Electric Airplane Basics

Magic numbers for modelers...

Schoolboys (and girls) know Watts, Ohms and Amperes. Modelers speak of props, lipos and BESC's. Not to forget the mysterious ‘KV’ and the famous ‘C’, which is not the speed of light... But what hides behind these cabbalistic concepts? And how do they relate to the everyday business of flying RC machines? Follow the magic numbers...

Today's pilots understand that you get more from a good electric setup than an average IC engine. Cheap sources of equipment have dramatically changed the price tag on brushless motors, ESC's and batteries. But it is still something akin to the dark arts to select the right combination of these three items in order to fly well. The best way to success is to follow the secret recipe of electrical gurus, based on kilometers of burned windings, and the third law of universal common sense. Enter the hidden side of real-life quantum physics, the one that mixes weight and mass, translates temperature in 'seconds-of-finger-on-the -motor-bell' and flying times in burned amperes... Who cares for the Science, as long as we can punch holes in the sky

Buy your watts by the kilo (or Pound)

The first magical number tells you how much watts you need to fly your plane. Of course, it works only for decently matched systems. A GWS parkflyer won't fly with a 300gr motor, however powerful it is...

Foamie, motorglider, Piper Cub: 100watt per kilogram (2lbs)
Trainer: 150 watts per kilo
Warbird, 'sport' aerobat: 200 watts per kilo
Racer, 3D: 300 watts per kilo
EDF Jet: 400 watts per kilo

Examples: a 3kg (6lbs) 150cm (60") Hurricane will fly on a 600watts setup. A 2.5kg Calmato will require 375 watts, etc.

Watt is pushing us forward?

The second magical number gives an idea of how much static thrust you can expect from a good setup. Once again, this is only true for a propulsion system that is performing normally.
These values give a good indication of what is possible... and what is not.

Brushless outrunner: 4gr per watt
EDF: 2gr per watt
Brushless 'inline': 2gr per watt

Brushless 'inline' with gearbox: 5gr per watt

Examples: A warbird with a 1000 watt brushless outrunner will have 4kg static thrust. An EDF jet having a 600 watts power system gives 1200gr thrust on the ground.

Powerful horses...

The third magic number is in fact a magic formula, one that most of us forgot after school...

Watts = Volts x Amperes
Volts = Watts / Amperes
Amperes = Watts / Volts

How does that relate to horses? Easy: you can convert watts to horsepower with the following rule: 1000 watts = 1.34 HP or 1HP = 750 watts.
Example: a Trainer aircraft with a 12 volt battery delivering 40Amps gives 480 watts (or 0.65HP). Note that the same plane having the same performance in IC would use a .40ci engine providing 1HP, which is 750watts... This is because electrics have a better efficiency, with more power at lower rpms. A similar phenomenon applies to diesel vs. petrol cars. The diesel drives better even if both cars have the same 95HP.

One Hot Minute!

E=Mc2 and the planet is warming up, everyone knows that. Electric motors also get warm. To know how much too warm the windings should not glow, here is a rule of thumb that is nothing short of magical...

Prop aircraft: motor weight in grams x 3 = max. watts.
EDF: motor weight in grams x 5 = max. watts.

Example: a 235gr brushless outrunner can dissipate 705 watts for a minute without meltdown.
A 200gr inrunner on an EDF will not die even at 1000watts.
Of course, this is assuming the motor is correctly used and cooled by adequate airflow.
This rule is only true for brushless motors. Old 'can-style' brushed motors like the Speed 600 don't survive more than their weight in watts...

Resistance is useless...

Gold is a fantastic metal when it comes to moving currents. Unfortunately it is also very heavy. That is the main reason for us to use copper in electrical wires. But then copper transforms some of the current into heat. Not only does it fuel

global warming, but it reduces the available in-flight power, which is a real catastrophe!
To avoid this dramatic event, one should always use large enough wires:

Up to 25A: 1.5mm² wire section (15 AWG)
Up to 60A: 2.5mm² wire section (13 AWG)
Up to 100A: 4mm² wire section (11AWG)

Not only wires, but connectors and soldering must be able to handle the current. In this field like in others, bigger is also better...

Round and round

You always wanted to know what the famous 'KV' stands for? This indicates the number of revolutions per volt provided by an electrical motor. It gives us the 'nominal' rpm of a motor on a plane.

rpm = KV x volts x 3/4

Examples: a 1200KV brushless outrunner connected to a 10 volts source will turn at 9000rpm. A 4200KV inrunner on 10 volts will spin at 31500rpm.

Full or empty, that is the question...

The voltage of NiMh cells is said to be 1.2 volts and lipos are sold for 3.7 volts. These 'nominal' values are confusing at best. The real figures depend on what you need. For instance, to know the wattage of a power system, you need to take into account the voltage of the battery at full throttle. But when you need to know if a battery is full, you measure the 'idle' voltage. The values written here give you an idea of typical 'real life' cell voltage.

Lipo in flight (motor full power): 3,3 volts
Lipo fully charged (idle): 4.1 volts
Lipo empty (idle): 3.7 volts

NiMh in flight (motor full power): 1.1 volts
NiMh fully charged (idle): 1.4 volts
NiMh empty (idle): 1.2 volts

Example: In order to get 300watts from a power system, you will need a 3-cell LiPo or a 9-cell NiMh battery and a motor loaded to about 30A.
Here are the (rounded) 'in flight' voltages of typical lipos:
2S = 7 volts, 3S = 10 volts, 4S = 13 volts, 6S = 20 volts, 10S = 33 volts.

Need for speed? Get some serious pitch!

Chosing a prop is not easy. Most people select the right diameter so that the motor doesn't soak too much current . But the pich is often disregarded. Nothing replaces the test flight, but here are some magic numbers to guide you when choosing the pitch of a prop.

Airspeed in kph = pitch (in inches) x rpm / 800
Airspeed in kph = pitch (in cm) x rpm / 2.000

Example: On a big trainer aircraft, a large 14x4" prop spinning at 8000 rpm will get you 40 kph of speed, which is marginal.But a 11x8" at 11000 rpm gives 110 kph which you don't need. The best choice will probably be a 13x6" spinning at 9600 rpm and providing a top speed of 72 kph. This is true for all planes, not only electrics.

Masters of the 'C'

The label on your brand new lipos reads '15-20C', but there is also a '1C' somewhere else on the sticker... WTH???
The '1C' in small letters means the maximum charge current is 1 time the cell's capacity (all lipos charge at '1C'). On the other hand, the '15-20C' note promises you can discharge the battery at 15 times the capacity and even push it briefly to 20 times the capacity without damage. The truth is that most manufacturers are too optimistic, so forget the second number and try to keep the 'peak' discharge current under the first number. A 'realistic' discharge current can be calculated like this:

Max discharge current on the ground = (first number) C x capacity / 1250
Max discharge current during 1 minute = (first number) C x capacity / 1500
Max continuous discharge = (first number) C x capacity / 2000

Example: A 3000mah '20/30C' battery should be able to discharge at 60A during a few seconds. It will survive a take-off at 48A. A whole flight alternating slow passes and full throttle at 40A will be OK. And it could be discharged at 30A continuous without degrading.
Whatever the 'C', remember to provide adequate airflow to cool the battery.

The heat is on!

To cool down an IC engine, you just cut some holes in the motor cowl. For an electric aircraft, you also have to provide cooling for the ESC and batteries. The warm air has to find it's way out of the plane so there have to be additional holes at the rear... But what size of holes do you need to drill?

Air entry surface (cm^2) = number of watts / 40

Air exit surface (cm²) = number of watts / 30

Example: a warbird using 1000 watts needs 1000 / 40 = 25cm² of cooling air intake and 33cm² of opening behind the battery to let the warm air exit. The exit MUST be larger than the entry to avoid warm air stagnation which is even worse than too small an air intake.

Check the internal resistance

Modern batteries provide tremendous performance thanks to a very low internal resistance ('Ri'). But all batteries are not equal. To compare two brands or to know if an older pack is still fit-to-fly, you must measure the Ri. All you need is a voltmeter and an (cl)amp meter (or a wattmeter that combines both functions).

Measure the voltage 'V1' during a discharge at a current 'A1' corresponding to ±1C
Measure the voltage 'V2' during a discharge at a current 'A2' corresponding to ±10C

Ri = (V1 - V2) / (A2 - A1)

Example: on a brand new 3-cell 2200mAh lipo you measure 11.4 volts at 2.2A discharge and 10.5 volts at 22A discharge. The Ri of the pack is (11.4 - 10.5) / (22 - 2.2) = 0.045Ω. This means a single cell Ri of 0.015Ω.
Several month later, your plane doesn't fly like it used to do. You measure Ri again with 11.2 volts at 2.2A and 9.5 volts at 22A, which gives 0,086Ω. This means that the battery has lost half its performance...
To be meaningful, Ri must be measured in 'standard' conditions. Ambient temperature, cells temperature and state of discharge have a direct impact on the results. The easiest is to always measure Ri on a freshly charged pack at ambient temp.

What goes up...
...Must come down. But when? Follow these magic formulas to estimate how long you can fly using a specific battery:

Contest or 'full throttle': Seconds = capacity (mAh) x 4.2 / max current on the ground
Aerobatics: Seconds = capacity (mAh) x 7 / max current on the ground
'No-stress' flight: Seconds = capacity (mAh) x 11 / max current on the ground

Examples:
FunJet race using a 2.400mAh battery discharging at 42A Max: 2400 x 4.2 / 42 = 240 seconds, or 4 minutes.
F3A aerobatics using a 4100mAh battery discharging at 52A Max: 4100 x 7 / 52 = 552 seconds, or 9 minutes.

Piper Cub flight using a 3000mAh pack at 34A Max: 3000 x 11 / 34 = 970 seconds, or 16 minutes.

Fly longer: add a cell!
The last magical number gives you an estimate of how much energy a battery stores:

E = capacity (in Ah) x voltage

For instance, did you know you can fly longer with a 3S 1000mAh lipo than with a 2S 1300mAh...? Indeed, to get the same flying style, the 2S at 7.4volts needs to discharge at 13.5A for 100 watts of power. The 3S needs giving only 9A for the same power. Using the time formula, we get a 'No Stress' flying time of 20 minutes for the 3S vs 18 minutes for the 2S. As a bonus, the lower discharge 'C' rate on the 3S battery means it will last longer.
The magic number tells the same story:

Energy in the 2S: 1.3 x 7.4 = 9.62
Energy in the 3S: 1 x 11.1 = 11.1

Some will say that a lower voltage usually means a larger prop and better efficiency. True, but the higher 'C' discharge and current on the motor cause losses that cancel the expected benefits.

Demonstration on my P-40 Svenson (170cm span, 4kg AUW, Motor HXT50-55)
The motor uses 51A Max current on a 6S lipo. The voltage magic number predicts ±20 volts so we can estimate the power: 20v x 51A = 1020watts or 1.36HP. This plane has more than 250 watts per kilogram, it is powerful and climbs vertically, just like the magic formula says: 4gr x 1020 = 4080gr thrust. But beware of the excess heat buildup because the motor weights only 320gr! In theory, it should not be used above 320 x 3 = 960watts. However, on this plane the 26 cm^2 air intake and 34 cm^2 air exit provide optimal cooling.
2.5mm^2 power cables are used for efficient current transfer. The motor has a KV of 500, it runs at 20 x 500 x 3/4 = ±7500 rpm. The prop is a 15x8", which gives a max speed of 8 x 7500 / 800 = 75kph, which is ideal for this warbird. I use a 4400mAh battery, So I can fly for 4.400mAh x 11 / 51A = 949 seconds or about 16 minutes of cruising 'No Stress' performance.
The battery is sold for '20/30C' and could deliver a maximum of 20 x 4400 / 1250 = 70.4A peak and 20 x 4400 / 1500 = 58A during one minute. I must avoid flying continuously at full throttle because I would discharge the pack above its safety limit: 20 x 4400 / 2000 = 44A...

ARTICLE 2

Electrical Basics

When it comes to our electric flight there are four things we typically think about:

Voltage
Current
Power
Capacity

As you probably know there are other electrical things that you might normally measure, like resistance etc, but we don't normally need to worry about them for electric flight.

The easiest way to think about all these things is to imagine electricity as water.

Voltage is electrical "pressure". It is measured in volts (v). Thinking of it like water, voltage is the the number of metres of pressure you have - so if the resorvoir is 50 vertical metres above you, you have 50 metres of pressure.

Current is electrical "flow". It is measured in amps (A). Thinking of it like water we would measure it in something like litres per minute.

Power is the combination of voltage and current (power = volts x current). We meaure it in Watts (w). This is easy to imagine with water as well. Think of one of those huge water wheels - the kind that were used to power saw mills in times gone by. Now imagine hitting it with a super soaker water pistol. Even though the water is at very high pressure, there is very low flow, and so the super soaker will probably not generate enough power to turn the wheel. Now imagine the gently babbling stream that feeds the wheel, and under the force of almost no pressure, but with a high enough flow rate, generates enough power to turn the wheel. Finally imagine the firehose - the best of both worlds - high pressure and high flow rate - it would probably make the wheel spin quite quickly.

Capacity is a measure of how long you can draw a specified current from a battery. It is measure in Amp Hours (Ah), or more commonly for the scale of equipment used for electric flight, mill-Amp Hours (mAh). Using the water analogy this is simply how many litres you have in your reservoir. It is a little more complicated for electrical power and we will talk about it a bit later.

How Much Power Do You Need to Fly?

To figure out the power you need to fly a model depends on the weight of the model, and the type of model it is, as well as what you want from it.

In one of those quaint exposures of the inadequacies of the Imperial measures system which the US still cherishes this is normally expressed as Watts (a metric unit) per pound (an imperial unit). For those that want to work with a measurement system that makes sense, one pound equals approximately 450g for the numbers below.

50-70 Watts per 450g - Minimum for reasonable performance flight. Slow flyers and slow park flyers
70-90 Watts per 450g - Slow flying scale models, Trainers.
90-120 Watts per 450g - Sports aerobatic. Fast scale models.
120-150 Watts per 450g - Advanced aerobats. High Speed Models. Excellent Vertical performance
150+ Watts - Very High Speed, Unlimited Vertical Performance.

Note - You must include the weight of all the plane's components in your calculations - anything that leaves the ground with the plane needs to be included - batteries, the engine, speed controller, etc.

So, if you have a 900g delta wing, that you want to have unlimited vertical performance, you are going to have to try and generate 300w (900/450 = 2, 2 x 150 = 300).

If you have a slow flying scale plane that weights 350g then you need to try and generate a minimum of 54 watts (350/450 = 0.77, 0.77 x 70 = 54).

Understanding the Limits of Your Equipment

Most electrical equipment will have limits on the amount of current it can handle, as well as sometimes the number of volts it can handle. Some equipment also states a power limit as well.

Batteries, and particularly the Lithium Polymer type, are rated in C for the amount of current they can discharge. So, if you have an 800mAh 20C battery the maximum current you can draw from it is 16A (20 x 0.8=16). With the battery's volts in hand (say a 3s 800mAh rate at 20C) you can generate the maximum power this battery can provide - 16A at 11.1v = 177watts. Batteries may have a burst rate, and a continuous rate - so 15C at burst, 10C continuous. Using the 800mAh battery again you might be able to draw 12A in burst, but only 8A continuously.

Speed Controllers are often rated by the amount of voltage, and current they can handle. The amount of current that is drawn through the speed controller depends on the engine. In general you need to make sure your speed controller can handle at least as much, and ideally a little more current and power than the engine. Obviously your speed controller needs to be rated at the voltage for the battery - it will not reduce voltage either (there isn't room for a transformer there).

Engines are usually rated at the maximum current draw they can handle. They will often have a burst and continuous rating. Sometimes engines are also rated for the maximum power they can handle. For example, and engine might say 18A or 200watts. This engine could handle a three cell LiPo (11.1v) @ 18 A = 198watts, but couldn't handle a 4 cell LiPo (14.8v) @ 18A (266watts). However, if you restricted the throttle so that the current never got above 13.5 A you could use a 14.8 volt battery with the motor (provided the motor can handle 4 cell LiPos).

How Much Current Does An Engine Draw

The current an engine draws depends on the propeller it spins and gearing. Generally if you buy a new engine information on propeller combinations, and how much current they draw will be included.

If it isn't, and you can't find it on the Internet, or you want to experiment with a different propeller then you really need a way to measure the current flow to make sure the engine is not drawing too much current for either the battery, the speed controller, or the motor.

If want to measure your current draw you will probably find that most cheap multimeters will only do 2 or 3 amps. I use a clamp meter(make sure it is capable of doing DC!), where the clamp is placed around the positive lead from the battery, and the current is measured through magnetic inductance. This has the big plus of being a lot less hassle (because you don't have to connect the meter in series) and a lot safer (as you aren't messing around with bare wires). Can strongly recommend a clamp meter if you are into this stuff.

Propellers with a larger diameter will draw more amps because they are moving more air. Propellers with a more aggressive pitch will draw more amps to a point, although the best pitch for a propeller is normally determined by how fast the engine spins (the kV rating for brushless engines - 1000 of rpm per volt).

There are two ways to reduce the amps a system draws - reduce the prop size, or limit the throttle throw if you have a computer radio.

A note on props

Props have two ratings, and by now you have no doubt figured out the first number is the diameter in inches. The second number is the pitch. What this number actually represents is the number of inches that the propeller would advance through the air in one rotation assuming no slippage.

Choice of propellers can significantly change the way an aircraft behaves. For example. A big propeller will give your aircraft a lot of thrust, and allow it to reach top speed very quickly, but top speed will be quite limited. A smaller prop will take longer to accelerate, but will have a higher top speed. Which prop you need depends on application. For a 3D model typically you are after thrust and quick acceleration. If you are building a warbird, you will probably favour higher speed at the cost of acceleration.

A few more thoughts on batteries

Flight times and capacity

If you know how many amps your model draws whilst "cruising" it is pretty easy to estimate an approximate flight time. For example, if you have an 800mAh, which draws 8A while cruising you will have an approximate flight time of 6 minutes (800/8000(8A)=0.1 of an hour, or 6 minutes).

Our model of imagining a battery as a reservoir of water holds pretty well for a lot of examples, but not under all circumstances. For example, given two batteries - a 2 cell 1200mAh LiPo, or a 3 cell 800mAh LiPo, which would provide the longest flight time.

The answer is perhaps not as simple as you might think. Because the 3 cell has higher voltage you do not need to draw as much current to achieve the same power.

Let's say you need 30watts to cruise your light parkflyer:

For the 3 cell: power = volts x current therefore 30 = 11.1 x A, A =30/11.1, A=2.7
For the 2 cell: power = volts x current therefore 30=7.4 x A, A=30/7.4, A=4.1

So, flight durations are as follows:
3s 800mAh: (800/2700=0.3 of an hour, or about 18 minutes)
2s 1200mAh: (1200/4100=0.3 of an hours, or about 18 minutes)

So, even though the 2 cell has higher capacity, because the current draw is so much higher to provide the same power, it ends up both these batteries have about the same flight time.