Electrical theory for model flyers

More and more flyers are using electric power for the motors in their model gliders and tugs. I can't think why. Can it be because it always works, never needs adjustment and doesn't cause noise problems?

Chats at the flying field tell me that many people don't know about electricity so I decided to set out the basics in good science but everyday language (the Feynmann method).

First we need to understand energy and power.

Energy (E) is what allows us to do things. Examples are heat and electricity. We use heat energy in our glow, gas turbine and petrol engines. We use electrical energy in motors. In both cases we turn propellors of some kind to speed up air to provide thrust. So our heat or electrical energy is turned into movement, called kinetic energy. Energy is measured in joules (J). Cells are chemical devices that store electrical energy. They have connectors labelled plus (anode/red) and minus (cathode/black).

Power (P) is how fast we use energy. We measure power in joules per second. This is also called a watt (W).
So 1 W is 1 J/s
This can be written power = energy divided by time or P = E/t (t is time in seconds).

Electricity is negatively charged particles called electrons. They are very very very tiny and light (10^{-30} kg). Electrical conductors are materials like carbon and metals. Some of the electrons in conductors are free to move around and constantly do so, similar in behaviour to gas in a pipe.

How do we measure electricity?

The **quantity of electricity** is measured in **coulombs (C)** and is known as **charge (Q)**. One coulomb is just over 6 million, million, million electrons. It can be trapped (static) in a conductor or forced to move through it.

If you connect a battery to a conductor, the negative cathode pushes more electrons in at one end and the same number pop out at the other (positive) end. So there is a drift of electrons through the conductor. This is called **current (I)**. Yes I know, current flows from plus to minus. This is called **conventional current** and was thought up before scientists knew about electrons. Current is measured in amperes (A or amps). One ampere is when one coulomb of charge drift past a point in the conductor in one second. Remember that this is a huge number of electrons.

How fast do they drift? It's less than one millimeter a second. That surprises people when they first hear it. It would take several minutes for an electron to drift from one end to the other of a 1 metre conductor. They might drift slowly but there is a huge number of electrons so the flow of charge (current) is still significant.

So how do electrical signal travel at great speed in a wire? It is just like particles in the kinetic theory (Oh no not that again!). The air particles as a mass move quite slowly but at the particle level they are moving randomly at the speed of sound. Free electrons move randomly at about one third of the speed of light in a conductor. It we apply a voltage at one end by throwing in more electrons, the electrons shove the next lot, which shove the next lot and so on to the far end. We call this a ‘signal’ and that is what travels at 100 million metres per second.

Take a look at https://byjus.com/physics/drift-velocity/
or http://wiki.c2.com/?SpeedOfElectrons

How are electrons pushed? In a battery the electrons have extra energy. This is like the extra energy that an object has if you lift it, and that you get back if you let it fall. The object’s energy is called potential energy. The extra energy in the electrons is called electric potential or more usually **voltage (V)**. So voltage is a measure of energy. If one coulomb of electrons is given one joule of energy it has a voltage of one volt. This is what pushes the electrons. This is shown as energy = charge x voltage (E = QV). Voltage is sometimes called electromotive force or EMF.

At everyday temperatures there is no such thing as a perfect conductor. Collisions (or more correctly interactions) with the fixed atoms in the conductor means the atoms take away some energy. We know this because the conductor warms. In a heater - for example in a glow plug - this is useful but in our models it is usually wasted energy. It is what warms up our batteries. The materials they are made from are not perfect conductors so they also heat up when providing electric current. This wastes energy, and as you will see later, reduces the voltage they can produce. Note that as the electrons move along the wire they lose energy and so the measured voltage falls. Perhaps in school Physics you moved a metal slider along a bare wire and saw the voltage drop.

Some conductors are better than others. We measure how bad the conductor is with an invented idea called **resistance (R)**. This is measured in ohms (Ω). If one volt is put across the ends of a conductor and a current of one amp flows the resistance is one ohm. This is shown in resistance = voltage divided by current (R = V/I). We will be using this later.

Power and electric motors

So back to power, which is what we want from our motors. Remember that:

Power is energy per second	P = E/t
Energy is charge times voltage	E = QV
So power is charge times voltage per second	P = QV/t
Q/t is charge per second which you already know is current (I)	
So power is current times voltage	P = IV
And energy is power times time	E = Pt (by rearranging P = E/t)

This means that the power of your motor relies on both voltage and current. Let’s say you want 500 W of power. This is about two-thirds of a horsepower (1 HP = 746 W). If you have a lower voltage battery it will need to produce more current. More current heats both the wires and the battery more so it is good to keep current as low as possible.

For example **for the same 500W**:
A three cell (3S) lipo produces about 12 V. To get 500W we need 500/12 or about 40 A
A four cell lipo (4S) has about 16 V so will need 500/16 or about 30 A
A six cell (6S) lipo has about 24 V so will only need to produce about 20 A
Note that to a scientist a battery is made from two or more cells.

What the battery numbers mean

We choose our batteries using voltage, capacity and C rating.

What do those numbers mean?

Voltage. We've covered that.

Capacity. This is given in amp-hours (Ah) or milliamp-hours (mAh). We understand that the higher this number is, the more energy the battery holds and the longer the run time is for a given motor. Note that when you use a 6S battery you will use half the current compared with a 3S, so you can drop the capacity to half and still get the same run time, or very likely more as we will see later.

We probably don't need to know more but for completeness let's cover it.
Earlier we learned that energy is power times time **E = Pt**
Power is current times voltage **P = IV**
So energy is current times voltage times time **E = IVt**. (time in seconds)
Amp-hours give us the **It** bit so we now just need the **V**.
To find the energy in the battery we multiply its voltage by its capacity. We then multiply that by 3600 to turn the hours into seconds. Phew!

An example:
For a 2.2Ah 3S battery, that has about 12 V, the numbers are:
Energy = 2.2 x 12 x 3600 = 95040 joules
1 kWh unit of electricity is 3,600,000 joules
In the UK electricity costs about 17 pence per kWh unit.
So charging the battery will cost about 0.8 pence or 1 cent assuming 50% efficiency

C rating. This tells us how much current we can safely take from the battery. That is 'safely' in the sense of extending the life of the battery and getting a usable voltage from it. It can vary from 10 to 75. To find the maximum current we multiply the capacity by the C rating. So a 45C battery of 2.2 Ah capacity will safely give us up to 45 times 2.2 or 99 A. Above that it will over-heat and the voltage will drop dramatically. Why? Internal resistance.

Internal resistance

Battery materials have resistance, called internal resistance, and so waste energy. Wasted energy means reduced voltage, so the electrons have less than the rated voltage/energy when they leave the battery. We see this as a lower voltage on the connector. As current rises the wastage goes up. If you use voltage telemetry you see the reported voltage drop as you increase the throttle and go back up when you reduce it. A high C rating shows you that the battery has lower internal resistance. The internal resistances of lipos have improved a lot recently. Even cheap cells now give a reading of 3 or 4 mΩ (milli-ohms) compared with 10 or more not long ago. Some are as low as 1. A decent charger will have a menu option to measure the internal resistances of the individual cells in a battery.

Internal resistance will be looked at in more detail in another article.

Power and resistance

Earlier we learned that R = V/I (this is called Ohm's Law)
We can rearrange this as V = IR equation 1
We also learned that P = IV equation 2
If we put V from equation 1 into equation 2 we get

$$P = I^2R$$

So wasted power goes up with the square of the current.
Doubling the current makes the energy wastage four times bigger.
Three times means nine times.
So keeping current down by using higher voltages has a strong effect on energy wastage.
That's why a 6S battery of half the capacity of a 3S one will probably give a longer flight time.

Incidentally this is why electricity supply lines use very high voltages, in the UK typically up to 400 kV. A lower voltage would mean higher current and stronger warming in the lines. There would be happy birds keeping their feet warm but very little energy (voltage) would get to the far end. It is also why when current is low at night in the winter, ice can build up on the unwarmed lines.

When Edison first started to power towns and cities with direct (one direction) current he chose 100 V because it is unlikely to kill you. However huge currents were needed from the power station and the sizes of cable needed became impracticable so higher voltages had to be used. To reduce these for use in buildings, transformers were needed so Westinghouse's alternating current (AC) systems were used instead of Edison's direct current (DC). DC is still used in some situations, for example sending electricity ashore from sea-based wind turbines or the solar cells on your roof. In a horrific but fascinating side story George Westinghouse and Thomas Edison engaged in a public battle over whether ac or dc was the safer. This involved electrocuting animals including dogs and a horse. It also resulted in the use of the electric chair for executions.
https://www.thoughtco.com/death-money-and-the-history-of-the-electric-chair-1991890

Voltage is your friend, current is your enemy

Occam's Razor is a principle that says, 'the simplest is the most likely to be true'. I have been playing with electric motors of increasing power, making mistakes along the way. I finally think I've got it in my head - simply.

From above we know that:
Power = voltage times current

Current

Each motor has a maximum current.
Current causes heating, so too much will destroy the motor.
Current must be kept down.
Current is your enemy.

Voltage
Voltage does no harm (unless enough to electrocute you).
Voltage is your friend.
So to get more power out of a motor you increase the voltage, by going from 3 cell to 4, 5, 6, 7, 8 cells and beyond.
Do not go beyond the maximum cells specified for the motor and ESC.

Now you choose a propellor.
More voltage means more rpm. A motor's kV, e.g. 500, means how many rpm for each volt.
If you fit too big a prop the motor won't run at enough revs and the current will rise.
So more voltage (cells) means using a prop with a smaller diameter and/or pitch.
The choice of propellor, including the meaning of kV, is the subject of another article.

So what size propellor?
You can be guided by the motor maker's suggestions but they will play safe. If you want the maximum safe power you must use a power meter that shows current and then experiment with different props at full throttle. Alternatively you can use telemetry such as a FrSky Neuron ESC to give you the data including power.

For two blade props a good way of comparing them is load factor:
Load factor = diameter cubed times pitch.
This is the subject for another article.

What power can I expect?
Some makers specify maximum power for a motor, but many do not.
Remember: Power = voltage times current.
Voltage is the number of lipo cells x 4 roughly (this will be the maximum cells specified for the motor).
For example 8S gives about 32 V.
Current is the maximum specified for the motor.
If the motor can take 60 A:
Maximum power = 32 x 60 = 1920 W or about 2.5 HP

And when you have done your experimenting, share your data with club members and the rest of the world. Nowhere can I find a list of motors with propellor sizes for different numbers of cells found by practical methods. I am happy to host it. Just send me the data.

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