

IR = Internal Resistance of a battery cell or pack. Or the reason for (almost) everything that goes wrong with our packs.

- 1) IR is a primary indicator of your batteries health. If you track each cells IR over time you can spot a bad cell happening before it has a chance to cause the loss of a model or a LiPo fire. You can also tell when its time to retire or dispose of the pack. You can even calculate its true maximum usable discharge C value.
- 2) The cells IR, combined with the current your setup is pulling, is what causes a pack to heat up.
- 3) The cells IR is also what causes voltage drop under load.
- 4) An imbalance in the IR between cells can cause longer charging times, and potentially dangerous over or under charging or discharging of individual cells.

The symbols E, I, R and IR are defined as follows. Remember these all are focused on the **battery alone** and nothing else.

E = voltage drop **across the pack or cell**. NOT the pack or cell voltage at rest or under load or anywhere in between. It's also not the voltage at the motor or its voltage drop. This is difficult to measure directly, so we will calculate it using the formulas below.

I = the current in the circuit

R, and IR = the Internal Resistance of the battery pack. NOT the motor, or esc or anything else in the circuit. This is difficult to measure without special equipment. A quality charger can give you values that are generally close enough to work with. For the most part the absolute value of the IR isn't that valuable to know. Its more useful to know how it changes over time and how each cell IR compares to its mates in the pack.

P = power loss in the form of heat generated **in the pack**. This is in watts. This is NOT the power going to the motor. It's heat loss in the pack.

Your battery has an Internal Resistance, and acts (almost) like any resistor in a circuit. In practice the IR varies with charge state, temperature, and load, but we can ignore all that for now. In the following circuit diagram the battery has a resistance value - IR - and the load has a resistance value. We will ignore the load completely, and focus on the battery side of things.

It's all a matter of Ohms Law: $E_{\text{voltage}} = I_{\text{current}} \times R_{\text{resistance}}$. In this discussion, the E is voltage drop across the cell/pack and NOT the pack or cell voltage. Shifting things around with a little algebra gives the formula for power loss in a resistive load or the heat generated in a battery pack due to its IR. This applies to motor heating too, but thats another topic.

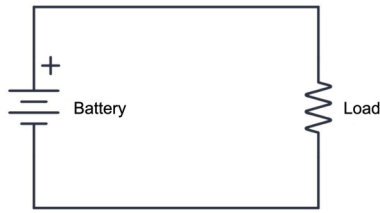
$$P_{\text{watts}} = I^2 \times IR$$

$$P_{\text{watts}} = V_{\text{voltage drop}}^2 / IR$$

$$P_{\text{watts}} = I \times V_{\text{voltage drop}}$$

Any of those formulas will work, but Im going to use the first one: $P_{\text{watts}} = I^2 \times IR$

In this case the “Load” below is your ESC, and motor/prop combo – which we are going to ignore for the most part.



Lets say you're flying a 3S1P battery in a model that should - in theory - pull 50 amps at 12.6 volts. Lets also assume each cell in your battery has an IR of 10mΩ. Thats a reasonable IR for a small, half decent pack you might be using in a glider. Say an 850mAh high C pack. That means the battery as a whole has a resistance of 30mΩ. Fill in the values in the formula for power loss $P = I^2 \times R$, and you get $P = 50^2 \times 0.03 = 2500 \times 0.03\Omega = 75$ watts of heat energy. If you consider that a 7 watt soldering iron will easily melt solder, thats a lot of heat, particularly if you give it time to build up. Hence short motor runs when using small, high C rated packs pulling high C loads. In this case over 40C.

Now imagine that your cells have aged. As they get older the IR increases. I have some older packs that started out with an IR of 6 mΩ, but now are at 18-20 mΩ. That means those older cells, if used in that same setup, will be generating as much as 150 watts of heat! Thats potentially very bad.

The other thing that happens because of the IR of the battery is voltage drop. If your battery had zero IR, then the pack would not have any voltage drop under load. Wouldn't that be nice! The reason for the voltage drop is Ohm's Law. When ever you have a current flowing through a resistor there will be a drop in voltage across that resistor. This applies to your battery and its IR. It seems strange to think that your battery, that is generating voltage in the circuit, has a voltage drop, but it does.

The formula for the voltage drop is $E_{\text{voltage drop}} = I_{\text{current}} \times R_{\text{InternalResistance}}$. In the example above that's $E = 50 \text{ amps} \times 0.03\Omega = 1.5$ volts. So if the pack starts at 12.6 volts, it will drop to 11.1 volts with a 50 amp load. If there was zero IR, and therefore zero voltage drop in the battery, and the motor was pulling 50 amps, the system would be generating $12.6 \times 50 = 630$ watts – in theory. With a 30mΩ IR, you get $11.1 \text{ volts} \times 50 \text{ amps} = 550$ watts. But wait! That lower voltage will mean your motor turns at a lower RPM, and so it will pull even less less current. It will drop to roughly 38 amps for a power out of $11.1 \text{ volts} \times 38 \text{ amps} = 421$ watts. This is what your watt meter will read. That's a loss of 630 watts (in theory), 421 watts in reality, equals a roughly 30% loss in power due to IR alone.

Also note that at 11.1 volts, the cells are already down to 3.7 volts per cell, which is getting close to cutoff voltage from the instant the motor powers up.

That older pack, with the double the IR, will have a voltage drop of 3 volts. So $12.6 \text{ volts} - 3 \text{ volts} = 9.6 \text{ volts} \times 50 \text{ amps} = 480$ watts. But that's before the drop in RPM due to the lower voltage. It will actually be closer to 28 amps, for a power out of roughly 269 watts. Thats a loss of more than 50% in power output due to age and the increase in IR.

Plus, at 9.6 volts the individual cells are down to 3.2 volts the instant you hit the power switch. Thats what I typically use as a cutoff voltage on my ESC's, so this pack is no longer usable as a power pack

for this setup. I would either discharge and dispose of it, or maybe save it for bench testing receivers, etc., or maybe use it in a low power setup, but only with close monitoring. See the next section.

The increase in IR as cells age is why it's a good idea to track the IR of your batteries cells, especially as they get older. You should at least check it every so often as they age. It's important to note that if one (or more) of the cells in a pack has a significantly different IR from the rest, the cells with a higher IR will charge AND discharge faster than cells with a lower IR. That means the voltage on that cell will climb faster than the other cells when charging and drop faster when discharging. That's why it's critical to use a good balancing charger. If you don't, then one or more cells may get over charged – with bad results.

A similar problem occurs when discharging the pack under load. If one cell has a higher IR it will not only get hotter than the other cells, as we saw above, but it will also drop in voltage faster than the other cells because of the higher IR and associated voltage drop across that cell. This can result in one cell being driven below the safe cutoff voltage or even to zero volts. In an extreme case it can even end up with a **negative charge** while the other cells are still fine. That is also very bad news for your battery and possibly your model.

An imbalance in the IR is also why it can take much longer for a pack to fully charge as it ages. This can also be the reason identical packs might charge at different rates and times if one pack has a different overall IR or if one cell has a high IR. The cells with a higher IR will reach full charge sooner than the lower IR cells. That will trigger the balance cycle in the charger. That typically involves the charge stopping while the high voltage cells are discharged down to match the voltage of the lower voltage cells. Depending on your charger that can be a slow process.

Calculating a pack's true maximum discharge rate based on IR.

As we saw above, the IR of a pack can limit its discharge rate by causing too much voltage drop, and triggering a low voltage cutoff situation. Let's say you have a cutoff voltage set at 3 volts per cell, and they start at 4.2 Volts per cell. That's a max voltage drop of 1.2 volts per cell, or 3.6 volts for a 3S pack. The formula is the same one we used above to calculate the voltage drop $E = I \times IR$. In this case $E = 3.6$ volts, so $3.6 \text{ volts} = I \times IR$ where I = the max current you can draw and have a voltage drop of 3.6 volts. A little algebra gives us $I = 3.6 \text{ volts} / IR$. If your battery has a total IR of $30\text{m}\Omega$ as in the example above, that gives us $I = 3.6 \text{ volts} / 0.03\Omega = 120 \text{ amps}$. Now that 120 amps will mean you go into low voltage cutoff instantly, so that's not very practical. I like to use half that voltage drop as a max. So I use 1.8 volts as the max voltage drop. That gives us $1.8 \text{ volts} / 0.03\Omega = 60 \text{ amps max}$. I have some newish 850mAh "150C" packs. My 3S packs actually had a total IR, after break-in, of $21\text{m}\Omega$. So in my case that's $1.8 \text{ volts} / 0.021\Omega = 85 \text{ amps}$. No way are these really 150C packs, unless you're talking 1 second runs, but they can do 100C in short bursts.

Breaking in new packs.

One of the main reasons to break in new packs by cycling them when you first get them, is to lower the IR from its starting point. When you get a new pack, its IR will always be higher in the beginning before it's ever used. Repeat cycling of the pack when it's new, ideally at a 1C or lower charge rate, will lower the IR significantly. For example, I got some new packs recently and the IR started at about $17\text{m}\Omega$ per cell. After about 8 charge/discharge cycles at a 1C charge rate, the average IR had dropped to $7\text{m}\Omega$. If I had just put those packs directly into a model and run them at full power, they would have run about 2.5 times as hot as they would after break-in. That's assuming they didn't just hit low voltage cutoff instantly. That could easily have damaged the pack and likely would shorten its life span, if it

didn't ruin it completely. There was also a significant difference in IR between some of the cells in the beginning – almost 4mΩ. After cycling, all the cells were within 1 mΩ of each other. However, one of the packs had a single cell that was 8 mΩ higher than the others at the beginning, and stayed that far off even after cycling. That's way too big a difference to be safe. I called the dealer and he replaced that pack with no questions.

The bottom line is that IR is an important and powerful tool to use in your battery care and feeding.