteries capacity or C rating. Why? Well because batteries are manufactured and divided into classified families. These classifications may have different mah ratings or cell counts but they all behave the same way when it comes to charging and discharging in terms of its capacity. So battery manufacturers tend to rate the performance of their products in generic terms without implying a specific capacity.

So what does a recommended max charge rate of 1C mean? Basically it is the maximum current that can used to safely charge a battery. If you have a 1000 mah battery with a 1C charge rating then you must charge it at 1000 mah. If the charge rate was specified as 5 C, then you could charge it at a maximum of 5,000 mA and so on. This is just like the discharge rate but here we are taking about the maximum rate that we are putting the electrons back into the battery.

Ok, actually the electrons never really left the battery; they simply went to the “dark side”. Ok this is where our water tank analogy has to stretch. Remember when we said the water comes out of our tank and spills on to the ground? Well in reality it made a big puddle and eventually it formed a lake. In electricity, electrons have to go somewhere too but they are a little bit tidier than the water in that they always return back to the battery. So the water tank and the lake need to be thought of as the whole battery. When we recharge a battery we are simply pumping the water from the lake back up to the water tank. (This lets us spin little wheels again as the water comes down!) To charge a battery we have to move the electrons out of the positive lead and back into the negative lead where they belong. Remember electrons are charged negatively!

Ok, at this point you may be a little confused. If you look at text books describing "current theory", they always talks about current coming out of the plus and going into the minus. That is the definition of "current flow". This called "conventional current" or sometimes "Franklin current". But in this discussion we are talking about electrons that leave the minus and go into the positive terminal when they are done??? Why does current go one way when electrons go the other way?

ANSWER: Well, it was simply a big mistake that happened a long time ago when scientist were defining "current" for the first time. They thought stuff actually left the positive terminal and went to the minus terminal. Later they discovered that electrons were the ones that were actually mobile and they lived in the negative end of the battery. Unfortunately it was too late to correct the mistake, so accept that "conventional current" flows plus to minus, but electrons go from minus to plus, end of discussion!

Some trivia

- In general, a charge rate of 1C or greater is considered a fast charge. 0.1C or 10% of C is considered an overnight charge for NiCad and NiMh batteries.

- Batteries suffer from an imperfection called "series resistance" This shows up the most when you are near the current limits of your batteries. The effect is that the voltage on the battery terminals drops slightly as if there was a little resistor inside the battery. This low voltage can trip off a low voltage cutoff circuit only to have the voltage pop back up after the load is removed. There is not much you can do about this imperfection but it is good to know that it exists and it is also good to know that it gets worse as a battery deteriorates.

Sometimes the only thing you can do is discard the battery.

The best batteries have around 5 milliohms of series resistance. That represents 0.005 Ohms per cell. Just like volts add when you put batteries in series so does this resistance. If that was a 10 cell series pack and you were pulling 10 amps your internal resistance would be .05 ohms causing a voltage drop of 0.5 Volts.

So how can we use all this new knowledge to maximize Power?

Well you have learned that to get more power out of a given load (like a motor); you can either increase the voltage or current or both! Let's first consider how we would increase the current going to a motor. When we are dealing with motors, a motor wants to turn a certain RPM (revolutions per minute) based on the voltage it sees. (This spec is usually called the Kv of a motor) If the spec of a motor rates it at 1000 RPM per volt and you have 10 volts, it will want to turn at about 10,000 RPM (within limits of course) To increase the current we can simply increase the load to the motor. This load increase makes the motor's resistance appear to decrease. These means changing to a bigger diameter prop, or maybe more pitch in the same diameter prop or bigger wheels in your robot. All these things make the motor pull more current in order to keep the pace that it wants to turn at, dictated by the voltage it sees. Therefore within limits (described later) leaving the voltage the same and increasing the load to a motor, increases the current and ultimately increases the power created by the motor. Aha! MORE POWER at last! (Grunt grunt)

We also learned that batteries are unfortunately limited in the amount of current they can produce without damage. This dilemma forces us to consider that it may be necessary to maximize power instead, by simply increasing the voltage. This is usually considered when you are close to the maximum current that your batteries can safely handle. But wait, there's more! It is not just batteries that break down under too much current. In general, more current requires bigger battery wires, bigger control circuits, bigger wires inside your motor, bigger connectors etc. If not, more current will mean more smoke!

Ok, this looks good, we increase the voltage and we get MORE POWER! So does that mean you can just keep increasing voltage until you get 2,000

Watts of power out of a tiny little CDROM brushless motor? Well unfortunately no. :-(In the case of a motor, increasing the power beyond its limits increases the magnetic fields inside the motor, which ultimately saturates the iron core inside. When this happens all the excess energy turns into heat and "pop goes the motor" Ouch! This is why a wattmeter is critical in determining when too much power is "way too much". The limits of the battery and the size of the little wires in the motor both limit the amount of current. The mass of iron in the motor and the design of your speed controller both limit the amount of power and consequently voltage that your system can handle.

So how do you start when you want to maximize power? If your existing batteries are not running near their maximum discharge rate you may want to start by increasing the current to get more power. First you have to remember that any time you increase the current demand from the batteries you shorten the running time. This extra demand can sometimes be solved with batteries with more mAh of capacity. However don't forget that increasing battery capacity can increase the weight and thus require even more power! So with that in the back of your mind, when you start increasing the load to get more power you should do that in a way to maximize your goal. For example, if your desire for more power has you wanting more acceleration or thrust, then consider increasing the prop diameter or changing your gearing for more torque. If your desire for power is in the form of speed then you will want to increase the prop pitch or change your gearing for more speed.

When you start to reach the current limits of your batteries or one of the other components in your system, you can then consider increasing the voltage by adding an extra battery cell. But be careful, with this extra voltage, your motor will now spin faster and demand more current if you don't back down on your load! (You thought this would be simple huh?) Well it's really not that hard. The best way to cut back on your load after increasing the voltage is by degrading the performance which you don't want! Need lots of thrust but don't need speed? Then back off on the prop pitch or gear increase gear ratio. Need speed but don't need as much thrust? Then reduce the prop diameter or decrease gear ratio. In this way the extra voltage applied to the motor will enhance the type of performance you want. After taking measurements and experimenting with different props and/or gear ratios, you will start to become intuitive on how your motor reacts to the changes you make.

There are also computer programs available that let you play “what if” games without destroying motors, batteries or controllers. It’s enough to say that there is more to understanding how to maximize power when selecting propellers and wheels and transmissions. A full discussion on this subject is a bit out of the scope of this document. But, if you have understood this discussion on maximizing power, then you really understand the basic fundamentals and you are well along the way to understanding how all these things interact.

What if I want to maximize the run time, not performance?

Ok let’s say you want long flights or run times, Of course one solution is to swap out your battery for one with higher milliamps. But let’s say you are willing to give up some performance for long run times. Then your solution may be to simply reduce the current flow by reducing the load on the motor. Take away the performance parameter you don’t want. If speed is not that important then reduce the pitch. If thrust is not that important then reduce the prop diameter. Your run time will increase as your current load decreases.

But wait, I am happy with the power I have; the plane just doesn't fly right?

Be it plane, helicopter, car or robot. Power has different forms. Accelerating slowly but eventually going as fast as you can, takes the same amount of power as accelerating a heavy load quickly but not topping out at a very fast speed.

If you fly a plane, you and your type of plane will have a style of flying. Do you like to go fast and turn left? Or do you like to pull the nose up and “hover” your plane like a helicopter?

In all these cases we are assuming you already have squeaked as much power as you can out of your battery but the style of performance is not exactly what you want.

Here are the rules of thumb for planes: If you want more speed, increase the pitch of the prop while reducing the diameter just enough to maintain the same watts of power. If you want more thrust, then increase the diameter: however decrease the pitch just enough to maintain the same watts of power.

Here are the rules of thumb for objects with wheels. If you want more speed then increase your gear ratio or increase tire diameter while you get rid of some weight to keep the power the same. If you want to haul more weight and don't mind giving up some speed then lower your gear ratio or put on smaller diameter tires while you increase the weight to keep the power the same.

Conclusion

Congratulations, you have learned the basics of electricity and how it can work for you. You should now understand the fundamentals of electricity; volts, ohms and amps. You now also understand how batteries are rated for charging and discharging safely. Lastly you also know a little bit about how to match motors work with batteries and how to safely maximize performance. Armed with all the information you have learned and TME's new Xtrema, you can now easily charge Lithium batteries, select motors, props, gear ratios, tire sizes, troubleshoot and solve problems you may have in your power system.

The continuation of this lesson will be available as a FREE troubleshooting guide that will show you how to use a wattmeter to solve common problems out at the field. The free download and revisions to this document will be available at www.theXtrema.com