Electronic Speed Controls and RC Motors

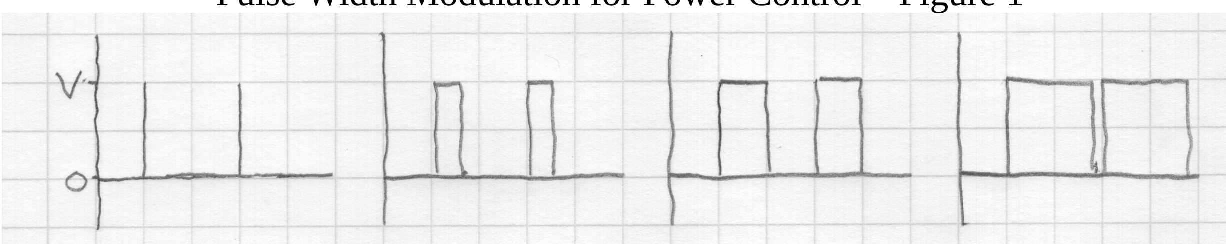
ESC Power Control

Modern electronic speed controls regulate the electric power applied to an electric motor by rapidly switching the power on and off using power transistors, typically FETs, or field effect transistors. The amount of power is regulated by PWM, or pulse width modulation. The width, or time duration of a pulse, can be varied from zero, essentially no pulse at all, to 100%, or a pulse that is constantly on, or any proportion in between.

A control on a radio control transmitter typically sets the position of a servo arm using a different PWM protocol. This protocol was adopted long ago in the history of RC so that servos could be compatible with different radio systems. The servo control protocol uses a constant 50Hz base frequency and pulses between 1 and 2 milliseconds to set a servo arm position anywhere between two extremes.

An ESC attached to the throttle control channel interprets the servo control PWM to set the pulse width for the ESC’s power control PWM. The power control PWM uses a much higher frequency, typically 20kHz to 50kHz, because higher frequencies are more efficient for power control. Keep in mind that PWM for servo position control and PWM for power control are two separate applications of the same principle.

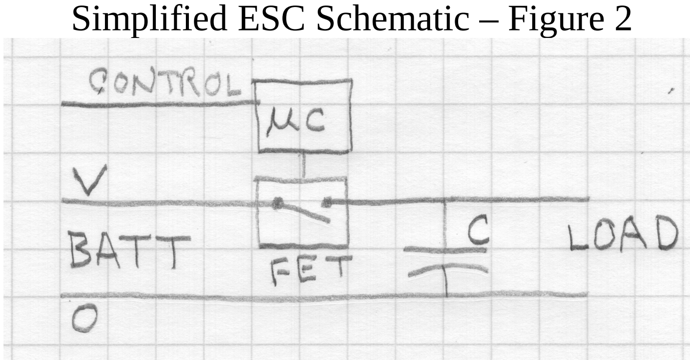
Pulse Width Modulation for Power Control – Figure 1



Very Narrow Pulse Near 0%	Narrow Pulse 25%	Half Width Pulse 50%	Wide Pulse Near 100%

The pulses in Figure 1 control power by the proportion of time the FET is switched on. A short duration pulse near zero duration delivers near zero power, a pulse half the duration of the base wavelength delivers half power, and a pulse of full width delivers full power, and so on in proportion to the pulse width.

Simplified ESC Schematic – Figure 2



The CONTROL signal in Figure 2 is decoded from the servo control PWM in the receiver and switches the power FET on and off using the high frequency power control PWM. A small microcontroller makes the conversion. Note that when switched on the full supply voltage from the power battery is delivered to the LOAD, and to the capacitor C. The capacitor charges almost instantaneously, limited by the internal resistance of the supply battery, and serves as a temporary storage of energy. When the FET is switched off capacitor C continues to supply voltage to the load until it is discharged. If we connect a voltmeter to the load what we see will be a time average of the supply voltage smoothed out in proportion to the pulse width.

For example, if the supply voltage is 12 volts, and the pulse width is 25% of the PWM wavelength, the average voltage at the load will be 3 volts and the motor will turn at about one quarter of its maximum RPM, and so on between 0 and 100% of the throttle position.

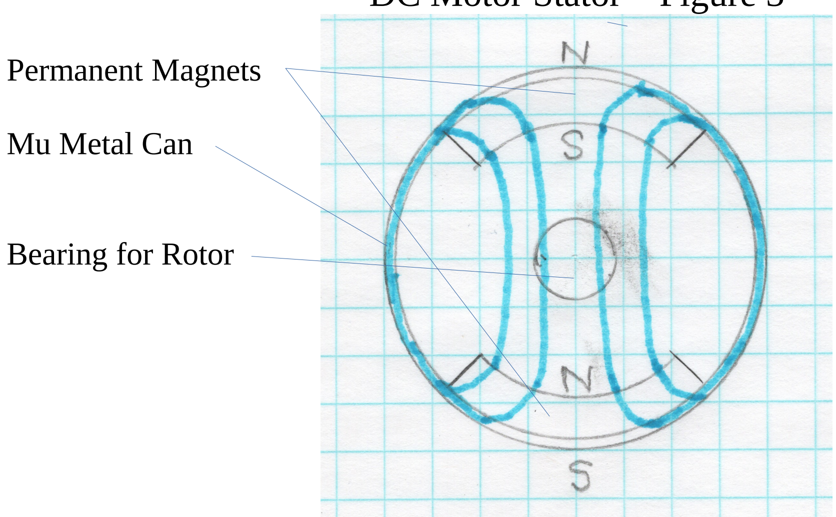
This description of ESC power control applies to both brushed motor/ESCs and brushless motor/ESCs.

Brushed Motor Basics

Brushed motors use a commutator to switch current to different windings in the armature as the rotor turns. This causes the electromagnetic field produced by the armature to pull against the field of the permanent magnets in the stator, and the resulting torque to turn the rotor. Angular momentum causes the armature to rotate to the next set of contacts for the next set of windings.

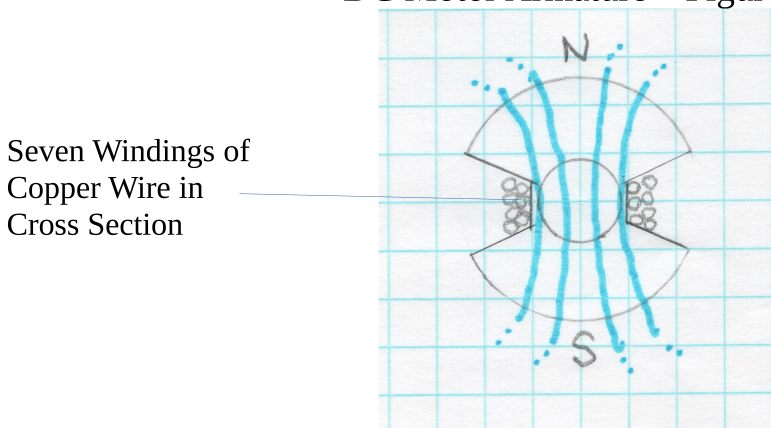
Simplified Brushed Motor Components

DC Motor Stator – Figure 3



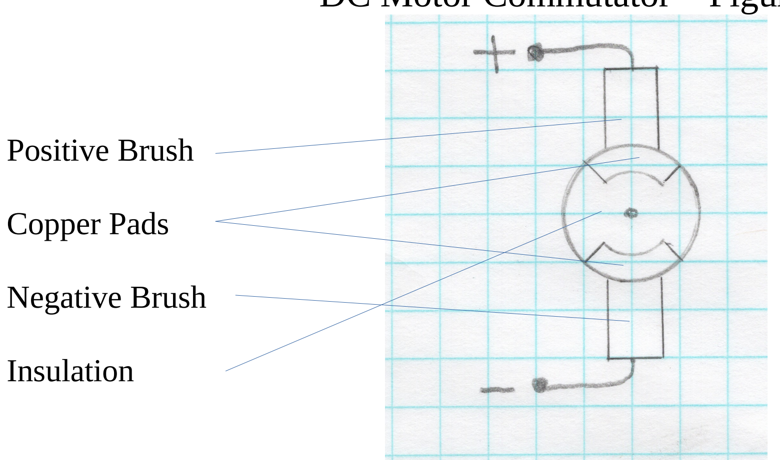
Typical brushed motors, also called DC motors, use multiple magnets and multiple windings for added torque. In this simplified DC motor, Figure 3, a cylindrical can holds two permanent magnets which are shaped as cylindrical sections. The magnetic poles are facing inward and outward, perpendicular to the axis of rotation. This sets up a strong magnetic field inside the cylindrical space between the two magnets shown by the bold blue lines of force between the inward facing north and south magnetic poles. The Mu metal can is made of an alloy with high magnetic permeability which means it is highly conductive for magnetic lines of force. This is shown by the outer magnetic lines of force in blue collapsed into the surface of the can. The Mu metal also serves to shield the outside environment from the strong magnetic forces that interact within the motor.

DC Motor Armature – Figure 4



The armature is built on the motor shaft using thin layers of Mu metal in a cylindrical shape to minimize the air gap between the armature and the permanent magnets in the stator as shown in Figure 4. As an example, seven windings of copper wire are shown in cross section wound in two gaps cut into the Mu metal armature. When a current is passed through the winding a strong electromagnetic field is created shown by the bold blue lines of force. If the direction of the current is reversed the magnetic north and south poles also reverse. A commutator with brushes is used to control the current connected to the winding in the armature. Seven turns of wire in the windings is typical of a moderately hot DC motor.

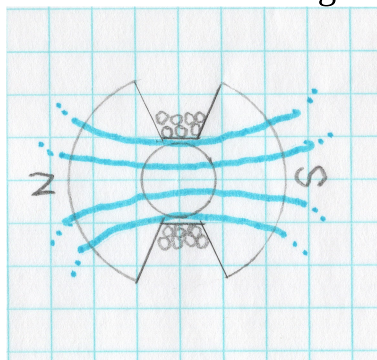
DC Motor Commutator – Figure 5



The cylindrical commutator as shown in Figure 5 is mounted on one end of the armature shaft with contact brushes fixed to the stator can. The pair of copper contact pads are soldered to the ends of the armature winding, and the brushes are fed with DC electrical power from a source such as a battery or an ESC for a brushed motor.

Now suppose the complete rotor assembly with armature and commutator is assembled into the stator with the electromagnetic poles rotated 90 degrees as shown in Figure 6.

Armature Rotated – Figure 6



And suppose the commutator brushes and contact pads align so that current flows in the winding and produces an electromagnetic north pole on the left as in Figure 6. The poles in the armature will be strongly attracted to line up with the magnetic field in the stator, as in Figure 3, north attracted to south and so on. This produces a clockwise torque that rotates the rotor, which then disconnects the brushes until angular momentum carries the rotor further to reconnect the brushes in the reverse direction creating a new electromagnetic field that continues the clockwise torque.

Brushes make the DC motor possible, but the brushes are also the biggest source of inefficiency. First, brushes sliding over the commutator causes friction that wastes mechanical energy. Springs are used to press the brushes into contact and the stronger the springs the greater the friction. Second, the sliding electrical contact is an imperfect conductor and is a source of electrical resistance that wastes electrical energy. Weaker springs would reduce friction but increase electrical resistance due to poorer contact. Third, as the current to the armature winding switches on and off arcing occurs which is current jumping across an air gap, which adds resistance to the flow of current and wastes more energy. Finally, brushes and commutators wear out due to friction and arcing and eventually require maintenance.

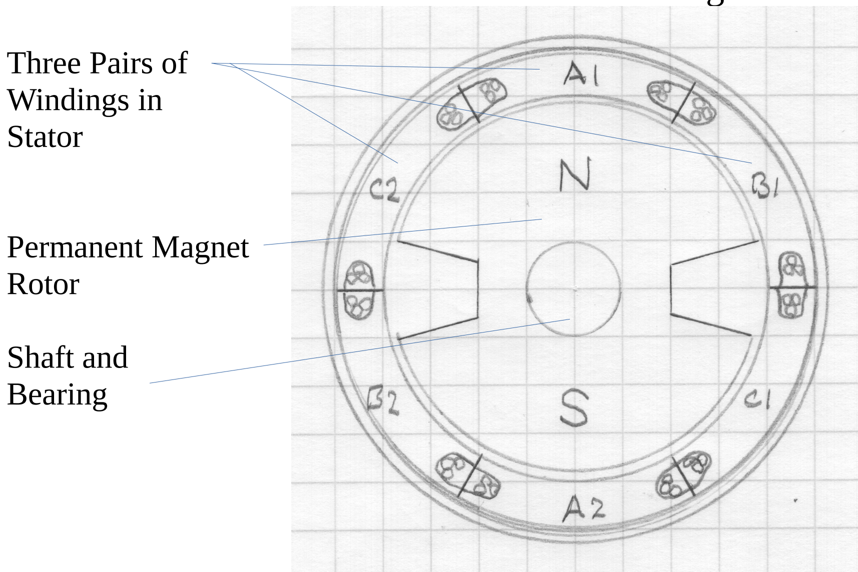
Three Phase AC Motors

How can we make an efficient motor for our hobby use without any brushes? We take a hint from industrial three phase AC motors; they have no brushes, have a history as long as DC motors, and are known to be very efficient.

Three phase AC power generation and distribution has been around since the beginning of widespread electrification of America and the world. Let's begin by examining a simplified three phase motor, Figure 7, that happens to have the same configuration as a three phase AC generator.

Brushless motors for hobby use have been made in two popular forms: inrunner and outrunner.

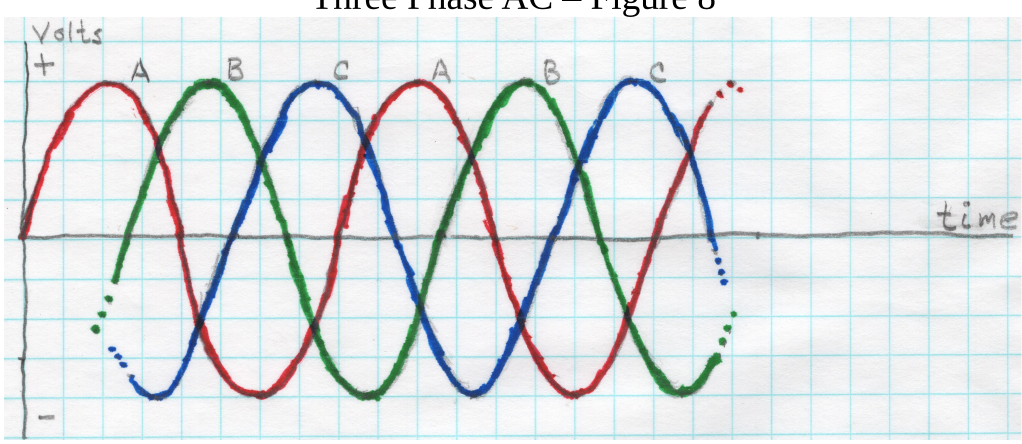
Brushless Inrunner – Figure 7



An inrunner mounts the permanent magnet on the rotor and the electromagnetic windings inside the Mu metal can of the stator. An outrunner mounts the magnets on the inside of the Mu metal can and the windings on the center shaft. Then the shaft is mounted to the airframe of our RC model so the windings need no brushes for electrical connection, and the propeller is mounted to the outer can that rotates around the stationary inner shaft.

Back to our example motor/generator in Figure 7, if an external source of mechanical energy can be connected to turn the shaft then three phase AC power will be produced according to the laws of electromagnetism. When the permanent magnet rotates the magnetic lines of force sweep through each pair of windings. If we connected an oscilloscope across the pair A1, A2 we would see the red sine wave in Figure 8 producing one complete cycle for each rotation of the magnet. Each pair of windings will produce a sine wave of alternating voltage spaced 120 degrees from the other two as shown by the colored sine waves A, B, and C.

Three Phase AC – Figure 8



There are two common ways to connect the pairs to three terminals called Delta wind and Y wind. Most brushless motors for hobby use are now using Y wind so that is what we use in this example. Delta wind, as the name implies, connects the three pairs of windings in a triangle.

Y Wind – Figure 9

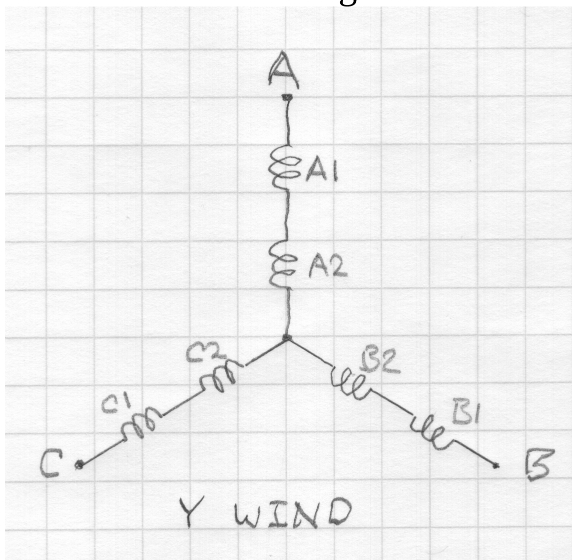


Figure 9 shows the internal connections of the three pairs of windings in the Y wind and the three external electrical connectors, A, B, and C. If mechanical energy is used to rotate the shaft three phase AC will be produced at A, B, and C as sine waves separated by 120 degrees.

If we take this experiment to the next level we could connect an identical motor/generator to the A, B, and C connectors of the first one. When the shaft of the first is driven by an external source the second motor will turn synchronized to the first. The amplitude of the AC, measured peak to peak, will be proportional to the mechanical energy applied as determined by the RPM. The frequency of the AC will be exactly determined by the RPM. The rotation has to be fast enough to generate current to overcome the internal friction in the second motor, then they will turn in sync.

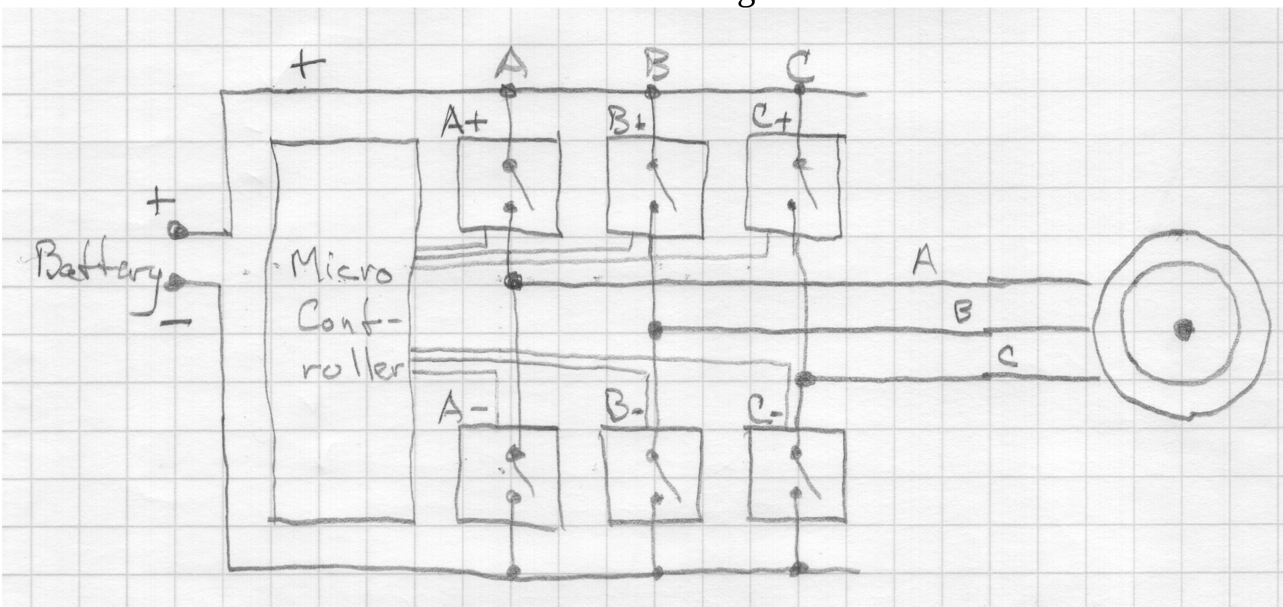
Brushless ESC

How can we generate three phase AC from a DC battery to run our brushless hobby motors? We use a microcontroller and FET power transistors. We need to switch each of the three phases between the positive battery supply, the negative supply, and off. For this we need six FETs in pairs. We'll call them A+, A-, B+, B-, C+, and C-, as shown in Figure 10. We don't need to worry about generating smooth AC sine waves because it is more efficient to switch power on and off.

We are going to have to go through a cycle of steps switching FETs on and off to force the magnetic rotor through one complete revolution. Suppose we start by switching FET A+ on. Nothing happens until there is a return path through terminal B or C. Next energize C-, so current flows through windings A1, A2, C2, and C1 as in Figure 9. Suppose the current through the A and C windings produces a magnetic field that turns the rotor left, counter clockwise, about 60 degrees. Now turn A+

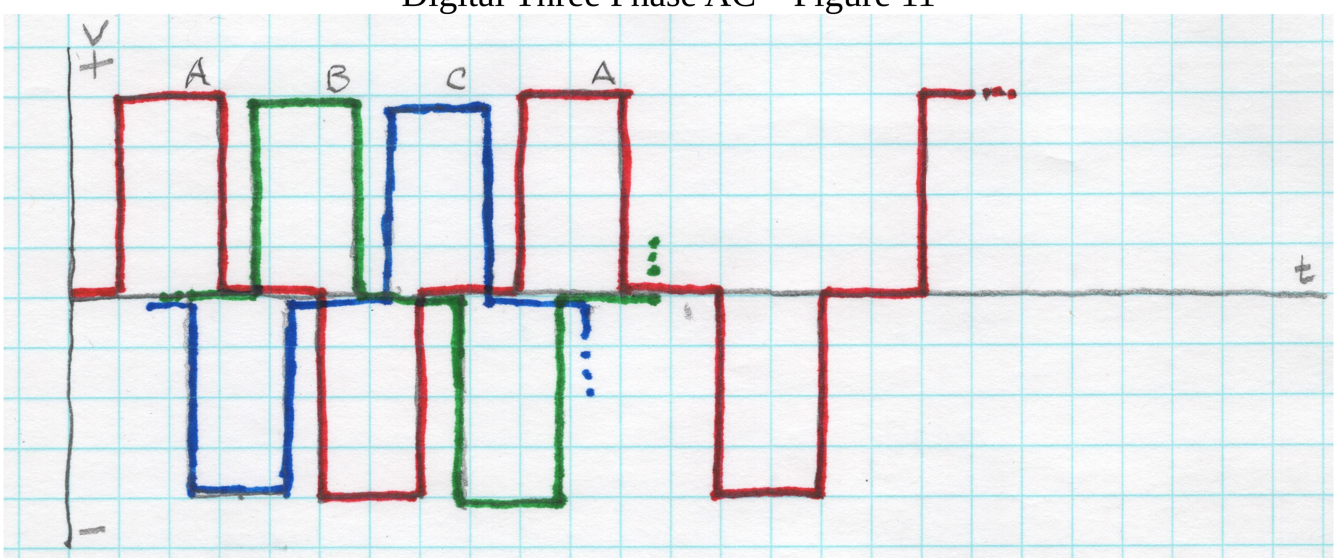
off, and then B+ on, this turns the rotor another 120 degrees CCW. Now turn C- off and then A- on. You can probably see how the pattern works by now.

Brushless ESC – Figure 10



Digital three phase AC shown in Figure 11 can help work out the sequence for switching the FETs on and off. Note how the peaks, both positive and negative in Figure 11 correspond to the peaks and valleys of the sine waves in Figure 8.

Digital Three Phase AC – Figure 11



Here is the complete startup and run sequence:

1. A+ on 2. C- on 3. A+ off 4. B+ on 5. C- off 6. A- on 7. B+ off
8. C+ on 9. A- off 10. B- on 11. C+ off 12. A+ on 13. B- off 14. C- on

Then repeat at step 3.

In order for the brushless motor to continue running the frequency of the simulated digital AC must stay in sync with the rotation of the rotor. If they fall out of sync, say due to a crash or stalled propeller for some other reason, the motor may burn up its windings or mechanically damage itself. To keep the AC pulses in sync the microcontroller must know where the rotor is in its rotation, and how fast it is turning. Early versions of brushless motor used separate sensors and leads to detect the position and speed of the rotor. Then a way was discovered to detect the position and speed without additional sensors, making sensorless brushless motors possible.

As the rotor turns powered by two of the power terminals there are moments when the third terminal is not connected to a power FET. During this interval a sensitive circuit on the unattached winding can detect the position, direction, and speed of rotation. This is because the rotor magnet is rotating and its magnetic field induces a voltage in the unattached winding. This signal can be interpreted by the microprocessor to determine that the rotor is where it is supposed to be within limits or adjust frequency and power accordingly. A detector circuit can be attached to each of the three terminals and determine the speed and direction of rotation for each 120 degrees of rotation..

The microcontroller determines the frequency of the digital AC pulses and this determines the RPM of the rotor according to the throttle control signal. The microcontroller must also regulate the power supplied to the motor using high frequency PWM superimposed on the digital AC pulses. These two parameters, RPM control, and voltage control, are built in to the programming of the ESC microcontroller, or may be programmable in some advanced models.

Matching Brushless ESC and Motor

The best way to match a brushless ESC with a corresponding motor is to buy them together from the manufacturer, typically in an ARF or other almost ready to fly model. If the ESC and motor are not well matched the result can be lost efficiency and overheating. For example suppose you try to use a brushless ESC rated at 60 amps with a motor rated at 20 amps. With a DC motor and ESC this is not a problem because the DC ESC controls only one parameter, voltage versus throttle control. But the 60 amp ESC is designed and tuned for a 60 amp motor that develops its power at a lower RPM than the smaller 20 amp motor. Even though you reduce the available supply voltage, ie. number of cells, for the 20 amp motor the ESC is mismatched to the motor and the result is reduced efficiency and can be seen as overheating of the motor or ESC or both.

The next step would be to use the more advanced programmable brushless ESCs. But that is beyond the scope of this discussion.