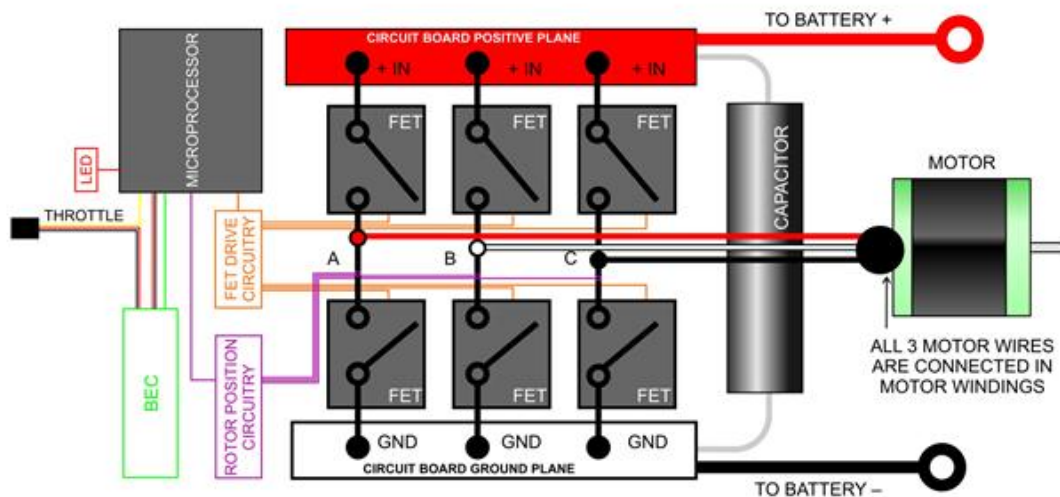**Electric Power Systems 102: Introduction to Electronic Speed Controls**

Mysterious events are often attributed to mystical causes and brushless power systems are about as mysterious as things get in RC. Some systems work and others don't. Why? The usual explanation is something along the lines of "It's a mystery!" Don't get me wrong, the reason for a component failure was no doubt a mystery to most involved, but understanding a bit more detail about brushless systems can go a long way to helping a hobbyist enjoy outstanding reliability in an electric plane or heli.

The quick explanation of the role of the brushless ESC is that it must accurately make and break connections between the three input leads of the motor and the power source in order to drive the rotor's magnets around the arc of the motor. The most accessible way to describe the operation of the ESC is to break it down by its functional sections.

 A brushless ESC uses a microprocessor to manage the operation of the FETs using information from a rotor position circuit. Let's look at each of these a bit more closely.


Caption: There are 4 main functional groups in an ESC. The power MOSFETs, the MOSFET driver circuitry, the microprocessor, and the motor position detection circuitry. A Battery Eliminator Circuit (BEC) is present in some controllers and it serves to reduce the voltage of the motor batteries to a level useful to the radio system in the vehicle.
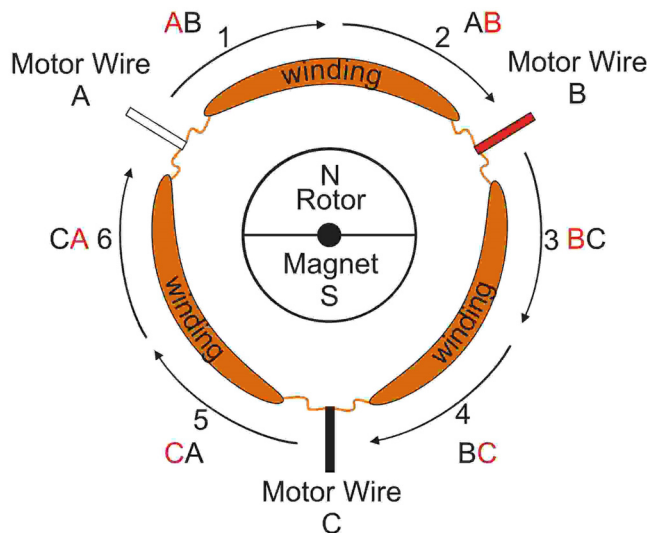
Making the Connection
Before we get too far, we need to understand a few things about the operation of a brushless motor.
1. Brushless motors use three sets of copper windings to push and pull permanent magnets attached to the shaft inside the motor. It's important to understand that
2. These windings are connected at one end inside the motor. There are two ways that this connection is made, one is called the Delta, or D wind and the other is the Y wind. Surprisingly, the controller really doesn't care which of the two is used, they just need to be connected. Keep in mind that the type of connection does affect the torque curve of the motor.
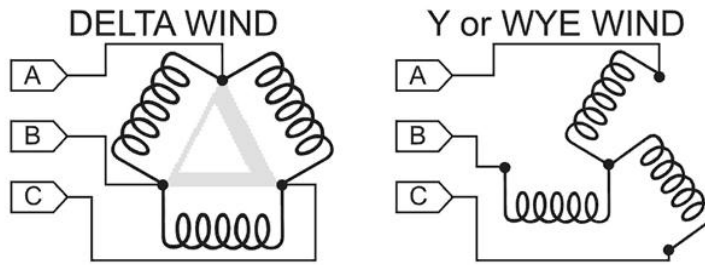
Caption The two wind termination types are known as either a Delta or a Y wind. Delta wind gets its name from the Greek symbol ∆, (delta). It's not much a jump from there to understand the name for the Y wind. Generally speaking, a Delta wind motor will have nearly twice the KV of a similar motor with a Y wind.

Let's call the three motor wires A, B & C, and their "free" ends, the ends that stick out of the motor, are connected to the ESC. The ESC uses electronics to connect any of these wires to positive or negative to achieve one of six possible combinations that result in an electromagnetic field in a precise location in the motor. The timing and duration of these connections is critical, and unbelievably short. Mechanical switches are simply incapable of the task, but high power electronic switches, known as MOSFETs (*MOSFETs – FETs for short – Metal Oxide Semiconductor Field Effect Transistors)* can turn on and off in a fraction of a second and they are ideally suited for this application.


Basic drawing of the connections required to drive a brushless motor. The three motor wires are A, B & C, and they can each be connected to the positive or negative poles of the power source by the ESC. The 6 possible combinations are numbered and the color coded letters indicate connections and polarity at each point in the process. Red indicates connection to positive and black indicates connection to negative.

Let's do a little bit of math to get an idea of the incredible activity going on in the ESC. An outrunner with 12 poles that has a KV (RPMs per volt) of 1,500 that is powered with 24V (6S Lipo) will spin at 36,000 rpm (24 x 1,500 = 36,000 rpm). The 6 coil combinations needed for a full magnetic rotation must be repeated for every north pole in the motor. The example motor has 12 poles, so the controller must switch the FETs 36 times per revolution of the shaft (6 north poles x

6 steps per magnetic rotation). That means there are 1,296,000 electrical cycles per minute (36,000 rpm x 6 winding phases x 6 poles = 1,296,000) or 21,600 cycles per second. The controller must successfully switch between the phases every $1/21,600^{th}$ of a second!

CURRENT FLOW THROUGH A SINGLE CIRCUIT
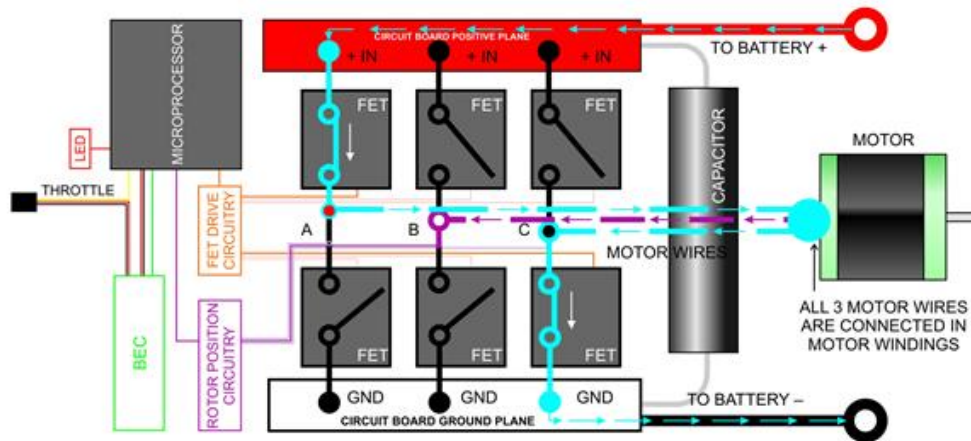
Caption: Current can flow in either direction on each of the three motor wires making six possible combinations of current flow. This diagram shows only one. The blue path traces the current flow from the battery through the FET controlling the "high" side of the red motor wire (A), to the motor windings and back through the black motor wire (C) and the FET controlling that phase's low side. ESCs vary throttle by switching the low side FET on and off rapidly during the period that a phase is powered, this is known as the PWM rate. The purple path traces the "back flow" in the 3rd motor wire (B) of current generated by the motion of the rotor magnets relative to the windings. The rotor position circuitry measures the voltage of this current to determine when to switch the FETs to drive the rotor around inside the motor.

THIS DRAWING NEEDS TO BE LARGE TO BE UNDERSTOOD. THE FINE LINES IN PURPLE AND ORANGE ARE IMPORTANT.

FET Drive Circuitry:
Turning a FET ON and OFF is not as easy as it may sound. Each FET has three connections; the gate, source and ground. In order to turn the FET ON and create a circuit, the gate leg has to be driven to a voltage that is 5 to 10V higher than the voltage of the source leg on the FET which is connected to the motor power source.

For example, if using a 4S LiPo battery, +IN will be around 14.8V (3.7V x 4). The gate requires (14.8 + 10 = 24.8) 24.8 volts for proper operation. The ESC must therefore be able to boost some of the power that it takes from the batteries to the increased voltage to drive the FETs.

Motor Position Detection Circuitry:
The ESC has to know the precise location of the rotor magnet(s) to accurately sequence the connections made by the FETs. This is the trickiest thing that the ESC has to do. There are two main ways to go about this,

- **Sensored**: sensored systems use electronic (Hall) sensors in the motor to track the rotor. This requires additional parts in the in the motor (sensors) and an additional wiring harness to connect the motor sensors to the controller. Sensored motors and controllers are popular in RC car applications as they provide a slightly smoother motor start than the second approach, the sensorless controller. Sensored systems were popular in the early days of R/C brushless aircraft power systems, but they are generally considered to be less reliable and less efficient than sensorless systems, therefore they are no longer popular for RC aircraft applications.
- **Sensorless**: modern ESCs can detect the rotor's position *through* the power wires by "listening" to the third wire for signs of motor position while the power to the motor is

applied to the other two leads. The changing magnetic field caused by the spinning magnets in the motor actually generates a voltage in the third wire and sensorless ESCs detect and measure this voltage to determine how far the rotor has turned. This information is then used to switch the FETs as needed to cause the correct magnetic push or pull in the phases.

The Microcontroller and its Firmware:
The microcontroller is the "brain" that runs the whole operation. Running a brushless motor takes tremendous computing horsepower and better controllers use processors that operate at 25 MIPS – 25 million instructions per second! Controllers with less capable processors may be unable to process the data quickly enough to run high pole count motors at high speed because they hit a computational redline long before the motor reaches its full rpm/power capability. This is particularly true with high pole count outrunners in high rpm (geared) applications, such as helis.

Microcontrollers run software in much the same way that computers run programs. The software must manage a number of processes taking place simultaneously in the motor/controller system. We've already discussed how the controller switches the FETs and keeps track of the motor position, but don't forget that the microcontroller also has to process the input from the receiver to compute the desired output power and flash indicator LEDs. Of course the user may not want to run at full-throttle all of the time, so we have to be able to limit the output power by pulsing those FETS in between the usual positional pulses. If that's not enough, there may be special routines that govern the motor speed, record data, monitor battery voltage, watch for over current or over temperature conditions and manage the activities of the switching BEC. There is a lot going on here!

Input Capacitors
The large tubular devices that are an obvious part of most ESCs are capacitors. These are essentially fast-acting reservoirs for electrical power and ESC designers use them to smooth out the power as it enters the controller, but why is this an issue at all?

Remember that the FET gates need to see a stable voltage to operate properly. In practice, the voltage that comes from the battery is not a constant value; a graph of battery voltage would actually looks like spurts of voltage. Each spurt starts at a higher level than it ends at during each power cycle of the FETs, however incredibly brief. A graph of this would look like a ripple. This changing voltage is called RIPPLE VOLTAGE. ESC designers can smooth this ripple out to some extent by using capacitors, but there is a limit to how much the capacitors can fix.

The FET gate must have a voltage that is 10V higher than source. If the **source** is crashing down and recovering up a bit between each cycle, there is a possibility that the voltage in the gate circuitry may unexpectedly meet/exceed the 10V margin over the source voltage in the FET – this causes the FETs to turn on unexpectedly -- and create nasty connections in the controller that almost always lead to a bad day at the field. (It's not really such a bad thing if the FETs turn off… it is when they all turn on at the same time that the smoke comes out.)

Advanced Topics in ESC Design include the following, any one of which would provide plenty of material for an engineering graduate paper. The following are very simple descriptions.

Controlling Speed
Running at partial throttle is just a more complicated case of running at full throttle. Instead of leaving two FETs (positive and negative) "on" for the entire period of the motor pole's transit of the motor winding, one is turned "on," while the other is pulsed on and off very quickly to reduce the average power seen in the winding. At low throttles this second FET is barely on at all, but it is on almost the whole time near full throttle. The frequency (times per second) that we pulse the power for speed control – not the polarity switches that drive the motor -- is called the **PWM rate**, or switching frequency.

One of the paradoxes of brushless motor controllers is that partial throttle operation actually generates more ESC heat than full throttle operation. FETS have a very small resistance when they are fully "on" and current is flowing through them. This generates a relatively small amount of heat but it is not a significant amount. As always, there's more to it. FETs don't just go from an ON to an OFF state, there is a bit of a ramp to the process, a period where the FET is neither open nor closed. Electricity can flow through the FET during these periods, but the resistance in the FET is much higher than when the FET is fully ON. This leakage across a high resistance generates a significant amount of heat. At partial throttle, the FETs are required to cycle much more rapidly than at full throttle, so a great deal more heat is generated at partial throttle than at full throttle. Similarly, more heat is generated in controllers set to run at high switching rates than those set to run at lower switching rates.

Hardware Voltage Limitations – 4S, 6S, HV
Brushless ESCs are generally rated for a very specific range of voltage. This is due in part to the voltage rating of the FETs themselves. Generally speaking, higher voltage FETs are usually more resistive than lower voltage FETs, so higher voltage controllers will require more FET capacity than lower voltage controllers to handle the same amount of current. The drive circuitry must also be modified to handle the higher voltages.

The FET voltage limitation is a hard number. Exceeding the FET's voltage limit usually results in instant destruction of the FET. Always pay attention to the voltage limits recommended by the ESC manufacturer.

Hardware Amperage Limits – 10 amps, 25 amps, 35 amps…
Unfortunately, amperage limitations are not always black and white. Here's a list of considerations that determine the current an ESC can handle successfully:

- There is a current above which the silicon inside the FETs or the metal legs or connections on the FET break down and fail. Damage from excessive amp draw takes place in an instant. Think of a fast acting fuse, except and ESC is not usually considered to be expendable. It is very hard to anticipate high currents and shut the controller down in time to prevent the current spike from damaging the controller.

- Partial throttle operation generates more heat as does high PWM rates.

- The amperage capability of an ESC is limited by the ability of the device to dissipate the heat generated by the resistance of the FETs and circuit boards. If a controller is making more heat than it can dissipate, a "runaway" condition occurs which can lead to thermal destruction of the controller -- the solder holding the components to the boards literally melts and the parts are free to float away.

A great way to rate a controller is to determine its "steady state amperage." That is the maximum current it can carry at its rated voltage without experiencing further temperature rise. This can vary a bit as the temperature rise is dependent on the ambient air temperature and the amount of cooling airflow over the ESC. A dangerous way to rate a controller is to state its "surge" or "burst" capabilities. These are an indication that the controller may be able to handle higher currents for short periods, but these periods are sometimes shorter than the pilot would hope. This is another area where manufacturers can rate their products' based upon their own, often ridiculous, definition of a controller's duty cycle. Always read the fine print.

Conclusion:
Much like the proverbial duck on the water, things look calm on top but there's a whole lot going on inside a brushless motor controller. A great deal of engineering goes into the physical design and the software is surprisingly complex. Always use a power system inside its performance envelope for best performance and reliability.

S08

POWER PACK

DRAIN

DRAIN

GATE SOURCE

GATE SOURCE
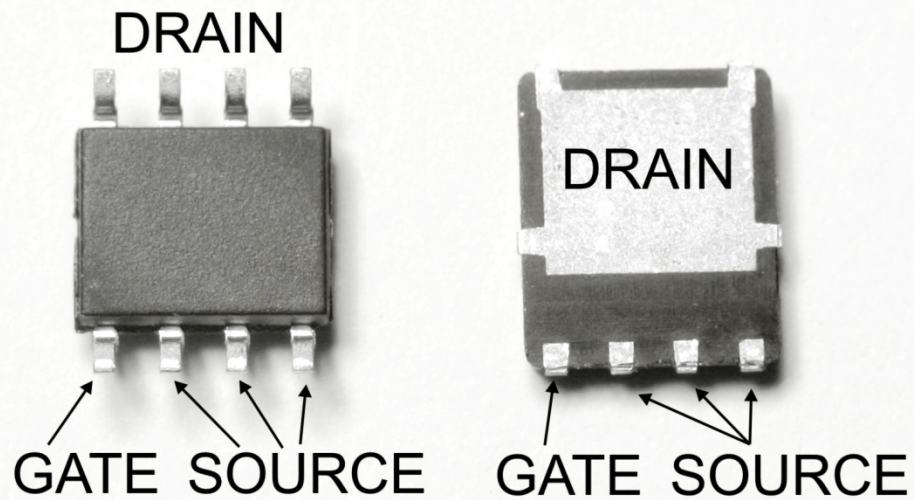
Improvements in FET packaging, the way that the internal silicon components are connected to the circuit board, play a huge role in the improvement of ESC over the past few years. The older S08 packaging on the left connects with the tiny legs while the huge Drain pad on the newer Power Pack FET on the right provides a much larger connection to the circuit board. The net effect of this is that much more of the heat generated in the Power Pack FET can be transferred directly to the circuit board.
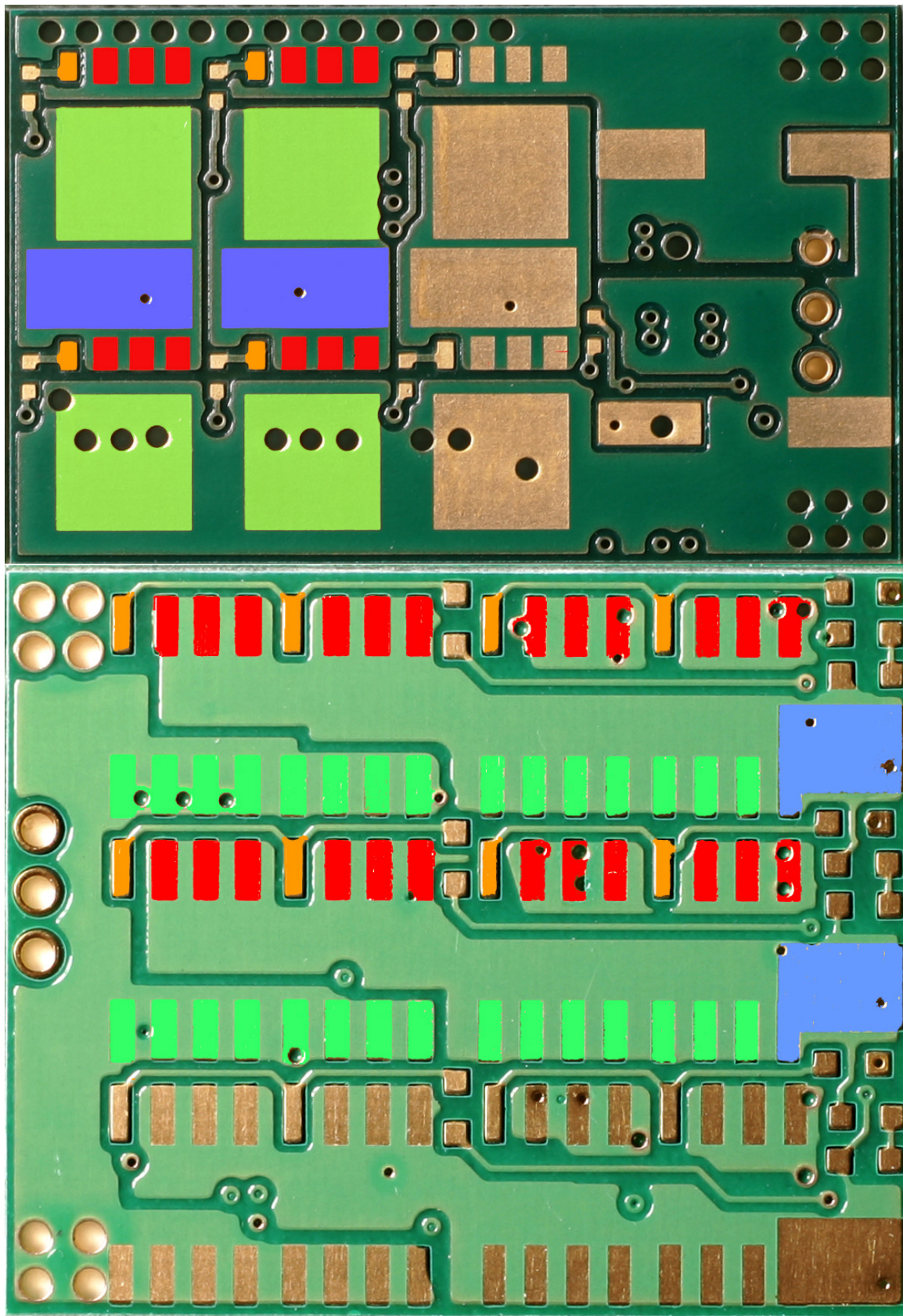
ESC power boards designed for the Power Pack FETS (top) and the older S08 FETS (bottom). Two of the phases are color coded, blue pads = the motor wire connection, green and red pads = the FET drains and the sources, and the orange pads = the gate connection.