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Part 3 of "Understanding Electric Power Systems".

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Understanding Electric Power Systems - Part 3

Time for the third installment in my series on electric power systems. If you haven't read parts one or two, please do so now.

Recap

Last month we discussed cell capacity and duration. I asked a few questions at the end of the column. Below are the answers:

Q&A

What happens to the full throttle duration of a model if I add a cell and change nothing else? Why?

The full throttle duration goes down because adding a cell will increase the current draw.

How long can an Ideal Cell produce 15 watts of power?

A single Ideal Cell can produce 15 watts of power for 4 minutes. This is because it requires 15 amps of current from the Ideal Cell to create 15 watts and the duration of an Ideal Cell is calculated as 60 divided by the current draw.

Suppose I had a cell that provided 2 volts of electricity and had a capacity of 2 Amp-Hours. How many Watt-Hours would that be? How long could the cell produce 20 watts? How long could the cell provide 8 amps of current?

4 Watt-Hours. 12 minutes. 15 minutes.

Suppose you were designing an airplane to compete in a distance task. What could you do to the battery to make your airplane travel farther?

Since we are talking about the battery alone, the only possible solution is to add cells. In our Ideal World, the motor will draw more current, the system will produce more power, and the airplane will go faster. It will cover more distance in less time.

What does increasing propeller size do to power? Duration? How can I increase both power and duration of an electric power system?

Increasing the size of the propeller will cause more current to be drawn through the motor which will increase the power of the system. The full throttle duration will decrease because the current is increased..

The third question might be a little confusing. The answer is to add cells. Imagine that the original system had 10 cells and drew 20 amps, providing 200 watts for 3 minutes at full throttle. Now add five cells, bringing the cell count to 15. If the pilot were now to throttle back (or switch props) such that the motor is drawing only 15 amps, the power system could now provide (15 * 15) 225 watts for 4 minutes.

I need a power system that provides 300 watts from a battery composed of Ideal Cells. List two different volt/current combinations to accomplish this and the duration they will provide at full throttle.

Combo 1: 30 cell pack, 10 amp draw. Duration is 6 minutes

Combo 2: 15 cell pack, 20 amp draw. Duration is 3 minutes.

A little bit of Reality

Up until now we have looked at our power system as being defined by a few fixed parameters. Our motor has always turned at 1000 RPM per volt, for example. Its now time to add a little bit of reality to our Ideal Power System by labelling and varying this relationship. We will also explore the relationship between propeller size, RPM, and power absorption. Note that for the moment we are still operating in the lossless fantasy land called Ideal World, but our world is becoming more and more defined all the time.

Our First Motor Constant: Kv

It turns out that, in the real world, not every motor turns exactly 1000 RPM for every volt of energy applied to it. Instead, each motor has its own, different RPM/volt value. This value is called the **voltage constant** and is usually abbreviated as **Kv**. The "K" comes from the fact that the value is a "constant" for any given motor and, apparently, electrical engineers failed spelling. The lower-case "v" is used to signify that this is the "voltage" constant we are talking about (which should be a good hint that there are other "K" values with different meanings and, hence, different lower-case letters - more on that later).

The RPM of a motor, then, is equal to the product of the motor's Kv value and the input voltage, as shown below:

RPM = Kv * V

Assume for a moment that I have two motors: one with a Kv of 1000 and the other with a

Kv of 500. Both of these motors are capable of spinning at any given RPM, but the second motor will require twice as much input voltage to do so as the first.

RPM = Kv * V

RPM = 500 * 10 = 5000

RPM = 1000 * 5 = 5000

Both motors are turning at 5000 RPM, but the motor with a Kv of 500 required twice as many Ideal Cells (volts) to do so. Therefore, one of the motors requires a battery pack which will weigh twice as much (but will also provide twice as much duration).

Now that we have better defined our Ideal Motors, lets further define output power so we can tie everything together and really get a good look at how Kv works.

Propeller Power Absorption in Better Detail

The first two installments of this series contained some tables that displayed the power absorption of two different propellers at various RPMs. As I noted, these values were mythical. I created those tables so that I could enter into the discussion without having to worry about the complexity of the actual values.

In the real world it is very difficult to predict the amount of power required to swing a propeller at a given RPM. There are many complex factors to consider such as the number of blades, airfoil, and planform. For our discussion, it is reasonable to simplifiy things a little bit. The following formula was taken from Bob Boucher's **Electric Motor Handbook**. It is accurate enough for our use. There are better, more complex formulas out there if you are interested in further study.

The following formula works well for most two-bladed propellers:

Power (Watts) = Kp * D^4 * P * RPM^3

In English: The power required to spin a propeller is equal to the propeller constant times the diameter of the propeller to the fourth power, times the pitch of the propeller times the RPM to the third power. Note that Diameter and Pitch are specified in feet (not inches) and the RPM is specified in thousands.

The "Kp" is the propeller constant, which is determined by which propeller brand is being used. Not all brands of propellers are the exact same, of course, so the constant is used to "fudge" the values one direction or another. Bob spent a great deal of time determining the constants of various propellers. I am reproducing them below:

Table 1. Kp of various propellers	
Propeller Brand	**Kp**
Top Flite, Zinger, Master Airscrew	1.31
APC	1.11
thin carbon fiber folders	1.18

What the formula means

Its all well and good to know how to calculate power absorption, but its much more important to have a good feel for what the formula means. For instance, the above formula can be used to show the following things:

Doubling Diameter requires 16 times the horsepower (e.g. spinning a 12x6 at 10000 RPM requires 16 times more horsepower than a 6x6 at the same RPM)

Doubling RPM requires 8 times the horsepower (e.g. It takes 8 times as much horsepower to turn a 12x12 prop at 10000 RPM than it does to spin it at 5000 RPM)
Doubling Pitch requires 2 times the horsepower (e.g. a 12x12 requires twice as much power to spin at a given RPM than a 12x6 prop does)

So the propeller's diameter is the primary governer of how much power is absorbed. After that, its the RPM. A distant third is the propeller's pitch.

Example Power Absorption Calculations

Using our formula, we can now determine how much power is absorbed by any desired propeller at any desired RPM. I tend to use and recommend APC props for sport airplanes, so I will be concentrating on these during the discussion. This means I've fixed the propeller constant (Kp) at 1.11 for the following illustrations.

Table 2. Power (watts) absorbed by three APC Propellers at various RPMs

RPM	12x8	10x8	8x8
4000	47	23	9
6000	160	77	32
8000	379	183	75
10000	740	357	146
12000	1279	617	253
14000	2031	979	401

Predicting Current Draw Based on Kv and Power Absorption

Given a motor's Kv value, we can easily see how much voltage is required to spin a propeller at a given RPM. Using the voltage and the power absorbed by our chosen prop we can quickly calculate current. Note that there are no losses to consider in our Ideal World so the calculation is very simple.

The following tables show the Power, Voltage, and Current required to spin a 12x8 propeller at 6 different RPMs. The first table assumes a motor with a Kv of 1000, while the second table displays values for a motor having a Kv of 500.

Table 3. Power, Voltage, and Current required to spin a 12x8 propeller at various RPMs with a motor having a Kv of 1000

RPM	Power	Voltage (RPM/Kv)	Current (Power/Voltage)
4000	47	4	12
6000	160	6	27
8000	379	8	47
10000	740	10	74
12000	1279	12	107
14000	2031	14	145

Table 4. Power, Voltage, and Current required to spin a 12x8 propeller at various RPMs with a motor having a Kv of 500

RPM	Power	Voltage (RPM/Kv)	Current (Power/Voltage)
4000	47	8	6
6000	160	12	13
8000	379	16	24
10000	740	20	37
12000	1279	24	53
14000	2031	28	73

Using the above tables, we can make a direct comparison between two motors of different Kv values. The Kv determines how many volts we need to spin our propeller at a chosen

RPM. This, in turn, determines how much current will be drawn by the motor. Increasing Kv will always increase the current draw, all other things being equal. This is why we commonly call motors with a high Kv a "hot" wind.

Imagine that our goal was to turn a 12x8 propeller at 10000 RPM. Given the above tables, which motor would you choose? As you can see from Table 3, a motor with a Kv of 1000 requires 74 amps to turn a 12x8 propeller at 10000 RPM. The second motor, shown in Table 4, is probably a better choice at it will draw only 37 amps to do the same thing. The only problem is that we will need twice as many cells, but there is no such thing as a free lunch.

Maybe a better way to solve the above goal would be to decide on a duration goal along with the performance goal and search for a motor that matches our needs. This way we could choose our current to be, say, 30 amps. Based on the power we need (740 watts) and the current we chose (30 amps) we could determine that we need 25 Ideal Cells (25 times 30 is roughly equal to 740). Since we know that we want to turn our prop at 10000 RPM on 25 volts we can now begin our motor search by looking for a Kv of 400.

Calculating Current Directly

Based on the tables above, it should be obvious that the current calculation is trivial once we know how much power and voltage we have in our system.

Power (W) = voltage x current = V x A

A = Power / voltage = W / V

Substituting our power absorption equation for Watts gives us:

A = Kp * D^4 * P * RPM^3 / V

But the RPM of our motor is actually equal to the Kv of the motor times the input voltage. Therefore:

A = Kp * D^4 * P * (Kv * V) ^ 3 / V

A = Kp * D^4 * P * Kv ^ 3 * V ^ 3 / V

A = Kp * D^4 * P * Kv ^ 3 * V^2

From the above we can see that:

Current goes up with the square of the input voltage
Current goes up with the cube of the Kv.

I cannot say often enough that all of this discussion is based on the premise that we are operating in an Ideal World. These formulas cannot be used to accurately predict the performance of a real world electric motor with real world props and real world cells. But they *can* be used to demonstrate important relationships that are normally hidden within complex formulas.

The Trouble with Kv

Modelers often write me email saying that they have found an unmarked motor at a surplus store or some other source. They want to know if they can use the motor in an electric airplane. Most of these motors are simple "can" ferrite motors which have high Kv values compared to a quality brushless or brushed motor that is designed for electric flight. I usually end up responding by explaining how difficult it is to find a general purpose motor that is suitable for our uses. The same typically goes for R/C car motors and motors found at Radio Shack or other non-hobby sources.

One of the problems with many of these motors is that they typically have very high Kv values. A quick look at the formulas above will show that this means that they will attempt to draw a lot of current. As we learned above, the current increases with the cube of the Kv. High-Kv motors love current.

One solution to this problem is to use a belt drive or gear box. These devices effectively reduce the motor's Kv, which allows a motor to swing a larger prop at a slower RPM given the same input power. A 2:1 reduction unit, for example, effectively halves the motor's Kv.

Naturally, this idea can be taken too far. There are motor limitations and losses which we are not considering yet but should be taken into account when determining how much of a ratio is too much. Though we can spin a big prop using an Astro 25 on a superbox, we cannot put nearly as much power through the system as we can with an Astro 60. To understand why you will have to wait for a future installment of this series.

Summary:

- The RPM of an Ideal Motor is equal to the product of the motor's Kv value and the input voltage (RPM = Kv * V).
- **Power (Watts) = Kp * D^4 * P * RPM^3** (where Kp is the prop constant (1.25 for general usage), D is the diameter of the prop in feet, P is the pitch of the prop in feet, and RPM is in thousands.)
- Doubling Diameter requires 16 times the horsepower (e.g. spinning a 12x6 at 10000 RPM requires 16 times more horsepower than a 6x6 at the same RPM)
- Doubling RPM requires 8 times the horsepower (e.g. It takes 8 times as much horsepower to turn a 12x12 prop at 10000 RPM than it does to spin it at 5000 RPM)
- Doubling Pitch requires 2 times the horsepower (e.g. a 12x12 requires twice as much power to spin at a given RPM than a 12x6 prop does)
- Current goes up with the square of the input voltage
- Current goes up with the cube of the Kv.
- Gearboxes and belt drives are devices which effectively reduce the Kv of a motor.

Q&A

Answers next month, as usual:

- How much power is absorbed by a 10x6 propeller that is turning at 9500 RPM?
- Which increases current consumption more: increasing propeller diameter by one inch or pitch by one inch?
- I need to provide my airplane with a 500-watt electric power system. Give two different Ideal Power Systems (cell count, motor, and propeller) that will accomplish this.
- I have an Ideal Motor with a Kv of 750 and a 12x10 propeller. I want to get 3 minutes of full throttle duration out of my Ideal Cells (1 Ah). How many cells should I use?
- I have an Ideal Motor with an unknown Kv. With an 8x6 propeller, it draws 56 amps on 4 cells. What is the Kv of the motor I am testing?

If you have any questions or criticisms about this series, then please email me at jbourke(at)ezonemag.com.

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