

R/C Electric Systems

By Russ Pond, January 8, 2009

This discussion is about electric power systems for R/C aircraft. The intent is to present the basics of electric R/C aircraft for club members who may have little or no experience with electrics. This will be divided into four parts: R/C Motors, Electrical Speed Controls (ESC's), and Putting a System Together.

R/C Motors

There are 3 basic types of motors available for R/C aircraft use. The first and oldest type is the brushed DC ferrite motor. The newest type of motors are the two types of "brushless" called InRunner and OutRunner.

All of these motors have common important specifications:

- Maximum Continuous Current (Amps)
- Surge Current Rating (Amps)
- Operating Voltage Range: (Min. to Max.) This is sometimes specified by the minimum/maximum number of NiCad or Nimh or Lithium-Polymer cells based on nominal voltages per cell (1.2V or 3.7V respectively).
- Max. Continuous Power (Watts) is sometimes given, although this can easily be calculated by multiplying the maximum voltage by the maximum current.

Specifications less interesting for the average modeler:

- KV: Voltage Constant (RPM/Volt) Knowing the voltage at which the motor is operating gives you the approximate motor RPM based on this constant without a tachometer.
- KT: Torque Constant (inch-oz./Amp) [where $KV \times KT = 1355$]
- IO: No Load Current (Amps)
- RM: Motor Terminal Resistance (Ohms)

1. Brushed DC Ferrite Motors

These standard brushed DC motors are also sometimes called brushed can motors. Some typical designations you've probably heard are "Speed 400", "Speed 500", Etc. This terminology was started by Graupner Co. in Germany long ago for naming their different brushed motors. They were one of the first manufacturers to make small DC motors for R/C aircraft. Other manufacturers in the US and elsewhere began using these designations to compare their motors to Graupner's. However, these designations, although still used for advertising, are mostly meaningless as to motor specifications. The brushed DC motors were used before any brushless AC motors were even heard of for R/C. Since the growth of brushless motors, the popularity of these motors has been decreasing. They require an ESC (electrical speed controller) made for brushed DC motors. The brushed motors are much less efficient than the brushless motors, even with modern electronic brushed DC ESC's. Brushed DC motors do have some advantages, one being that they are mostly less expensive than brushless motors, and another important one is their advantage for powering twin motor electric aircraft. It is much easier and cheaper to use two brushed motors connected in series

to a single brushed motor ESC and single battery, which pretty much assures that both motors will be at the same speed and that one motor will not shut down prior to the other. This is more complicated and expensive with brushless motors.

2. Brushless InRunner Motors

All “brushless” motors are really 3 phase AC motors whose associated ESC’s are very sophisticated DC to AC miniature inverters. More about these ESC’s later on.

The so-called InRunner motors are a fairly conventional 3 phase motor configuration. They have a stationary case, on the inside of which is mounted the 3 phase wound armature (usually with 12 poles) with the three leads exiting the rear of the case. (See the photo below) There are two bearings, one on each end of the armature, between which is the rotor with high strength magnets mounted on the shaft. The output shaft exits the front of the motor case. For some InRunners, there is also a planetary gearbox mounted inline with the output shaft on the front of the motor case.



3. Brushless OutRunner Motors

The so-called OutRunner motor is best described as an InRunner motor, built inside out. The back of the motor is stationary and holds the rear bearing. The stationary, wound armature (usually 6 or 12 pole) is also mounted on the back plate. In this case the wound poles face outward. The shaft runs from the rear bearing through the center of the armature, then through the front bearing and the motor case front to a prop mount. The front case is cup shaped and turns with the shaft. Around the inside of the front case (cup) are mounted very strong magnets that run close to the pole faces as the case front/sides turn. (The following photos show two typical outrunner motors).



For either type of “brushless” motor, a general principle applying to all of them is that motors with higher numbers of winding turns per pole spin slower for every volt applied to the motor. They have a lower Kv (RPM/V). They spin a larger propeller at slower speeds and at a lower current than lower turns motors. Similarly, motors with lower numbers of windings per pole

spin faster for every volt applied to the motor. They have a higher Kv (RPM/V), and will spin a smaller propeller at higher speeds and at a higher current than higher turns motors.

InRunner motors are generally long but narrow and usually need to be mounted in a separate clam shell-like mount. OutRunner motors are generally shorter in length but larger in diameter. They are easy to mount by the back plate onto a firewall, and many of them come with the necessary mounting hardware. There are slight differences in timing between InRunners and OutRunners, but most brushless ESC's take care of that automatically.

R/C Electric Aircraft Batteries

Definition of "C" Given a battery with one or more cells of 2400 mah capacity, C is defined as the discharge current at the 1 Hr. battery rating, or in this case, 2.4 Amps (2400 ma).

NiCad and NiMh Batteries

Everyone is most familiar with NiCad and Nimh cells, which have similar characteristics with some differences. They are the same in the following ways:

- The nominal voltage is 1.2 V Per Cell, Fully charged voltage is about 1.4 VPC. These cells should not be discharged to less than 0.9 V (unless some loss of life is acceptable). For R/C radio use, most modelers as well as battery cyclers and transmitter low voltage alarms use 1.1 VPC as a minimum discharge voltage.
- To determine the state of charge for these cells, a loaded voltmeter must be used. Typically, all ESV's (expanded scale voltmeters) provide for 200 to 500 ma load while measuring voltage. Open circuit voltage of NiCad and Nimh battery packs means nothing, except it will indicate if one or more cells are shorted.
- New nickel based batteries, or those stored for a long time, should be "initialized" by slow-charging at C/10 ma for about 16 Hrs. Doing a slow-charge every few charges tends to keep nickel battery cells equalized.
- Occasional cycling of nickel batteries will let you know how much max. capacity is left compared to when the battery was new. Cycling is also considered to be helpful in maintaining capacity of nickel based cells, although it is now considered by some experts to be not really helpful with newer cells. Modern NiCads are not very susceptible to the so-called "charge-discharge" memory problem.
- Cold nickel batteries should not be fast-charged, as this can lead to high internal pressure, cell leakage, and catastrophic failure.
- Hot nickel based batteries should not be charged. Charge efficiency will be greatly reduced and charging a hot battery could cause a thermal runaway and loss of control of a delta peak or pulsed charger. Even at room temperature, the charging efficiency of nickel based batteries is only about 50%, which means one must input 2 mah for every 1 mah of capacity when the battery is charged.

Differences between NiCad and NiMh Cells:

Nickel based batteries generally may be fast-charged at the 2C rate (or sometimes more) without damage, providing that the charger will detect when the battery is fully charged, and either shut-off or automatically reduce to a safe trickle charge of approximately C/50. Most automatic fast chargers sold recently will handle both NiCad and NiMh cells; however, the two cell types have different behavior at reaching full charge. NiCad batteries use a method known as “peak charging”. As NiCad cells are charged, their voltage steadily increases until fully charged. At that point, the cell begins over-charging and the temperature starts to rise. This temperature rise causes the cell voltage to drop off slightly. This voltage drop is sensed by the charger to switch to trickle charge. NiMh cells, however, act differently. When they are fully charged, the voltage stops rising with the voltage curve flattening out. This point of the voltage change per unit of time going to zero is sensed by the charger to switch to trickle charge.

Other differences:

- NiMh cells are lighter weight than NiCad cells for the same capacity.
- NiCad cells have less self-discharge than most NiMh cells.
- NiMh cells generally have higher internal resistance than NiCad cells which, until recently, limited the discharge current of NiMh cells compared to similar NiCad cells.

Lithium-Polymer Batteries (Li-Po)

Li-Po batteries are pretty much the latest battery widely accepted for R/C use. They tend to be much lighter weight than the nickel based batteries for a given capacity. They now are available in many different capacities, but have had a troublesome reputation for catching fire, mainly due to mishandling or physical damage.

They have a nominal voltage of 3.7 VPC, with a maximum safe voltage of 4.2 VPC. The minimum voltage during discharge is between 2.5 VPC and 3.0 VPC, depending on the manufacturer or to whom you listen. Certainly, a minimum 2.9 or 3.0V is conservative. The problem with Li-Po's is that if they are discharged to below the minimum voltage per cell (even once), they may be ruined.

Because Li-Po's are very sensitive to minimum and especially maximum voltage, it is almost universally agreed that it is important to keep the cells of a Li-Po battery well balanced to avoid over-charging any cell. Li-Po batteries must be charged with a charger designed for Li-Po cells. If one grossly overcharges a Li-Po cell using the wrong type of charger, it is likely to swell up, and if overcharged enough, it will probably rupture and catch fire (due to the exposure of Lithium metal to air/moisture). Li-Po batteries must be charged by CC/CV (constant current/constant voltage) combination charge at the 1C rate maximum. When the charge begins, the charger supplies 1C current to the battery until the voltage reaches 4.2 Volts per cell. At this point, the charger switches to constant voltage (4.2V) with the current decreasing until it reaches about 5% of the original charge rate. This is usually considered a full charge.

Charging at the 1C rate, most Li-Po's will reach full charge from discharged in less than 2 hours. Most good Li-Po batteries are now capable of discharge rates of at least 15C,

with many capable of 20C or more without damage. However, experience is showing that operating near the published discharge current limits shortens the life of the battery.

A123 Model M1 Lithium-Ion Batteries

These batteries are a fairly new version of Lithium-Ion (Li-Ion) cells that are made by A123 which is a brand name. They are a ruggedized design of Li-Ion cells which A123 calls Li-NanoPhosphate. They have a nominal voltage of 3.3V per cell, a fully charged voltage of 3.6V per cell, and a rating which is based on the 3.6Volts. The M1 Cells have a capacity of 2300 mah. These cells are heavier than Li-Po cells of equivalent capacity; however, they are more rugged and reportedly not prone to catching fire. They can tolerate discharge current of up to 30C (69 Amps), and charging current of up to 5C (11.5 A). Supposedly, they can be discharged to 2.0V per cell without damage, per the manufacturer. So far, these cells have only been available to hobbyists by taking apart certain Black & Decker or DeWalt power tool batteries and building your own packs from them.

What follows is an energy density comparison of the four battery cell types discussed, using published manufacturer's data for a battery of approximately 11Volts with similar size cell capacities. It shows that for some typical batteries available for each type, the Lithium based batteries have significantly higher available energy per ounce of weight.

1) NiCad

Sanyo Cadnica Cat# CP-2400SCR, Fast Charge, High Current, Sub-C size.
1.2V, 2400 mah, weighing 2.09 Oz. per cell.
Charging rating: Between C/10 and 1.5C
Maximum Discharge: 8C
For a 11 Volt battery, 1 Hr. discharge rate
9 cells → 10.8 V nominal, Total Wt.: 18.8 Oz.
At 1C Discharge rate (2.4A) → 25.9 Watts
1Hr. Energy Density: 1.4 Wt-Hr. per Oz.

2) NiMh

Sanyo Cat# HR-4/5SCU, High Discharge, 4/5 Sub-C size
1.2V, 2100 mah, weighing 1.6 Oz. per cell.
Charging rating: Between C/10 and C
For a 11 Volt battery, 1 Hr. discharge rate
9 cells → 10.8 V nominal, Total Wt.: 14.1 Oz.
At 1C Discharge rate (2.1A) → 22.7 Watts
1Hr. Energy Density: 1.6 Wt-Hr. per Oz.

3) Li-Po

A) Thunder Power ProLite 2100 mah, 3.7 V per cell
11.1 V nominal, 4.7 Oz. (Incl. wiring & connectors, Very light weight Li-Po)
Rated steady state discharge rate: 15C
At the 1C discharge rate (2.1A) → 23.3 Watts
1Hr. Energy Density: 5.0 Wt-Hr. per Oz.

B) Electrifyly Balanced, Power Series, 2100 mah, 3.7 V per cell
11.1 V nominal, 6.14 Oz. (Incl. wiring & connectors)
Rated steady state discharge rate: 20C
At the 1C discharge rate (2.1A) → 23.3 Watts
1Hr. Energy Density: 3.8 Wt-Hr. per Oz.

4) A123 M1 Cell

Li-NanoPhosphate cells, 2300 mah, 3.3 V per cell nom., 3.6 V per cell charged
3 cells → 9.9 V nom., 10.8 V fully charged, weighing 8 Oz. Total
Charging rating: Up to 5C
Discharge rating: Up to 30C (69A)
At the 1C discharge rate, (2.3A) → 24.8 Watts
1Hr. Energy Density: 3.1 Wt-Hr. per Oz.

Electrical Speed Controls (ESC's)

We will concentrate mostly on brushless ESC's since they are the predominant ones used now. These ESC's are very complicated devices so I will try to cover the important features and specifications for applications. There are now many manufacturers/vendors of ESC's and there are large differences between some. Some are basically "black boxes" with default settings, few of which can be changed by the user. Some have optional settings that can be manually set by the user per a procedure provided in the manufacturer's instructions. Some even provide a USB link so all the settings can be made on your computer. The following are important specifications to look for:

- Input voltage range: Minimum to Maximum, Quite often the voltage range is specified by the min. to max. number of NiCad/Nimh or Li-Po cells which can be used.
- Maximum continuous current (Amps)
- Maximum surge current (Amps)
- Maximum input power (Watts)
- Brake (On/Off) The brake function is normally only used for glider type aircraft with folding props to prevent windmilling with power off. This can always be switched On or Off as desired.
- Battery Eliminator Circuit (BEC), Max. Voltage and Max. current load

The BEC is pretty much supplied in all ESC's now, and the purpose is to provide power to the receiver and servos from the main battery, eliminating the need for a separate onboard battery for the receiver and servos. These functions usually have limiting factors regarding whether or not to use them. They have a maximum current rating which is often shown by a table indicating the number of servos of which size can be powered based on the voltage of the main battery. If the main battery voltage is over a certain level, the BEC cannot be used and must be disabled per the ESC instructions. Likewise, if you have too many servos per the table, the ESC cannot be used and has to be disabled.

In those cases, one can either add a separate controls battery, or install a separate standalone BEC device that is directly powered off the main battery.

- The last important ESC function is the Low Voltage Cutoff. The purpose of the setting is to shutdown the flight motor if the main battery voltage drops to preset limits. It should be noted that when this happens, the BEC circuit will keep supplying power to the receiver and servos. In many ESC's the user can set the values for cutoff; however, some do not allow adjustments, and use 3.0 V per cell for Li-Po batteries and 0.9 or 1.0 V per cell for NiCad/Nimh batteries. Some manufacturers do not even specify what the setting is for low voltage cutoff in the instructions (Ask me how I know). Others use a fixed setting of a percentage of the initial power-up voltage, so you must always start with a fully charged battery, or you could risk the cutoff voltage being too low for the battery.

Putting It All Together

In order to select a complete electrical power system for an R/C aircraft there is a fairly straight forward procedure to select components. The first thing needed is a fairly accurate total weight of the completed aircraft without the battery, ESC, or motor. As a start, a first guess for a system should be made, and the weights of the proposed electrical components be added to the weight of the bare aircraft for estimating.

The following Tables 1 or 2 should be used as a guide for design. The required input power in Watts per Lb. or Oz. is very important. These values have come from persons experienced in electrical flight and have also been published by AMA in some magazine articles.

Watt/Ounce	Type of Aircraft
1.00	Model that barely gets off the ground
1.25	Powered sport sailplane, indoor RC airplane
2.00	Parking lot/backyard flyer
3.00	Aerobatic flier
5.00	Electric 3-D model

Table 1. Watts/Ounce (Models weighing less than 1 Pound)

Watts/Pound	Type of Aircraft
30	Model that barely gets off the ground
40-50	“Sunday flier”, Sport sailplane, Old-Timer
60-70	Mildly aerobatic model
80-100	Aggressive airplane
100 plus	Ducted-fan aircraft, Competition sailplane, Electric-powered 3-D model

Table 2. Watts/Pound (Models weighing more than 1 Pound)

These values should be used for the selection of a power system. This is called the “power loading”. It is important that once the final system has been selected for an aircraft, the total input power divided by the total aircraft flight weight should be checked against these Tables to make sure that it is still in the appropriate range.

Another factor that should be considered is the pilot skill factor of the plane that is to be powered, based on the following Table 3, wing loading using total flight weight.

Wing Loading (Oz. / Square Ft.)	Type of Aircraft and Skill Level
5-10	Park flyer, Basic trainer, Powered sport sailplane
10-15	Faster sport flier, Smaller trainer, "Sunday" flier
15-20	Larger trainer, Sport scale model, Sport aerobatic model
20-25	Fast sport model (usually with more than adequate power)
25-35	Scale model, Larger multiengine model
35 plus	Not for most modelers!

Table 3. Wing Loading and Skill Level

Table 3 should be considered with Tables 1&2 above. It is not recommended to have an aircraft that is extremely overpowered such that its wing loading is too high. You may need to limit the size of the power system, especially the battery, to keep the wing loading reasonable.

The next step is to begin collecting motor data from catalogs or hobby vendor websites online. Picking an input power target from Tables 1 & 2, one can select several candidates from the desired motor manufacturers. Remember that if the maximum watts is not published as a motor specification, it can easily be calculated by multiplying the maximum motor voltage by the maximum motor continuous current. Once several promising motors have been selected, compatible ESC's can be selected. The ESC is selected based on the associated motor specifications and options desired in the ESC that were discussed above. Once the possible ESC's have been selected, several possible NiCad, Nimh, or Li-Po batteries can be selected based on the voltage, current, and input power needed.

Selection of the total power system is an iterative process. Once a potential system or systems have been selected, go back and add the weight of each potential combination of motor, ESC, and Battery to the bare aircraft weight and re-calculate the power loading to see if it is still in the desired range of Table 1 or 2. The choice of battery type will probably affect this value significantly.

Once you have a power system that meets the criteria discussed, you can also make a rough estimate of the motor run time for each system. Use the formula:

$$\frac{60 \times \text{Batt. Capacity in Amp Hrs.}}{\text{Motor Current (Amps)}} = \text{Minutes}$$

Using the maximum motor current will yield the minimum runtime. Typically, with a properly sized electric power system, there will not be the need for flying at full throttle or maximum motor current continually, but instead part of the flight would be at part throttle which will result in longer runtimes (flights).

The whole selection process can be helped and made much more precise by several computer software programs available for purchase or, in one case, online. You can perform many what-if cases for proposed systems by selecting different components whose electrical specs have

already been loaded into the program (in many cases). Most of the time, the use of one of these programs is the best way to select the correct range of propellers for a given system. For electric systems, a slight difference in prop selection can make a large difference in system performance. Once a system has been selected and installed in the plane, if at all possible, it should be connected to a “Whattmeter” or equivalent with several different props as recommended by the computer software runs to make sure that maximum currents and input power for the motor and ESC are not exceeded. This measurement of the operating voltage, current, and power will show the relative efficiencies of various props for that system. Measurement of the thrust using an electronic fish scale while doing the electrical measurements is also helpful with the prop selection. I have seen testing results showing that optimizing prop selection can make large differences in power, current, thrust, and flight duration.

Another thing to consider in selecting an electrical system is to be careful of recommendations. There are many ARF aircraft now available from reputable manufacturers that have recommendations for motors, ESC's, batteries, and even propellers. In many cases, the reviews of these aircraft by RC magazines have verified these recommendations as correct. However, if you are trying to select an electrical system for a normally glow or gas powered aircraft, don't rely on a seat-of-the-pants recommendation of a guy at the hobby shop who might say “that motor should work”. I have seen several instances where this resulted in an electrified aircraft with totally insufficient power to even fly, or with very short flight durations.

References

Electrical Computer Software For Purchase

ElectriCalc This software is available for purchase at www.slkelectronics.com/ecalc
This software is listed at \$50, but is available from some vendors for about \$35.

MotoCalc This software is available for purchase at www.motocalc.com/index.html
It is listed at about \$50.

Free Calculator Online

A calculator called **P-Calc** is available on the following website: www.flydma.com
I have used this calculator, and it can be helpful, although there are only electrical data for a limited assortment of manufacturers and motor models, ESC's, and batteries. However, it is fairly easy to pick motors, ESC's, and batteries whose specs have been entered into P-Calc, that have electrical parameters similar to the system you want to evaluate.

Other Online Test Data Sources

1. The Great Electric Motor Test, (Test data for some motors), Available on the following website: www.flyingmodels.org

2. Aircraft Inc, Motor and ESC Data for Some Manufacturers. This is available at the website: www.aircraft-world.com/default.asp?id=18
3. Astroflight Data for many electric flight components, at www.astroflight.com
4. AXI Motors This has an AXI Motor Selector Tool online, and can be found at the website: www.hobby-lobby.com/brushless_axi.htm
5. Motor, ESC, and Battery data are available at most of the manufacturer's websites. Many of the manufacturers can be found by searching www.RCGroups.com and also www.RCUniverse.com