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A Guide to Electric Power Systems

I've been asked by a few people about sizing electric motor/prop/battery combinations, so I thought I'd put together a guide. With most electric planes, the manufacturer recommends a particular motor/prop/battery combo... but, what if you have salvaged a motor from a previously crashed plane? Or, what if you want to go with a *bargain* motor with similar (but not exactly the same) specs? Or, what if you want to convert a nitro plane to electric. For this guide, I'll be using the later as an example. I have a Hangar 9 Twist, which was previously powered by a .46 nitro engine that I converted to electric power. If you want to skip the details and get right to the "tell me how to do it", read "Sizing the Motor", "Sizing the ESC", "Sizing the Battery", "Sizing the Prop", and/or just skip directly to "The Easy Answer".

This guide is aimed at those that want to squeeze all the power they can get from their electric power system.

Sizing the Motor

The second easiest thing to size properly is the electric motor you'll be using. The first thing is to determine how much power you'll need (Watts). The general rule of thumb is based on watts per pound. A thicker wing (airfoil) or a low aspect ratio (short wide wings) will increase the amount of power you need due to the extra drag. For example, my Twist is about a 5.5lbs AUW (ready to fly weight). A Twist is a 3D plane, so my goal was about 150W - 175W per pound, so I needed a motor rated for at least 825W, but 900W is a good round number ☺. Here's a general guide to how many watts per pound you will need for different plane types:

50W - 80W/lb
Light park flyers, gliders, trainers (it flies, but not much else)
80W - 120W/lb
Sport flying, light aerobatics (rolls, maybe a loop or two), scale aircraft, many "warbirds" fall into this category
120W - 150W/lb
Aggressive aerobatics, some Pattern flying, scale racing planes
150W - 200W/lb
3D, Pattern flying, unlimited vertical performance, blistering speed

I picked an AXI 4120/14 (because I had it laying around). Going into the differences between brushed vs. brushless or inrunner vs. outrunner is beyond the scope of this guide. I'll just assume you're using a brushless outrunner (in most cases you will be).

AXI 4120/14 Specs:
- 4-5S LiPo
- 850Watts
- 55A max
- 660KV (more on this later)

AXI is known for underrating their motors quite a bit, and plenty of airflow will bump these numbers up a bit. As with most power systems, heat is the enemy.

Sizing the ESC

Your electronic speed controller (ESC) is the easiest part to size. Figure out what the maximum amount of current (amps) your motor will be running (in my case, the max amps for the motor is 55A) and go above that (10% is usually safe). For my setup, I used a 60Amp ESC because it's what I had laying around. That might be cutting it a bit close, but since this is a 3D plane, I won't be flying at WOT (wide open throttle) much, and at lower RPMs, the current consumed by the motor is much less.

Sizing the Battery

It gets a bit more complicated here.

I assume you'll use a LiPo (Lithium Polymer) battery. I can go on for hours about why LiPo is far superior to NiMh or NiCad. Let's leave it at "go buy a few LiPo 's". So a LiPo battery has 3 specs of interest, number of cells (3S, 4S, etc), capacity in Milliamp Hours (1500mAh, 3000mAh, etc.) and the "C" rating (20C, 35C, etc.).

I'm using a 5S 3000mAh 20C LiPo battery. This means:

5S = 5 LiPo cells "in series" = 18.5 volts (5 cells x 3.7V per cell)

3000mAh = 3 amp hours (There's 1000mAh in 1Ah)
20C = 60Amps of continuous output (20C x 3 amp hours)

The first thing we need to do is make sure the battery can supply the amount of current (amps) that the motor needs. The C rating and the capacity are used to determine how much current the battery can supply. Simply multiply the capacity in amp hours (3Ah in my case) by the "C" rating (20C) and you get 3 x 20 = 60Amps. This is how much current the battery can supply constantly. Since the 60Amps my battery can supply is more than the current I expect to use (55A), this battery will work fine. Sure, I could just use a 45C battery, but that adds more weight and more cost.

More on Batteries

The second thing about batteries is the number of cells. The 5S rating on my batteries tells me there's 5 cells. A LiPo cell ranges from 3 volts per cell to 4.2 volts per cell. For example, when my battery is fully charged, it will put out 21V (5 cells x 4.2V), and when it's completely empty, it will put out 15 volts (5 cells x 3V). Don't ever run your LiPo batteries below 3V per cell under load. I have a Spektrum Telemetry system on most of my planes, so I know what the voltage is while in the air, and land when my batteries are sagging below 3.3V per cell under load. LiPo batteries are usually rated by their nominal (average) voltage, which is 3.7V per cell. My 5S will show 18.5V on the package.

Voltage is important because it largely determines the RPMs your motor will turn. Your motor has a KV rating (mine is 660KV). This means that for each volt I pump into my motor, it will turn 660RPM with no prop. Realistically your motor will run much slower than that, especially with a prop on it. For now, just know that more RPMs mean you'll want a smaller prop.

The last thing is the capacity of the battery. For a 3000mAh battery, this means it can supply it's nominal voltage (3.7V x number of cells) at 3Amps for one hour. Don't ever run your LiPo this low. Most people I know only run their LiPos down to 1/3 - 1/2 capacity before landing. More capacity basically means more flight time (and more weight). Since I'm a big nerd and I like to overcomplicate things, I will multiply the capacity (3000mAh) by the voltage (18.5V) and get a Watt/Hours number (55.5Wh). This makes it easier to compare batteries with different cell counts. For instance a 4S 3850mAh battery would give me about the same flight time as my 5S 3000mAh battery does:

(5S) 18.5V x 3Ah = 55.5Wh
(4S) 14.4V x 3.85Ah = 55.5Wh

As a personal rule of thumb, I like to give my planes 7 - 10 watt hours per pound. This gives me 10-14 minute flights.

Really, you can just use whatever battery you think will work (whatever is laying around), and if you want more flight time, try a higher capacity battery. If your plane is flying too heavy, try a smaller capacity battery.

The Yin and Yang of Power

So there's a law about electricity called Ohm's Law. For our purposes, Ohm's Law says "Watts = Volts x Amps". The best way to explain why this is important here is with some examples.

So with my plane, I want 900 Watts. I have a 5S battery laying around (18.5V), and I don't want to go over 55Amps (max motor/ESC current). If you remember Algebra, you can convert "Watts = Volts x Amps" to "Watts / Volts = Amps". I estimated my setup as:

900Watts = 18.5Volts x 48Amps

So in this case, this battery will work for me. But what if I had a 4S (14.4V) battery laying around I wanted to try?

900Watts = 14.4V x 63Amps (too many amps!)

Notice when volts go down, amps goes up. Likewise, when volts go up, amps go down. If you find that your setup pushes your Amps above your max amps limit, consider going with a higher number of cells (up to the maximum recommended by your motor manufacturer). For my setup, 63Amps is too much, so I went with a 5S battery to bring those amps back down. Even though my AXI 4120/14 is rated for 4S-5S, I've run it on 3S and 6S with no issues (Do this at your own risk).

There are actually a lot of reasons why more voltage generally works better, but to keep it short, know that you get more punch out of more voltage. But, more voltage means more RPMs, which means you'll need to use a smaller prop. If you need lots of "prop wash", this can be an issue, especially on smaller 3D planes.

Sizing the Prop

The last piece of this puzzle is the most complex, the prop. A prop will say something like 12x6 or 15x8 on it. The first number is the diameter (size) of the prop, the second number is the pitch.

A quick and dirty explanation of prop sizes says, *with RPMs staying the same*, more diameter means more thrust, and more pitch means more speed, AND an increase in diameter or pitch means more amps are consumed.

Here's where you can get yourself into trouble. Your motor will consume all the power it can get to turn the prop at the speed your ESC is telling it to, and since the voltage of the battery stays the same (for the most part), it does that by consuming more amps. If you have a prop that's too big (pitch or diameter), then you'll consume too many amps, and you'll blow something up. If you have a prop too small, you won't consume enough amps, and you'll be shorting yourself on power. The trick is to get a prop that's just right, so you're pushing the amps as high as you can go, safely. To complicate this more, there's Thrust and Speed to think about.

The Yin and Yang of Thrust

In the same way that there's a give/take relationship with Voltage and Amps, there's a give/take relationship with Thrust and Pitch Speed. *With power consumed staying the same (900Watts for me)*, more thrust = less speed, and more speed = less thrust.

Imagine you and a buddy holding a pillow case up in a 7mph breeze. You can feel the pull of the wind, but it's not very strong. Now imagine holding up a bed sheet. The wind isn't any faster (no increase in pitch speed), but it's pushing a lot harder now. You're catching more air, which for this example, means more thrust. Now, if the wind were to speed up, that would be like an increase in pitch speed. The thing to know is that even if you have a huge prop that gives you 25lbs of thrust on a 3 lb plane, if the pitch is very low, then the air coming off the prop is slow. If your pitch speed is only 25mph, your plane will never go faster than 25mph in level flight. Another example would be blowing through a straw at the same bed sheet. The air would come out of the straw very fast (high pitch speed), but the amount of air is very low (low thrust).

Since there's a yin/yang relationship between thrust and pitch speed, you'll have to get the right balance between thrust and pitch speed. You want enough thrust to get your plane in the air, but you need enough speed to stay above the stall speed of your plane (usually 2 to 3 times higher actually).

Details on RPM and Prop Pitch

Prop pitch is a theoretical number that represents the distance in inches that a prop would travel forward with one revolution. For example, imagine a screw. As you turn the screw into a piece of wood it goes in a certain distance per turn. If the threads on the screw were at a different angle, one turn would go a different distance into the wood. A prop is the same way. A 12x6 prop should go 6 inches forward per full revolution, a 12x8 prop should go 8 inches forward (in level flight, while not accelerating, with no drag, blah, blah, blah). In the real world, this doesn't happen because of many different factors, which is why prop pitch is a theoretical measurement. Basically, more pitch means more speed.

If you know the RPMs and the pitch, you can approximate the pitch speed. For example:

13x6.5 prop @ 9000RPMs

9000RPMs x 60 = 540,000 revolutions per hour
1 revolution = 6 inches
540,000 x 6 = 3,510,000 inches per hour
3,510,000 / 12 = 292,500 feet per hour
292,5000 / 5280 = 55 miles per hour

Realistically your plane won't go this fast in level flight because of drag, but take 10%-20% off of this number and you'll probably go somewhere close to this speed. Obviously if you go way up in the air, then power dive at full throttle you'll go much faster because gravity is helping out.

As you can see, to go faster you'll want more RPMs (which means more voltage) and a higher pitch speed. If you need more prop wash and more thrust, you'll want to go with a lower voltage and a bigger diameter prop.

There's a caveat to prop wash. Generally when someone is talking about more prop wash, they *mean the prop wash covering a larger area of the wing, making your control surfaces more effective at slow or stalled speeds. If the prop wash is too slow (low pitch speed) then it won't make it all the way back to your rudder and elevator. In addition, faster prop wash makes your plane respond more quickly to it.*

For my converted Twist, I'm not as concerned about speed as much as I am thrust. For my 5.5lb plane, I want at least 6lbs of thrust (bare minimum). If you've ever seen a Twist, you know it has a very large wing area, very low wing loading, very large airfoil, and therefore a very slow stall speed.

Another thing to be aware of is the maximum RPMs your prop is rated for. The prop manufacturer's web site will generally tell you how to figure this out. I'm using an APC 13x6.5E. To compute the max RPMs for this prop, APC says take 145,000 and divide by the prop diameter (in inches) which turns out to be 11,153RPM.

If you multiply my battery voltage (18.5V) by the KV rating of the motor (660KV) you get 12,210RPMs, and without a prop on it, my motor may actually go that fast. Since the prop adds drag, it will actually turn quite a bit slower. My prop actually goes a little less than 10,000RPMs, so I'm safe.

The Easy Answer

So now you want the easy answer to "what size prop should I use". Well sorry, there isn't an easy answer. There's no simple formula like Ohm's Law to calculate what prop you'll need. There IS an equation, but it involves a "prop constant", air density, electrical efficiency and some other things that are over my head.

Just to sum it up:

- You picked a motor that will give you the "Watts per Pound" you need.
- You picked an ESC that is rated higher than the max amps your motor will consume.
- You picked a battery that will supply enough amps
- Now you need a prop ... time for some testing.

Sure, you can be safe and just use whatever prop is in the middle of what the manufacturer recommends for your motor, then fly the plane around and tweak based on what it "feels like", but you can most likely get more power (safely) out of your power system with a properly sized prop. The down side to the "feels like" method is that you can easily over prop your plane, and burn something up.

To Test Your Watts/Amps

A good place to start is somewhere in the middle of the manufacturer recommended props for your motor. AXI recommends between 12x6 and 14x10 for my motor. That's a pretty big range. Testing is going to require a Watt Meter. They're $20 - $40 and plug in between your battery and your ESC. After it's all plugged up, run your plans (slowly) up to full throttle, and read the watts and amps your plane is consuming. If your motor is rated for 55A, and your watt meter only shows 35A, you can safely go to a bigger size prop, or a higher pitched prop.

To Test Your Pitch Speed

So, you tested your power system with your watt meter and you have some room to grow. Well, do you go up in prop diameter or prop pitch? For that you'll want a tachometer. This device counts RPMs. I got mine for $2 at an RC swap meet. Run your plane up to full throttle, and point your tachometer at the prop. With the RPMs you prop is running, you can calculate the pitch speed (remember the section "Details on RPM and Prop Pitch"?).

If your plane could use a little more speed, go up in prop pitch, if you need a little more thrust or vertical performance, go up in prop diameter.

Let the Computer do the Math!

So, if you don't have a ton of extra props and batteries laying around or you don't want to do all this math each time, there's an easier way. There are quite a few "prop/motor" calculators out there on the internet. I heard "MotoCalc" is nice (google it), but I actually use a web based calculator (http://www.ecalc.ch/motorcalc_e.htm). This makes it very easy to approximate what different combinations of parts will do in the field.

It looks complicated at first, but really you just fill out your setup in the top section (Battery, ESC, Motor and Prop), and it computes all kinds of crazy stuff in the bottom section, complete with a neat little graph. I only use a couple of the computed values. In the bottom section there are several horizontal lines with computed data. Starting with the the top line:

Battery: "Load" is the only one I use. Just make sure the "C" rating it shows here is below your battery's "C" rating. The "flight time" values seem to be WAY under what I get out in the field.

Motor: "max. Current" and "RPMs" are pretty accurate.

Propeller: "Static Thrust" and "Pitch Speed" are usually pretty close. Static
thrust is what you will get on the ground when your plane is held in place.

Entire Drive: "P(in)" is the Watts your power system should consume.

My Real Life Example

My Twist has:
- AXI 4120/14 rated for 850W and 55A
- 60Amp ESC
- 5S 3000mAh 20C LiPo
- APC 13x6.5E prop

If I punch in the numbers, I should get about:

- 134oz (8.3lbs) of static thrust (on a 5.5lb plane, this means unlimited verticals)
- 63mph pitch speed
- 1000W of total power (which is 180W/lb)
- consuming 51amps

In reality, my RPMs are a little less than 10,000, so my pitch speed isn't quite that fast (I've never clocked the actual speed of the plane though), and my amp draw is a little less than 50amps. This is a pretty well sized power system for this plane. You might be saying, "but wait, your motor is only rated for 850W!" That's true. Several factors play into this, but I have excellent airflow around my motor and ESC, I fly at half throttle mostly, I'm below the 55A max rating on the motor, and I'm at the max number of LiPo cells it's rated for (5S).

My flight report on this plane is full of smiles; it flies fast or slow, and climbs until I tell it not to. Acceleration is scary fast.

Another Real Life Example

Yesterday I was talking to a guy at the field, and he said he'd like to get some smaller batteries (I assume because of cost, but weight could also be a factor) for his Hangar 9 Frenzy (about 7lbs AUW). He's using all the recommended stuff in the power system:

- Power90 brushless motor
- 85A ESC
- ThunderPower (2x) 4S 3850mAh 45C LiPos in series (which makes it a single 8S 3850mAh 45C)
- 18x8 Prop (?)

We hooked up my watt meter, and ran it up to full throttle. It was cranking out about 2500Watts (350W/lb holly crap!) at 84Amps. Believe me this plane is a rocket. I've seen this plane do a 5ft takeoff, and launch directly into the air like a bullet. He's cutting it a bit close on the ESC, but this is a 3D type plane, so he's rarely at full throttle. In fact, there's so much power there that he probably never goes above 3/4 throttle even in long verticals. A quick Google search revealed to me that his motor is only rated for 65A burst, and we measured 84A of current from the battery yesterday. There's a couple of reasons why his plane hasn't spontaneously burst into flames. First, there's some inefficiency in your ESC, which means the Amps consumed from the battery is higher than the Amps that actually get to your motor. Second, Amps aren't really the issue, Heat is the issue. It just so happens that amps create heat. If your motor is adequately cooled, you can run it a little harder. Third, we did a test on the ground, which is "static thrust". When your plane is moving, it consumes less amps at full throttle. And finally, and probably the biggest factor, is how heavy your thumb is on the throttle. If you never go over half throttle, you'll never be pushing 84 amps. Personally, that's cutting it too close for me, as I like to "hot rod" my planes on occasion.

So let's analyze. His batteries are capable of putting out 173Amps constant (3.85A x 45C), but he's only consuming 84Amps. He would be perfectly fine using some 25C batteries (3.85A x 25C = 96Amps), which would make his new batteries smaller, cheaper and lighter without sacrificing any power or speed.

To take it a bit further, I punched his specs into the propCalc web site, and got:
- 325oz (20lbs) of static thrust
- 84Amps
- 67mph pitch speed
- 2650 Watts total (378W/lb)

Notice that his pitch speed is only 67mph, which means his plane probably goes 55-60mph in level flight, but he's got 20lbs of thrust, so his acceleration is almost instant, and he could take his 10lb cat for a ride to the moon.

I played a bit with the numbers on propCalc, and put in a 17x10 prop with his current setup:
- 342oz (21lbs) of static thrust
- 84Amps
- 84mph pitch speed
- 2635 watts total (376W/lb)

Not that he needs more power, but notice that he gets more than 15mph more speed, and another pound of thrust without increasing the amp load, just by adjusting his prop a bit.

If he went with a 17x8 prop:
- 287oz (18lbs) static thrust
- 69mph pitch speed
- 71 Amps
- 2232 Watts total (318W/lb)

The 17x8 prop is more like what I would have done to this plane. That gets it down closer to that 65A max for the motor with a full battery, and still gives (way more than) plenty of thrust, and also adds a small amount of speed.

Hangar 9 recommends a wide range of motors for this plane (Power60 to Power110). (We have another guy at the field that actually has a Power110 on his Frenzy, I think he's compensating for something🙂). If he wanted to cut the weight down more, he could easily go with a smaller motor, which means a smaller ESC, which means a smaller set of batteries, all of which means less cost. I personally like slow flying planes (which means light weight), so I lighten up my planes wherever possible. Since he already has this plane built and flying, the only changes I would make are changing to a 17x8 prop, and getting a few 25C-30C batteries.

Let me give a word of caution on overpowering a plane. Since this plane doesn't travel excessively fast, there's not a lot of worry about high-G maneuvers. If you build a plane that goes 100mph+, and power dive at full throttle, be very careful pulling out, or you might be digging your plane out of the ground and fishing your now detached wings out of a nearby pond.