Brushless DC Motor Primer

By

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Last Revision: July, 2008

Foreword

This primer on brushless DC motors has been written for the benefit of senior management executives of OEM companies in whose products, the electric motor is a major cost and feature component. The focus of this primer is permanent magnet brushless DC motors (BLDC), sometimes referred to as ECM (Electronically Commutated Motors).

The material has been written from the stand point of top management. It has technical depth but is really meant to be used as a tool for senior management to get a quick and broad overview of the technology and the underlying pros and cons.

It is my intent that the material presented will quickly make the reader well versed with the technology and give him or her a deep understanding of major impact of BLDC technology on their own competitiveness. Most important of all, the material is designed to point out ways in which the technology can be harnessed to advantage. Conversely, the material also points out the perils of ignoring these profound changes in the motor technology landscape.

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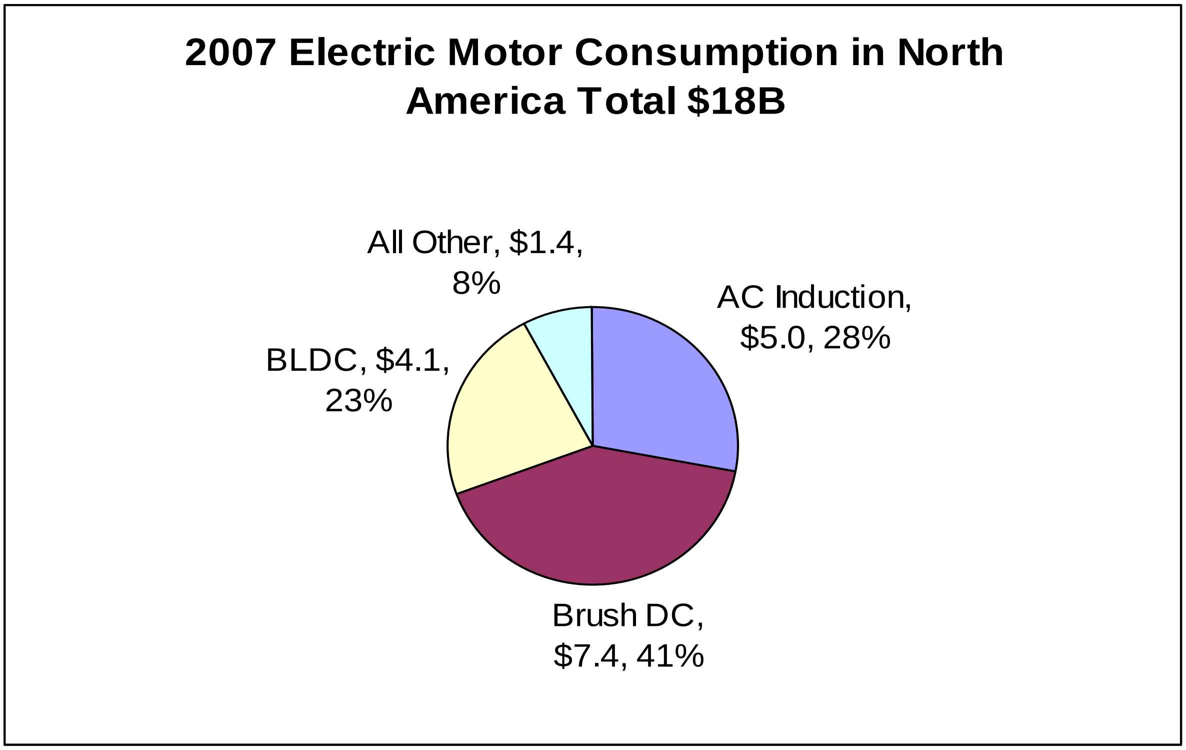
July, 2008

Overview of the Electric Motor Business in North America

According to some estimates, the overall consumption of electric motors of all types in North America will be $18 Billion by 2007 up from $14 Billion in 2002 with an annual growth rate of 5%. The breakdown of this overall picture of consumption by motor technology looks as follows for 2007[1].



The consumption of electric motors is heavily influenced by the automotive industry and consumer applications. A majority of electric motors used are brush type DC motor, followed by AC induction motors and brushless DC (BLDC) motors. All other category of motors include, AC/DC motors called "Universal" motors used in appliances and stepper motors, used in low end position control applications.

With this broad picture presented above, it is now relevant to look at the details, differences and applications of the various motor technologies.

[1] Source: MTT NA Market Model. www.motioninfo.com

Motor Technology

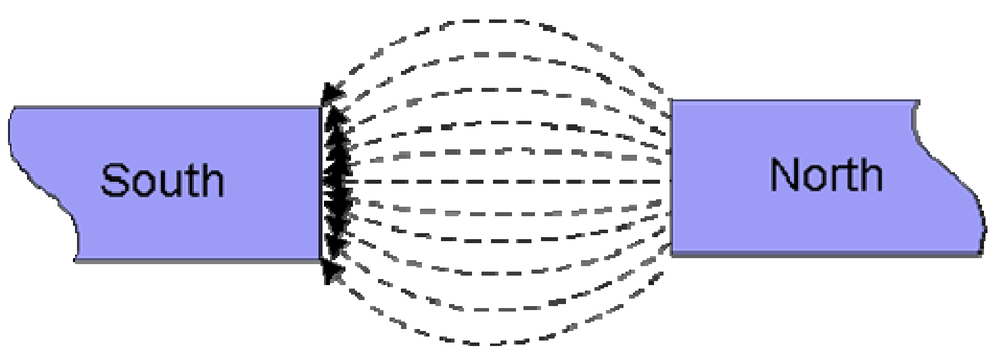
General Principle of All Electric Motors:

All electric motors have a common principle in that they function as converters of electrical energy to magnetism to mechanical rotating motion. The underlying way in which this conversion takes place is fundamentally the same in all types of electric motors. The differences lie in the details of the manner in which magnetism (magnetic field) is generated to get rotational force or “torque”.

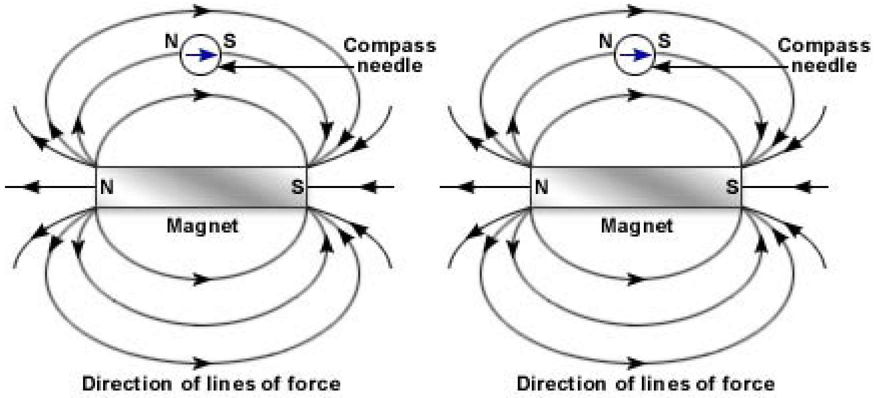
Underlying Basics of All Types of Electric Motors

Electrical Energy → Magnetic Energy → Mechanical Energy (rotating force: torque)

From fundamentals, we know that bar magnets have invisible lines of force around them and flow from the North Pole to the South Pole.



The concept of magnetic attraction and repulsion

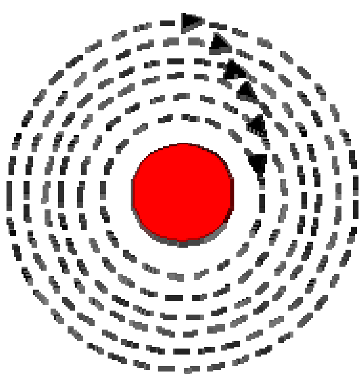


When magnets are brought close to each other, they generate a force of attraction (with adjacent unlike poles) or repulsion (with adjacent like poles). The generation of the mechanical force is fundamental to the way in which all electric motors operate. It can be intuitively seen that to get greater electromagnetic force, the following notions are true:

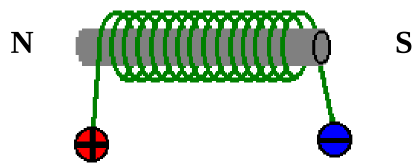
- Larger magnet area will result in a larger electromagnetic force.
- More powerful magnets will result in a larger electromagnetic force
- If the magnets are brought closer together (reduced air gap), the electromagnetic force can be increased.

As an extension to the fundamental notion that like poles attract and unlike poles repel, we can look at an "electromagnet" generated by the flow of current through an electrical conductor. So, in place of a permanent magnet pole, we now have a electromagnetic pole. In the following picture, imagine the current is flowing in a conductor through the paper. Magnetic lines of force are generated around the conductor as shown.

The Concept of a magnetic field generated by a flow of current in a wire.



The Concept of an Electromagnet….. current flowing through "N" number of turns of wire

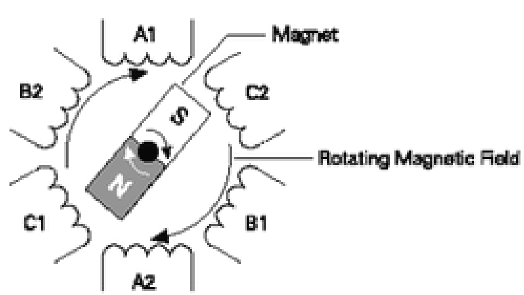


So, we have a conversion of electrical energy to magnetic energy… the force of attraction or repulsion between magnetic poles.

Now, if we introduce the concept of a rotor (moving magnetic poles) and a stator (stationary magnetic poles) we can see how rotating movement may be generated.

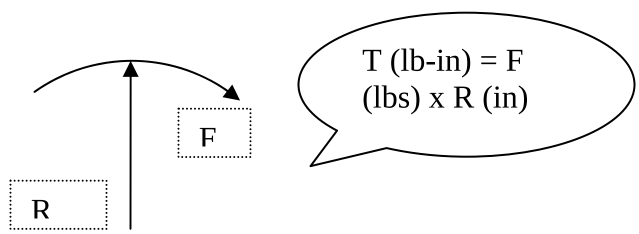
If there are just two poles one north and one south, there will be attraction between the two and they will line up. The force with which they will line up will depend on the current flowing through and the number of turns if they are electromagnets or the strength and the size of the magnets, if they are permanent magnets. If one of these poles is somehow moved to an adjacent spot, the other magnet will follow. If it is moved again, its mate will follow again and a rotating motion will be achieved by this "rotating field". The rotating force will depend on the strength of the magnets, the air gap and the length of the fulcrum – the torque arm.

The Concept of Rotating Field



Before getting into the differences in the various types of motors based on how the rotating field is generated, we now introduce the concept of torque, which is a very important concept in the study of electric motors and common to all types of motors. After all, the purpose of an electric motor (any type of electric motor) is to generate torque (or rotating force). By definition, torque is the rotating force x the distance at which the force is being applied. So, intuitively we can see that in order to get greater torque, we need to either increase the force (stronger magnets, more current) and increase the distance at which this force is being applied (physically larger magnets)

The Concept of Torque



T (lb-inches) = Force (lbs) x Distance (inches)

Or in the metric system:

T (Newton-Meters) = Force (Newtons) x Distance (meters)

The next important concept in the study of electric motors is the concept of "Power". In a rotating device such as an electric motor, Power has two elements: the rotating force (torque) and the speed at which this power is being applied. The product of torque and speed is the power in watts. This is the same concept electrically, where the power is the product of Volts x Current.

The Concept of Power

Power = Speed x Torque
Watts = Speed (Radians/sec) x Torque (Newton-meters)
746 Watts = 1 Horse Power

Electrical Power = Volts x Current (amps) = Watts

To finish the discussion, we now introduce the concept of efficiency. Efficiency is not only important from the stand point of how much electricity is consumed but also, everything else being equal, a higher efficiency motor will generally require lesser amount of materials to produce a given amount of power. This of course has implications on the overall cost of the motor. There are nuances relative to real power versus imaginary (not in phase) power, but the following box illustrates the general concept of efficiency.

The Concept of Efficiency

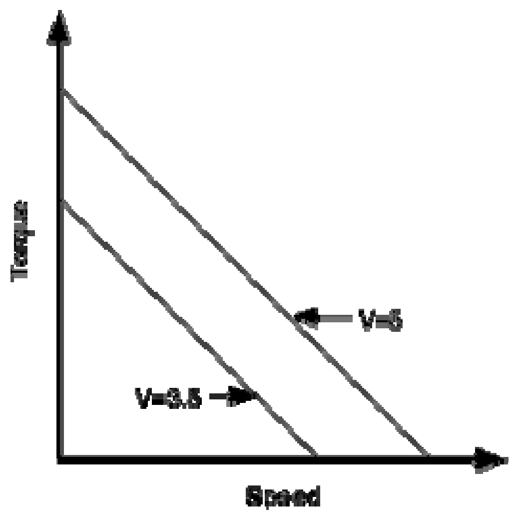
Power output ➔ Po
Power input ➔ Pi
Losses ➔ Po-Pi

Efficiency ➔ $\frac{\text{Power Output (Po)}}{\text{Power Input (Pi)}}$ % = $\frac{\text{Speed x Torque}}{\text{Volts x Amps}}$

One other important concept in the study of motors, before we get into the different types of electric motors is the concept of the speed torque curve or speed-torque chart.

Any type of electric motor produces rotating force (torque) at a given speed. Intuitively, as the torque is increased (for example when the motor is loaded down such as with a brake), the speed will decrease. The overall power output remains the same less of course any loss in efficiency, but the product of the speed and torque (the power) remains the same. A useful concept to describe the performance of a motor is the speed-torque curve. This is a fundamental way in which the performance of any motor is characterized. Here is an example of a speed torque curve.

The concept of a speed-torque curve… Speed is commonly called out in RPM (or Radians per second) and the torque in lb-inches (or Newton-meters). As the voltage is increased, the speed-torque envelope moves upwards.



CHAPTER 2: DIFFERENT TYPES OF ELECTRIC MOTORS

Induction AC Motors

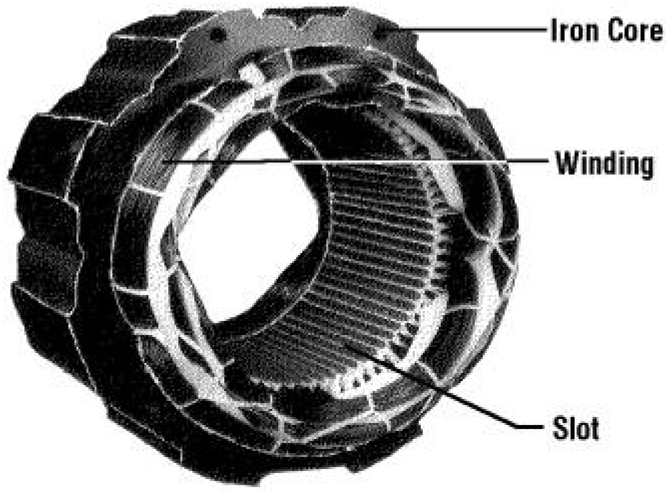
Earlier we introduced the concept that all electric motors shared the common underlying principle which converts electrical energy to magnetic energy to rotating mechanical energy. We also introduced the concept of a rotor and stator and the rotating field which results in rotational movement. The different types of motors result from the various clever ways in which the rotor and stators are constructed and the manner in which the rotating field (which is essential to rotating movement) is generated.

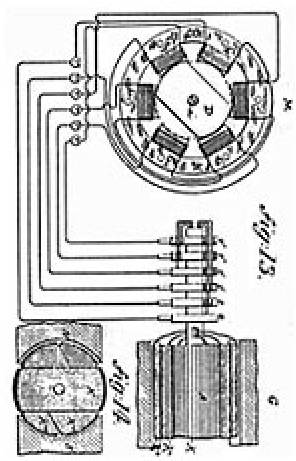
In an induction motor, the rotor is the inner part and the stator is the external part. The AC electrical current is fed into the stator. As the sine wave of the AC electrical current goes up and down, it creates a rotating field. The rotor consists of a series of bars which are welded together at either end. The current is "induced" in the rotor from the electrical field in the stator. This current circulates in the bars of the rotor and the magnetic field generated by it reacts with the stators field. As the magnetic field in the stator rotates, the rotor follows and rotating force (torque) is generated.

The AC induction motor was first invented by Tesla in 1888. It works on the rotating field principle from an AC current source. It is rugged, almost unbreakable, cheap to manufacture and the motor of choice whenever the source of power is AC.

AC Induction motor rotor.

AC Induction Motor Stator





This diagram from
an 1888 patent shows
Tesla's AC induction motor

Even though it has been nearly 120 years since the invention of the AC induction motor, it is still a motor of choice, especially when the power source is AC and not battery operated DC. There have been improvements in materials over the years but the basic principle has remained essentially the same.

Although there are many advantages which AC induction motors offer, they suffer from the following disadvantages:

- Induction motor technology is more than a hundred years old and is essentially the same as it was a hundred years ago.
- The efficiency of induction motors is generally low due to current circulating losses in the rotor and the losses in the stator-- unless high efficiency (more expensive designs) are chosen.
- Induction motors are more difficult to control, due to their non linear speed-torque characteristics. This is due to the complex relationship between the rotating magnetic field in the stator and the induced magnetic field in the rotor. As such they are more difficult to control with electronics and intelligent devices such as DSP's (Digital Signal Processors).
- Commercially available induction motors are generally much bigger and heavier when compared to motors using other technologies. There is no real inherent technical reason why this is so -- it is just that the commercially available parts are generally relatively bigger and heavier. Cast iron end caps instead of aluminum end caps is a case in point.

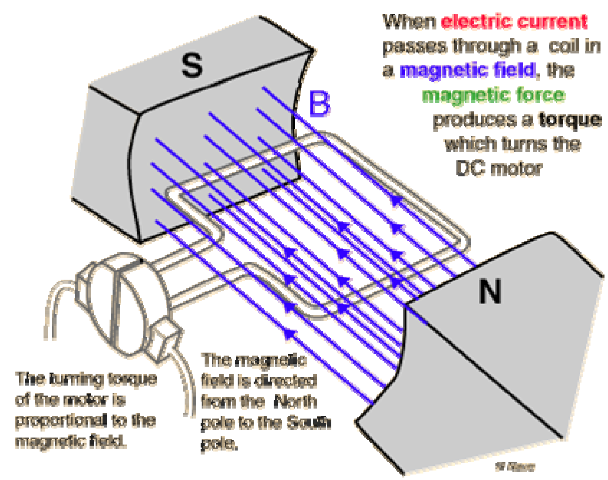
Brush DC motors

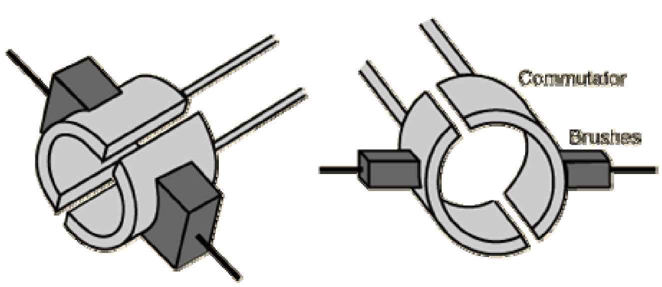
Before the invention of AC induction motors, electric motors were all brush DC motors.

In a Brush DC motor, the rotor has the windings and the stator is either made of permanent magnets (in a brush DC permanent magnet motor) or an electromagnet (in a wound field brush DC motor).

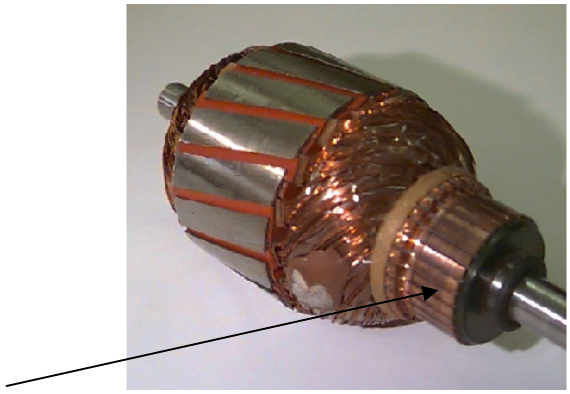
The rotating field is generated by a very clever device called a “commutator”. Essentially, with the brushes, it functions as a current reverser. As the current reverses in each coil, the net effect is a rotating electromagnetic field which is the essential for generating rotating movement.

Principle of Operation and parts of brush type DC motor



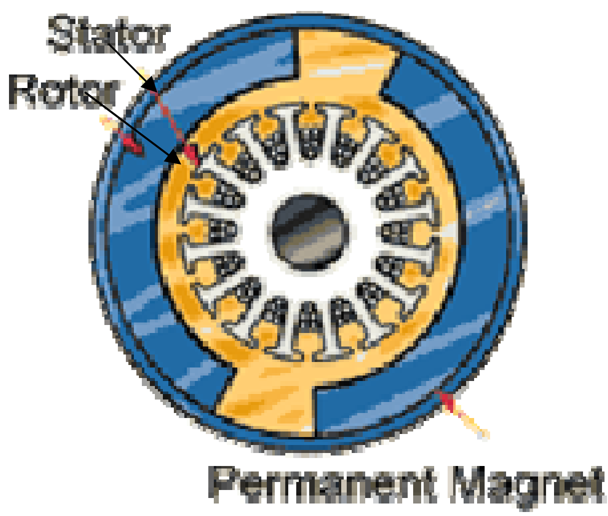


Armature (rotating part or rotor) of a brush type DC motor. The stator is made of a pair or more of permanent magnets or a wound field.



Commutator attached to the armature of a DC motor

Cross Section View of a permanent magnet brush type DC motor. The armature (windings) is the inner rotating member (the rotor).



The biggest advantage of a brush type DC motor of course is the fact that is a natural choice for applications when the power source is DC. There are other advantages of this type of motor however, which make it the motor of choice for a lot of applications where the power source is conventional AC line supply and not necessarily a battery.

Advantages of Brush Type DC Motors:

Since the motors have an internal feedback (with the commutator), current is fed into the right winding naturally and not just blindly as in the case of an induction motor with a rotating field generated by the swings in the AC line supply. For this reason, DC motors always have ***high starting torque*** **–** significantly higher than in the case of an induction motor.

Another advantage of a DC motor is that has linear speed torque characteristics, which again is a direct result of the permanent magnets in the stator and internal feedback from the commutation—the current in the windings is switched from winding to adjacent winding based on the shaft position feedback from the mechanical commutator. For this reason, DC motors were preferred and are still often used ***for adjustable speed applications*****.** The speed of the motor can be varied linearly (i.e. proportionately) to the applied voltage.

Disadvantages of Brush Type DC Motors:

The main disadvantage of brush DC motors of course is the fact that they have brushes. These brushes have to be inspected from time to time and replaced when they are worn out. So, brush DC motors have a limited life and often this life cannot easily be predicted.

Another major disadvantage of brush DC motors in some applications is that their windings are on the armature which rotates. For rapid start-stop applications the inertia of the heavy armature can be a major drawback.

Other type of Motors:

Depending upon the construction of the rotor, the stator and the manner in which the rotating magnetic field is generated, there are other types of motors which are used for specialized applications. Examples of such motors which are prevalent in commercial use are:

- Stepper motors. These motors have serrations in the rotor and stator teeth so that the rotor moves in detent positions. These motors are used for low cost position control and sometimes for low cost velocity control as well. Follow this link for further details: http://mechatronics.mech.northwestern.edu/design_ref/actuators/stepper_intro.html

- Switched Reluctance Motors. These are specialized brushless DC motors which have a "reluctance rotor" instead of an induction rotor as in the case of an induction motors. There has been much written about these motors in the press but they have really not caught on due to only marginal cost advantages and many difficulties in implementing quiet controls. For further information, follow this link: http://www.freescale.com/webapp/sps/site/overview.jsp?nodeId=02nQXGrrlPb02R&tid=tMfp

- Slotless motor. These are specialized brushless DC motors. (We will be dealing with the subject of brushless DC motors in the next section). Slotless motors have been proposed by some manufacturers as a solution to all problems of precise motion control. History has not borne out this contention and the use of slotless motors is limited to very specialized applications where smooth rotor positioning at low speeds is an important criterion of the application. For further details on slotless motor, please follow the link to this web site: http://www.manufacturing.net/ctl/article/CA269671

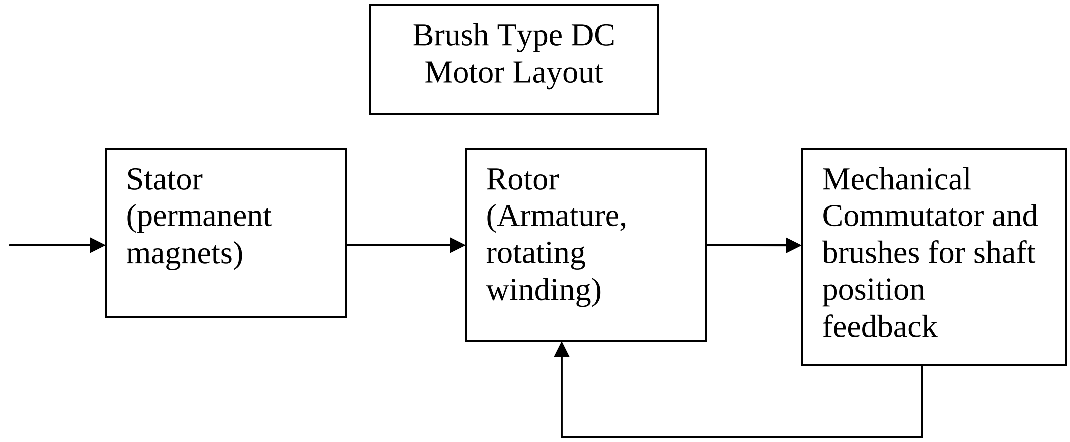
- Brushless DC motors. These motors are the focus of this article. The description, application, advantages etc. are covered in detail in the next section.

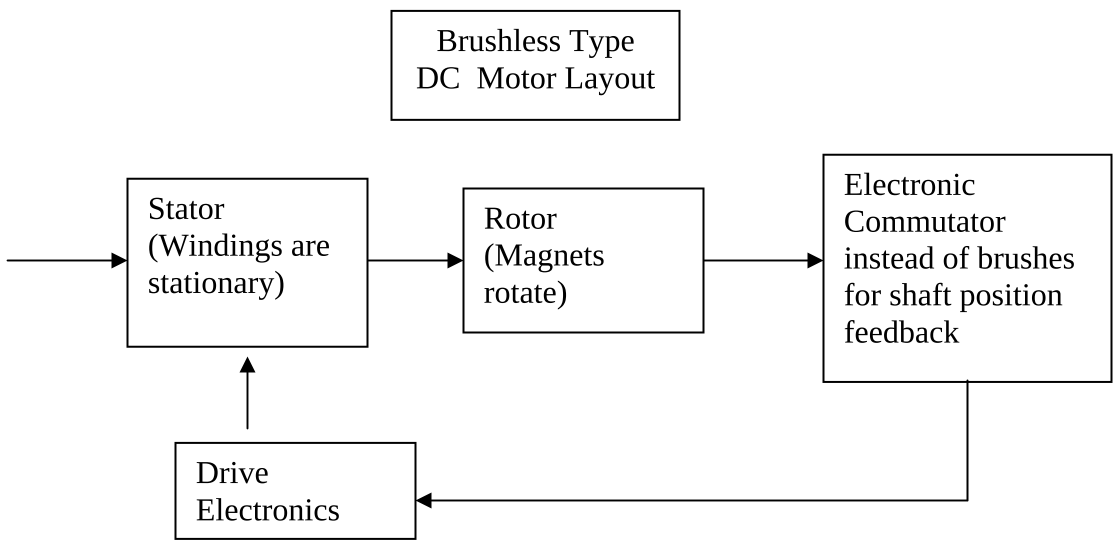
CHAPTER 3: BRUSHLESS DC MOTORS (BLDC)

This is a relatively new class of motors whose application have been increasing at a rapid rate each year, due both to declining costs as well as increasing functionality.

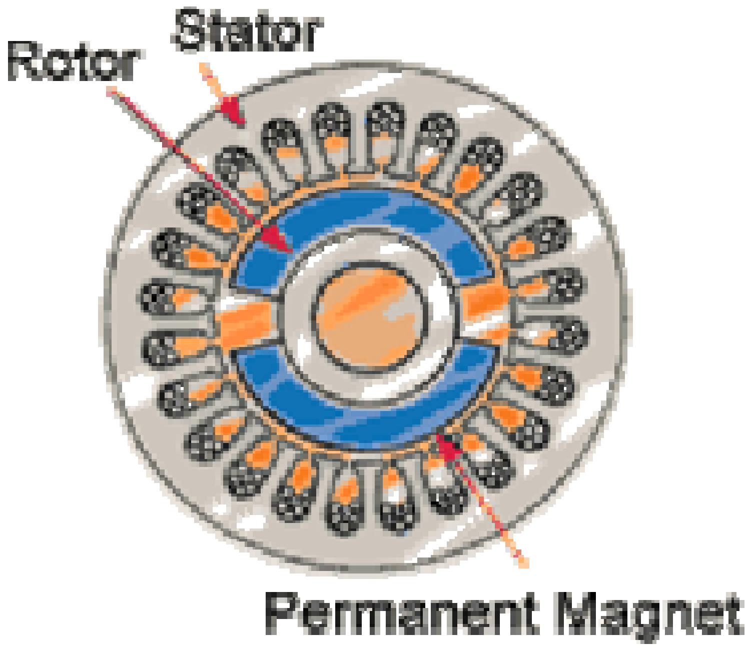
What is a brushless DC (BLDC) motor?

A brushless DC motor is similar to that Brush DC motor in that it has an internal shaft position feedback which tells which windings to switch on at which exact moment. This internal feedback gives both the brush DC motor and the brushless DC motor their unique characteristics: linear speed-torque curves which are well suited for speed and position control and high starting torque. The internal feedback is accomplished in a brush type DC motor with the mechanical commutator (a series of copper bars which are insulated from each other) and the mechanical brushes through which the current is fed into the commutator bars and switched sequentially into the appropriate winding in the armature. In a BLDC motor, the internal feedback is accomplished by a shaft position feedback sensor of some type which give the required shaft position information to the drive electronics. The drive electronics in turn switches on the appropriate windings at exactly the right moment. This internal shaft position feedback also gives the BLDC characteristics which are similar to the DC the characteristics of a DC motor: linear speed-torque characteristics and high starting torque. The power supplied to a BLDC motor can be DC power but it can also be AC if the drive electronics has the necessary circuitry to convert the AC power to DC.





Note the similarities in the basic construction between a brush type DC motor and the brushless DC motor. In both cases, there is an internal shaft position feedback which gives these motors high starting torque and linear speed –torque characteristics which are so essential for precise speed and position control. In the case of brush type DC motors, the feedback is with a mechanical commutator and brushes and in the case of brushless DC motors, the feedback is with some electronic feedback sensor such as magnetic Hall sensors, encoders or resolvers. They key point is that the windings are sequentially switched with the drive electronics in BLDC motors. Without the electronics, the motor cannot even run. Conversely since the BLDC motors have electronics any way, they can be used to accomplish adjustable speed control and many other useful functions.



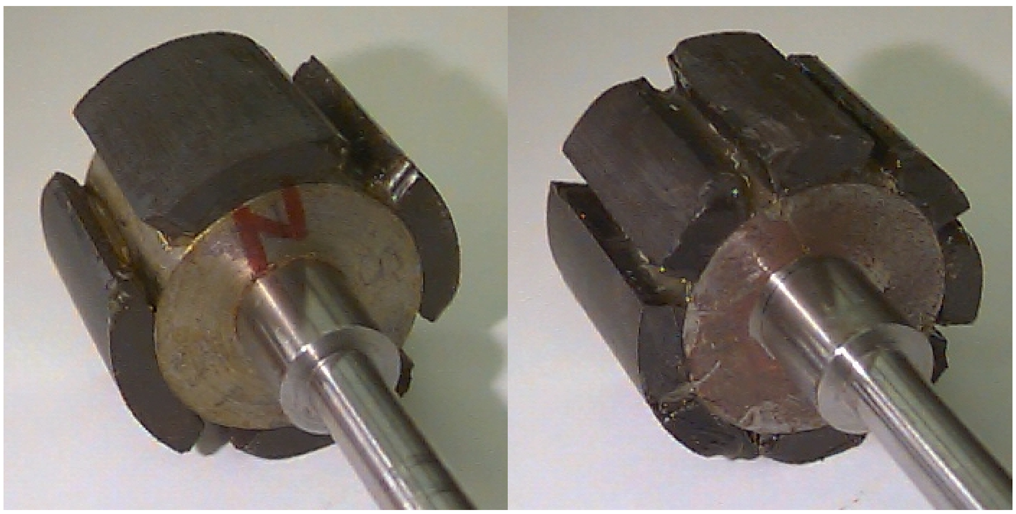
The above is a cross sectional view of a typical brushless DC motor. The permanent magnets are on the inside and on the rotor. The stator is on the outside and has the windings.

Components of a BLDC motor

The Rotor:

The rotor of a typical brushless DC motor consists of the shaft, the hub (on which the magnets are glued on) the magnets and the bearings.

Here is a picture of a four pole and eight pole BLDC rotor: the higher the number of poles, the higher the torque but the lower the speed.

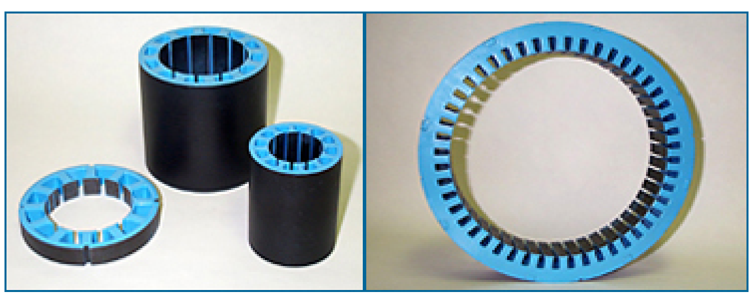


There are many advances which are taking place in the magnet technology. Twenty years ago, the magnets material of choice were ceramic magnets. Today bonded and sintered Neodymium Boron Iron (simply known as Neo) are commonly available. Bonded Neo magnets are suitable for smaller motors and are available in the form of very convenient rings. Sintered Neo magnets are much more powerful but they are commercially available in individual pole pieces which then must be individually glued on to the shaft.   A figure of merit used to describe the strength of permanent magnets is the “BxH” (flux density in Mega Gauss x Coercivity in Oersteds) product or simply the energy product. To give an idea of the rapid advances in magnet technology, it may be noted that ceramic magnets of the mid-seventies had an energy product of 4 MGOe. Bonded Neo magnets now have an energy product of 10-12 MgOe. Sintered Neo magnets have an energy product of 30 to 45 Mg Oe. It also must be noted that most brush DC motors for historical reasons have only low energy ceramic magnets. BLDC motors on the other hand almost always have bonded or sintered Neo magnets. For this reason, BLDC motors are usually significantly smaller in size compared to BLDC motors with comparable power output.

The Stator:

The BLDC stator starts out with steel laminations (lams)which are stamped out of low loss electrical steel with a high quality stamping die. The lam design and manufacturing of it is crucial to the performance of the BLDC motor. The stamping die is a major investment and the type used (low volume/low cost/high maintenance high speed steel die versus high volume, higher cost/lower maintenance carbide die) used depends on the volume of the job. In any event in custom BLDC motor manufacturing, choosing the right lam design and then choosing the right type of die is very important decision. A bad decision made at this stage will lead to failure and or problems down the road in production.

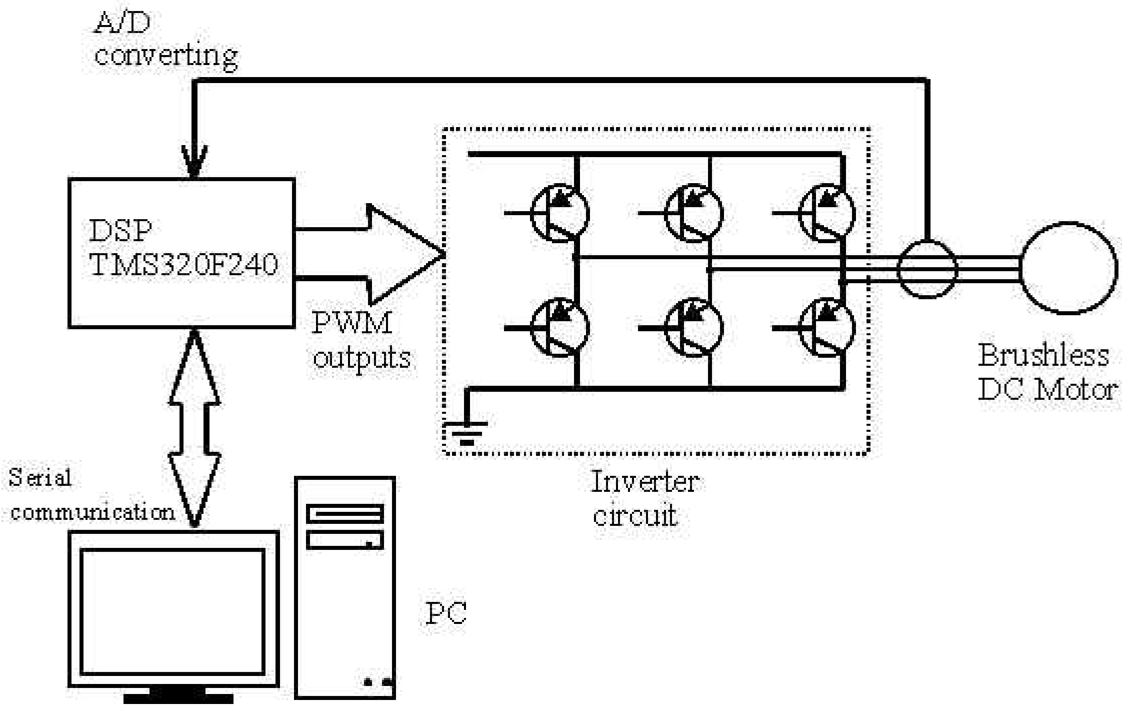
The next step in the stator manufacturing is the stacking of the lams. This done in different ways, such as welding, pinning or gluing, depending upon the motor manufacturer's experience. Once the lams are stacked, they need to be insulated, to protect the copper wire from shorting out to the steel of the stacks. This is accomplished in various ways (such as powder coating, illustrated in the characteristically blue coating shown below or plastic insulators) depending upon the volume. At this stage, the stack is ready to go into the winding machine. Next to the lam die, the most critical decision regarding BLDC motor manufacturing is the type of winder that is used. This is a major investment and can run into thousands of dollars. The right winder needs to be chosen after careful consideration to the investment, throughput, flexibility and most important of all, reliability. An unreliable winder can spell disaster in production since it controls a critical process (winding) without which no motor can be made.



Here are some examples of finished stators, after they are wound. There are optional processes after the winding like varnishing, lacing, shaping the end turns and attaching connectors to the wires, to prepare the wound stacks for final assembly.

Drive Electronics:

The third major element in the BLDC system is the drive electronics which is often termed loosely as the controller. This can be attached to the back of the motor or it can be located separately in its own housing.



There are four main elements in the drive electronics:

- The inverter (drive transistors these are the most expensive parts, generally 6 transistors for the three phases of a three phase motor). The higher the power ratings, the higher the current rating and the higher the cost of the transistors.

- Logic circuits which may include a DSP and other logic devices to decode the shaft position feedback information and turn or the right transistors (commutation) to affect motor shaft rotation. The logic circuit generates the required PWM (Pulse Width Modulation… a very clever means of adjusting the input voltage to the motor) signals for obtaining adjustable speed. The logic circuit may also have hooks and handles for digital communication to the outside world for command and or reporting interface.

- Heat sink and thermal management hardware to manage the heat generated in the switching process.

- AC front end including filtering capacitors for the conversion of the input voltage to a suitable internal DC voltage.

The key points to keep in mind regarding BLDC controllers are:

- The main cost of controllers is in the power transistors. These costs are coming down. Smaller motors use MOS FET (Metal Oxide Semiconductor Field Effect Transistors) as the technology of choice for small motors (3 HP or less). Larger motors use IGBT (Insulated Gate Bipolar Transistors) as the main switching elements.
- Logic circuits, especially with DSP's (Digital Signal Processors) in them offer numerous features at great speeds without much addition to cost. DSP's can be viewed as very fast microprocessors with "multiple pipes" for parallel calculations for quick response even as the load and the environmental conditions change rapidly.
- Companies who are proficient in both motor technology as well as power electronics technology have a much higher chance of delivering solutions successfully. Separating the sourcing of the motor and the controller to two different vendors is a surefire recipe for disaster. The motor has to be matched to the controller and the two have to be designed in tandem to ensure optimum cost and optimum performance.

Advantages of BLDC motors

Brushless DC motors have several advantages over competing motor technologies. The following table summarizes these advantages and the underlying reasons for these advantages.

BLDC Advantage	**Underlying Reasons**
Smaller motor	Modern permanent magnets and no losses in the rotor enable BLDC motor to be smaller compared to both brush DC motors and induction AC motors.
More efficient motor	Permanent magnet in the rotor. Unlike AC induction motors, there are no core losses in the rotor.
Higher speeds	No brushes to limit speed, lower speed losses by design. BLDC motors have been designed for speeds as high as 100,000 RPM. The problem of retention of magnets, in a rotor spinning at high speeds, have long been solved.
No maintenance	No brushes to replace, inspect or maintain
Faster response	Lower rotor inertia compared to a brushless motor or an induction motor
Lower RFI (radio frequency interference)	No brushes
Linear speed-torque characteristics	Internal shaft position feedback. Permanent magnet design with internal shaft position feedback gives BLDC motors linear speed-torque characteristics when compared to “open loop” AC induction motors.
High starting torque	Internal shaft position feedback gives BLDC motors higher starting and low speed torque when compared to “open loop” AC induction motors.
Adjustable speed	The commutation electronics can be used for speed control without added cost.
Better heat removal	The heat generating element is the stator which is on the outside of the motor as opposed to being in the inside as in the case of a brush DC motor
Much better controllability versus induction motors	Linear speed torque characteristics due to internal shaft position feedback and permanent magnet design.

The primary disadvantage of BLDC motors has been cost. This is so not because of any inherent reason in the motor itself -- the construction of a BLDC motor is actually simpler than that of a brush DC motor or an induction motor. The higher cost of BLDC motors in some applications is due to the fact that BLDC motors require drive electronics. For a single speed application, this extra cost burden may not be justifiable despite the numerous advantages. However if the application is for adjustable speed or position control where electronics is required any way, then BLDC motors are actually not only advantageous but they are also a less expensive solution. Application after application, from disc drives to machine tools, have all been converted over to BLDC technology. The advantages in these situations are just too compelling.

Application Considerations

As we have stated earlier, the suitability of BLDC technology depends up whether or not the application is for single speed, adjustable speed or position control. The following chart summarizes the suitability of BLDC technology by type of application.

Application	**Suitability of BLDC technology**
Single speed	For single speed applications, induction motors are the most suitable. However, even in single speed applications, the cost of the BLDC with electronics can approach the cost of induction motors. Along with the advantages of better efficiency and smaller size, faster response, soft start and soft start, BLDC technology can offer a viable and more attractive alternative
Adjustable speed	BLDC motors are a clear winner here. They have the commutation electronics any way and with very little additional circuitry, they can be used for precise adjustable speed control. They can offer a less expensive solution when compared to an induction motor with inverter electronics solution and they can be less expensive and maintenance free relative to a brush DC solution with adjustable speed electronics
Position control	BLDC in almost all cases are clear winners here both with respect to technical advantages as well as price.
Low noise applications	Since BLDC motors do not have brushes, they are devoid of brush noise. Within BLDC motors, there are two distinct means of commutation which have a profound effect on the noise (both audible noise as well as RFI) generated: the standard way to commutate (i.e. sequentially feed current into the windings is to use Hall position sensor feedback. This type of control is referred to as the 6 step (in reference to the shape of the current wave form in the motors phases) or “bang bang” control. As the name implies this type of control is somewhat crude and results in distinctly

Application	Suitability of BLDC technology
	audible noise. For low noise applications sine wave control (the shape of the current waveform fed into the windings is a smooth sine wave) is the ultimate method for commutation. It is more expensive however, since it required a higher resolution (higher than the 120degree resolution of the three Hall sensors) position sensor such as an optical encoder or an electromechanical “resolver” along with non-trivial software.
High speed applications or very low speed smooth operation.	A sub-class of BLDC motors referred to as “slotless” motors with their very low inductance are specially suited for very high speed (in excess of 10,000 to as high as 100,000 RPM) applications and for applications requiring very smooth (very low “cogging”) operation at low speeds.

Slotless Versus Slotted (conventional Brushless DC motors):

The term slotted refers to slotted shape of the steel laminations which make up the stator stack in the stator of a brushless DC motor. There are slots in the laminations to keep the winding wire in place while still proving a very tight air gap for the magnetic flux between the rotor and the stator. The winding wire incased in the stack of steel laminations is then referred to as the “iron core” and slotted motors are also called iron core motors. This is the traditional method of making brushless DC motors and it was actually also used in the very first patent by Tesla for an AC induction motor. Most brushless DC motors used today are of the “slotted” stator type.

In a slotless (also referred to a coreless) motor, there are no slots or teeth at all in the stator. The stator laminations are simply which steel rings stacked together to form the stator stack. The winding wires are held together by glue or polymer molding to give the windings shape, form and rigidity. The windings are in between the stator steel ring and the rotor. Since space must be allowed in the air gap in slotless motors is generally larger than in slotted motors. The manufacturing of the winding structure is a non-trivial exercise and a lot of thought and efforts has to go into the reliability of the winding structure, especially with the inevitable heat generated under load.

Slotless motors have the following advantages when compared to conventional slotted motors:

- *Higher speeds:* since there is no iron core in slotless motors, the inductance is very low and this feature allows the current to get into the windings very fast. For this reason, slotless motors are ideal for high speed applications. It is not uncommon for slotless motors to run at speeds between 10,000 to 100,000 RPM.

- *No cogging at low speeds:* since there are no teeth in the lamination stack, there are no detent (preferred rotor position) or cogging. This makes the slotless motor ideally suited for very low speed applications requiring very smooth rotation without cogging.

- *Higher efficiency:* Since slotless motors have lower “iron” losses with the absence of an iron core, the efficiency of a slotless motor can be higher.

The main disadvantage of slotless motors is cost. Since the air gap out of necessity to fit the windings in a slotless space is higher, more magnet material (the single biggest cost item in a brushless motor) is needed for the magnetic flux to traverse the larger air gap. In addition, the manufacturing challenges of making a rigid winding structure with no lamination slots and teeth to contain the magnet wires, are non-trivial and require specialized machines and higher labor.

It is important to note that the drive electronics for slotless motors and conventional slotted motors can be exactly the same and therefore exactly the same cost.

Conventional (“Slotted”)BLDC manufacturing processes

The BLDC manufacturing process can be looked at in terms of the following elements: stator manufacturing, rotor manufacturing, final assembly, test and drive electronics manufacturing and final system test.

Stator Manufacturing:

Stamping of laminations (lams)

The first step is to stamp the laminations (lams) out in the right geometry with a suitable stamping die and stamping press. This is a critical stage of the manufacturing process. A poorly designed lam or a poorly manufactured lam can cause heating, loss of efficiency and problems in final assembly. Low loss electrical steels such as M19 or M36 with surface coating for rust protection are commonly used in this process. The tooling of the lamination and choice of the die is a very important decision and great care must be taken before choices are made. Stamping dies can cost between $3000 to 10,000 (for a high speed steel low volume die) to $100,000 (for a high volume carbide die). Poor choice of dies are a source of major disaster down the road when the motor is in production.

Stacking

Once the lams are stamped, they are stacked using a variety of processes such as notching, gluing, welding or pinning, depending upon the experience of the motor manufacturer.

Insulating of stack

The next step is to insulate the stack with electrostatic (characteristically bright lue in color) coating to insulate the copper wire from the sharp edges of the steel lam stack. Plastic insulators are used for high volume applications and in some cases paper insulators are also used.

Winding

The next most crucial process is winding. The choice of the winder must be made with care with due consideration to capacity, flexibility, set up time and above all, reliability. A poor choice of winder can break the project. Winders range in price form a few thousand dollars for low volume labor intensive applications to several hundred thousand dollars for high volume automatic manufacturing of multiple stators at a time.

Prepping

After winding the stator wires need to be properly connected and end turns formed as required by the design, varnished to keep the wires in place and get the stator ready for final assembly.

Stator Manufacturing Process:

Manufacturing Step	**Critical parameters**	**Cost implications**
Lam stamping	Lam geometry, no burs or sharp edges, the cut of the lams needs to be smooth and clean	Lam dies can cost from $10K to $100K depending upon volume requirements
Lam Stacking	Lams stack has to be welded, interlocked with notches, glued or held fastened together with steel pins. The lams in some cases need to be skewed to achieve certain performance characteristics of the motor. The stack needs to be perfectly lined up to avoid problems in final assembly.	Stacking fixtures and process are critical to the overall manufacturing process.
Stack insulation	This process is to prevent shorting of the magnet wire in the slots to the stack. 1500 volts DC is a typical "high pot" test to ensure the integrity of the insulation. The insulation material must provide the needed electrical isolation but it also needs to be very thin in order not to occupy too much of the valuable slot space.	Low volume stacks are coating with characteristically blue powder which is electrostatically deposited. Plastic insulators are used for high volume applications.
Winding	This is the most critical process and its integrity depends much on the winder and the winding tooling	Winders can cost between $10K to $250K depending upon the volume requirements, flexibility and capacity
Prepping	The ends turns are shaped, connectors attached with a suitably reliable process and the assembly is varnished to keep the windings in place	Automatic trickle varnish systems and fixtures for end turn shaping if required are critical processes
Test	High pot test and resistance test at this stage are used to ensure the integrity of the stator	Automatic in line data logging is done at this stage to offer traceability in case of problems down the road.

Rotor Manufacturing:

Shaft machining:
The rotor manufacturing starts with the machining of the stainless steel shaft. The bearing journals need to be ground to tight tolerances. Shafts are either manufactured in house or procured from subcontractors who specialize in the manufacture of shafts or complete rotor assemblies with magnets. In correct machining of the shafts, especially the grinding process, can lead to trouble down the road.

Hub machining:
This is a round piece of steel with a hole through it for the shaft and it has the right diameter for the magnets to be glued on to it. The hub is sometimes made from powder metal with higher tooling cost but lower piece part cost.

Magnets gluing:
Magnets are typically bonded Neo rings for smaller motors and sintered Neo pole pieces for larger motors. These magnets are glued on to the hub. The gluing process is not trivial at all and has been perfected by each individual manufacturer based on years of experience. Kevlar tape or a steel band is added over the magnets for extra security especially for rotors which are to be used in high speed applications.

Bearing press:
At this stage, the bearings are pressed on and the rotor is ready to mate with the rest of the parts in final assembly. Care needs to be taken with appropriate fixtures to avoid improper or cocked seating of the bearings.

Manufacturing Step	**Critical parameters**	**Cost implications**
Shaft machining	Machining tolerances especially around bearing journals and where feedback sensors are to attach	This is a labor intensive part and best sourced as a complete machined part or a a complete rotor assembly with the hub and magnets
Hub machining	The ID and OD of the hub are critical for trouble free assembly to the shaft and to the magnets.	Powder metal parts are sometimes tooled to reduce labor cost. Powder metal tooling may cost as much as $10,000.
Magnet gluing	This is deceptively simple process. If it is not done properly it can cause a great deal of headache down the road.	Gluing fixtures and tools need to be put in place to reduce the manufacturing cycle time.
Bearing press	Fixtures need to be in place to prevent improper and cocked installation of the bearings.	

Housing and End Bell Manufacturing:

In most modern small motors, the end bells are made from aluminum or from Zinc. The housings are steel shells or extrusions suitable for good heat transfer. Castings and machining are done at subcontractors. The bearing journals again are critical dimensions, which must be held to tight tolerances. Normal casting hygiene (no porosity or bubble holes) need to be practiced.

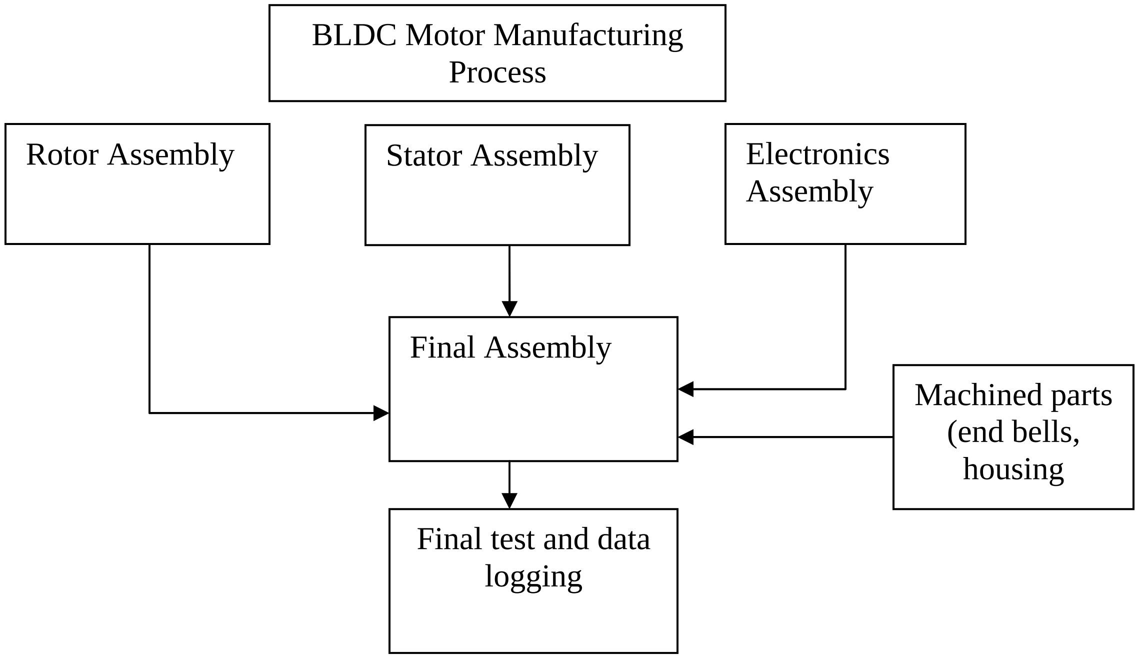
Electronics Manufacturing:

The printed circuit boards (PCB's) are normally not done in house at most motor manufacturers. This is a very capital intensive part of the business and there are numerous companies globally whose business it is to make PC boards and place the electronic components on them. These components can be "through hole" which is an older technology or "surface mounted" (SMT), which is a much newer technology and which is suitable for modern PC boards which have small size tiny components.

An issue which has just come up with PC boards is ROHS compliance. ROHS is European directive against the use of hazardous materials. Past 2006, any boards which are not ROHS compliant will not be allowed to be shipped to any EU country. This is a non-trivial but well defined change in the environment. It does have a cost implication on all PC boards, including PC boards used in BLDC motors.

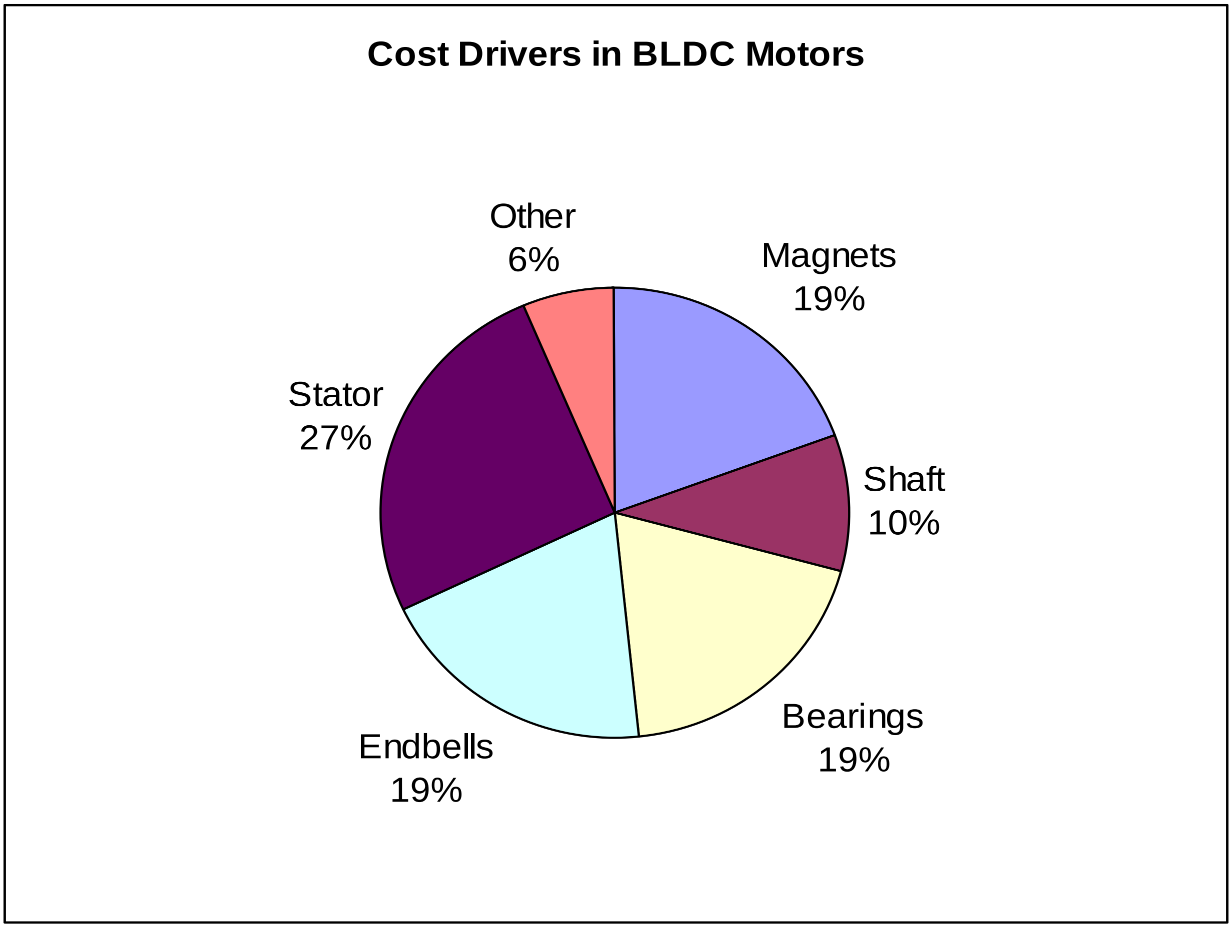
After the PCB's are fabricated at a PCB house, they are shipped to a contract manufacturer for "stuffing" or placing of the electronics components on to the PC boards. This again is a capital intensive business and most motor manufacturers get this portion of the manufacturing done at the premises of contract manufacturers rather than doing the work in house.

Thermal management (getting rid of the heat generated in the electronics and detecting and protecting against over temperature conditions), is handled by the heat sink and the associated hardware. This is a major part of the electronics and it represents a case where the motor engineer and the electronics engineer need to work very closely together.


BLDC Motor Manufacturing Process
Rotor Assembly
Stator Assembly
Electronics Assembly
Final Assembly
Machined parts (end bells, housing
Final test and data logging

Costing of BLDC motors

The following are the main cost drivers in a BLDC motor: magnets, bearings, shaft, end bells, housing and electronics assembly. It is difficult and even misleading ot generalize but at least to get a general idea, the following pie chart with the main cost drivers are shown below.



Typically, the cost of the electronics is about as much as the cost of the complete motor. Here again, it may be misleading to generalize but this is a first approximation to give the reader a general idea about the cost and the cost drivers.

Technology Drivers behind BLDC motors

Advances in BLDC technology are driven by two main factors:

- Advances in magnetic materials.
- Advances in DSP's.

Advances in magnetic materials:

Early permanent magnet motors (primarily brush type DC motors) appeared on the scene in the early seventies. By the early eighties, BLDC motors were establishing themselves in an increasing number of applications.

The early permanent magnet motors had ceramic or ferrite permanent magnets in them. The figure of merit of these magnets was quite low (about 3-4 MGOe[2]). Bonded Neo (Neodymium Boron Iron) magnets with 10-12 MgOe came on the scene in the eighties, followed quickly by sintered Neo magnets with 30-45 MgOe. As the materials have advanced in their energy product, BLDC motor designs have kept up with them. The higher the magnet strength, the higher the motor efficiency and the higher the torque which can be put out by the motor. It is interesting to note that while BLDC designs have kept up with advancing materials, vintage brush type DC motors continue to be offered only with low performance ceramic magnets. The gradual progression of the performance envelope of Neo magnets will continue in the near future.

Advances in DSP's:

The advent of low cost DSP's in the late nineties, has given the BLDC motors a major boost. The performance of motors using DSP's is significantly increased with very little incremental cost. New and innovative features which were never possible before are now routinely available. Features such as high speed feedback control loops (servo loops), digital communication, diagnostics, memory, programmable input/output control are now all possible with very little extra cost. It is like having a small PC inside the motor! As the advances in DSP's continue clever BLDC motor companies will ride on the crest of these waves and harness the power of DSP's to their advantage. Conversely, those companies who do not use DSP's in their BLDC products will lose and be left behind.

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[2] MGOe➔ Mega Gauss- Oesterds (B{magnetic flux density} x H {Magnet Coercivity} or Energy Product)

With increasing performance of magnets, DSP's and declining costs of power electronics, BLDC motors will continue to be the adopted in an increasing array of of new products. They are already in automobiles, appliances, HVAC, Mil-Aero applications. They will continue to make inroads into an increasing number of commercial applications where the incumbent technologies are either brush DC or induction AC. The advantages offered by BLDC technology are much too compelling to ignore.

The future of BLDC motors seems bright indeed. Conversely, OEM's who ignore BLDC technology run the risk of adopting obsolete and indeed more expensive technology.

Other New Motor Technologies on the Horizon

There is a lot of talk in the press about completely new technologies such as "Piezo electric motors" and ultrasonic motors. Refer to the following URL for a brief introduction to the technology:
http://www.physikinstrumente.de/products/section7/piezo_motor_index.htm
http://www.magnaphysics.com/an_introduction_to_ultrasonic_mo.htm

At this time these technologies are either laboratory curiosities or suitable for very tiny power levels in biotechnology or very small consumer products such as camera and nano positioning tables. It is unlikely that within the next decade these radically new technologies will pose a threat to proven BLDC technology. In this respect, the future of BLDC technology at least looking into the foreseeable future not only very secure but has a lot of upside potential as an increasing number of main stream consumer applications begin to see the cost versus benefit payoffs of BLDC technology.

The Business of Brushless DC motors

The Thomas Register lists more than a hundred manufacturers of BLDC motors in the US. These manufacturers range from the truly giant companies such as GE, Emerson and Reliance (Rockwell Automation) to numerous small to medium size companies in the $10-$50 M annual sales range. Each one of these companies is focused on some basic older motor technology and has BLDC technology in the forefront of their new product development. While there are many players in the BLDC business, it is difficult to find intelligent electronics, motor design/manufacturing, total customization for cost and low cost approach under one roof.

For a long time the Japanese have had a monopoly on the market for most of the early applications for BLDC motors, like disc drives and low end copiers. For example, they sell more than $200-$250 million dollars worth of BLDC motors for disc drives in the US. Today nearly 100% of disc drives use BLDC technology. We see almost the same level of adoption of BLDC technology in machine tools, transfer lines, robots and material handling systems and a variety of factory automation applications. A lot of the critical functions in automobiles such as steering control and drive by wire have already converted to BLDC. A lot of HVAC (Heating Ventilation and Air conditioning) applications are converting from single speed induction motors to adjustable speed BLDC technology. We see a similar kind of adoption of this technology in Mil.Aero[3] applications.

This is not to say that all induction motor and brush DC motor applications will be converted over to BLDC in the near future. Induction motors are cheap, unbreakable and manufactured in huge volumes. As such they will continue to be the work horses of industry for many years to come, even as BLDC technology makes inroads into many erstwhile induction motor applications. Likewise, brush DC motors are simple, convenient to apply and do not need any electronics for basic battery or adjustable speed applications, especially where high starting torque is required. While a number of brush DC applications have been converted over to brushless, the brush type business is still alive and well. Things just do not happen very fast in the motor industry!

What is next? We have already noted that innovations evolve very slowly in the motor industry. A hundred years after their invention, improvements are still being made on AC induction motors. Changes in this industry are evolutionary and not revolutionary.

We foresee incremental improvements in materials, especially in magnet materials. We also foresee improvement in the cost versus functionality in power electronics and DSP's. Further down, we also see the impact of the Internet on the motor

[3] Military, Aerospace

industry. It is not too far fetched (and indeed the technologies exist to enable this here and now) to imagine a future wherein all motors worldwide are connected in a network via the Internet. So, diagnosis, trouble shooting or just monitoring of motor run processes for motors located anywhere in the world from any computer in the world will be a matter of simply logging on, submitting your password and seeing the information on your computer screen or receiving e-mail or cell phone alerts. We have seen the convergence of computer technology and communication technology with astounding speed. The convergence of motor technology and communication and Internet technology is not far behind! Thoughtful people can prepare and take advantage of this coming Tsunami deluge instead of being swept away by it.

Conclusions:

By applying the potent combination of BLDC technology and DSP technology, OEM’s can bring to their customers innovative and advanced features. Applications which were cost prohibitive for the consideration of BLDC motors just a few years ago are not only viable today but also are thriving on the competitive advantages brought forward by the BLDC technology. Conversely if OEM’s ignore the advantages of technology, they run the risk of being over taken by their competition.