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OVERVIEW OF BRUSHLESS D.C MOTOR: CONSTRUCTION AND APPLICATION

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Abstract: Conventional brushed type DC motor, wherein the brushes make the mechanical contact with commutator on the rotor so as to form an electric path between a DC electric source and rotor armature windings. A Brushless DC Motor is similar to a Brushed DC Motor but as the name suggests, a BLDC doesn't use brushes for commutation but rather they are electronically commutated. In conventional Brushed DC Motors, the brushes are used to transmit the power to the rotor as they turn in a fixed magnetic field. The modern power electronics and microprocessor technology has allowed the small Brushless DC Motors to thrive, both in terms price and performance. This paper focus detailed constructional details, its working, comparative study with other conventional motors and its possible application in various field. This paper also reviews details of design features of low cost BLDC motor used for Pumps.In this paper the cost reduction design is studied to release the cost burden of BLDC motor for electric water pump using Nd-Fe-B material magnet. In order to minimize the material cost of permanent magnets, firstly, the magnet material is changed as ferrite magnet

I. INTRODUCTION

Brushless DC Motors or BLDC Motors have become a significant contributor of the modern drive technology. Their rapid gain in popularity has seen an increasing range of applications in the fields of Consumer Appliances, Automotive Industry, Industrial Automation, Chemical and Medical, Aerospace and Instrumentation

A brushless DC motor (known as BLDC) is a permanent magnet synchronous electric motor which is driven by direct current (DC) electricity and it accomplishes electronically controlled commutation system (commutation is the process of producing rotational torque in the motor by changing phase currents through it at appropriate times) instead of a mechanically commutation system. BLDC motors are also referred as trapezoidal permanent magnet motors.

As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors.

This electronic commutation arrangement eliminates the commutator arrangement and brushes in a DC motor and hence more reliable and less noisy operation is achieved. Due to the absence of brushes BLDC motors are capable to run at high speeds. The efficiency of BLDC motors is typically 85 to 90 percent, whereas as brushed type DC motors are 75 to 80 percent efficient. There are wide varieties of BLDC motors available ranging from small power range to fractional horsepower, integral horsepower and large power ranges.

1. Block diagram of Brushless D.C Motor (BLDC):

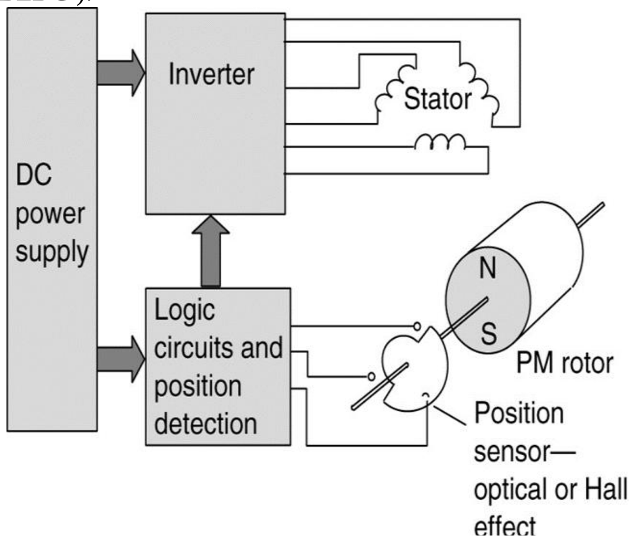


Fig (1.a) block diagram of Brushless D.C motor.

A brushless DC motor consists of a rotor in form of a permanent magnet and stator in form of polyphase armature windings as per the block diagram shown in fig(1.a). It differs from conventional dc motor in such that it doesn't contains brushes and the commutation is done using electronically, using a electronic drive to feed the stator windings.BLDC motor used electronic commutation and thus eliminates the mechanically torn brushes.

The armature coils are switched electronically by transistors or silicon controlled rectifiers at the correct rotor position in such a way that armature field is in space quadrature with the rotor field poles. Hence the force acting on the rotor causes it to rotate. Hall sensors or rotary encoders are most commonly used to sense the position of the rotor and are positioned around the stator. The rotor position feedback from the sensor helps to determine when to switch the armature current.

2.Constructional Details of BLDC.

The construction of this motor has many similarities of three phase induction motor as well as conventional DC motor. This motor has stator and rotor parts as like all other motors.

BLDC motors can be constructed in different physical configurations. Depending on the stator windings, these can be configured as single-phase, two-phase, or three-phase motors. However, three-phase BLDC motors with permanent magnet rotor are most commonly used. Fig 2. a) and 2.b) shows constructional details of BLDC motors.

Fig.(2. a)

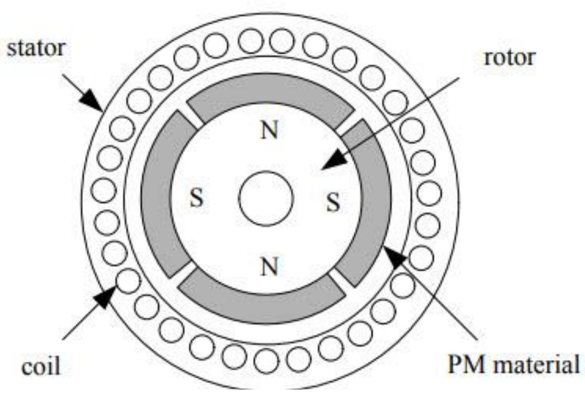
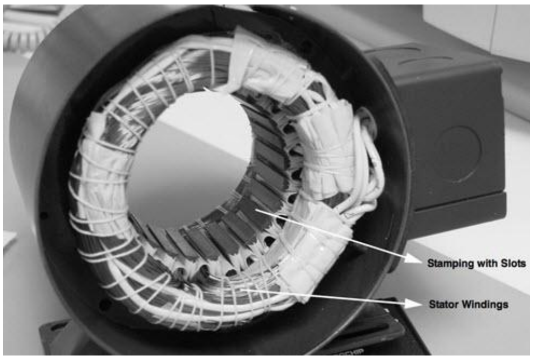


Fig (2.b)

2.1 Stator

Stator of a BLDC motor made up of stacked steel laminations to carry the windings. These windings are placed in slots which are axially cut along the inner periphery of the stator. These windings can be arranged in either star or delta. However, most BLDC motors have three phase star connected stator.

Each winding is constructed with numerous interconnected coils, where one or more coils are placed in each slot. In order to form an even number of poles, each of these windings is distributed over the stator periphery. The stator must be chosen with the correct rating of the voltage depending on the power supply capability. For robotics, automotive and small actuating applications, 48 V or less voltage BLDC motors are preferred. For industrial applications and automation systems, 100 V or higher rating motors are used. Fig 3. a) shows constructional details of stator of BLDC motor.



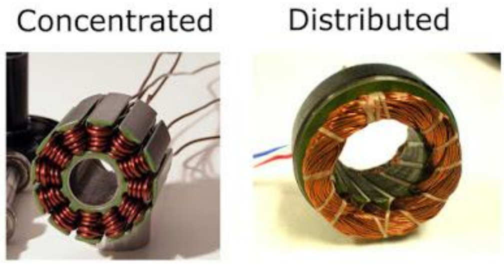
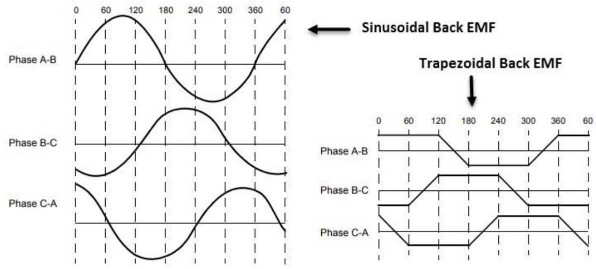


Fig 3. a)

Generally, most BLDC motors consists of three stator windings that are connected in star or 'Y' fashion (without a neutral point). Additionally, based on the coil interconnections, the stator windings are further divided into Trapezoidal and Sinusoidal Motors.

In a trapezoidal motor, both the drive current and the back EMF are in the shape of a trapezoid (sinusoidal shape in case of sinusoidal motors). Usually, 48 V (or less) rated motors are used in automotive and robotics (hybrid cars and robotic arms).



2.2 Rotor

BLDC motor incorporates a permanent magnet in the rotor. The number of poles in the rotor can vary from 2 to 8 pole pairs with alternate south and north poles depending on the application requirement. In order to achieve maximum torque in the motor, the flux density of the material should be high. A proper magnetic material for the rotor is needed to produce required magnetic field density.

Ferrite magnets are inexpensive, however they have a low flux density for a given volume. Rare earth alloy magnets are commonly used for new designs. Some of these alloys are Samarium Cobalt (SmCo), Neodymium (Nd), and Ferrite and Boron (NdFeB). The rotor can be constructed with different core configurations such as the circular core with permanent magnet on the periphery, circular core with rectangular magnets, etc.

Based on the application, the number of poles can vary between two and eight with North (N) and South (S) poles placed alternately. The following image shows three different arrangements of the poles. In the first case, the magnets are placed on the outer periphery of the rotor.

The second configuration is called magnetic-embedded rotor, where rectangular permanent magnets are embedded into the core of the rotor. In the third case, the magnets are inserted into the iron core of the rotor.Fig 4. a) shows various rotor construction.

Basically a BLDC motor can be constructed in two ways- by placing the rotor outside the core and the windings in the core and another by placing the windings outside the core. In the former arrangement, the rotor magnets act as a insulator and reduce the rate of heat dissipation from the motor and operates at low current. It is typically used in fans. In the latter arrangement, the motor dissipates more heat, thus causing an increase in its torque. It is used in hard disk drives.

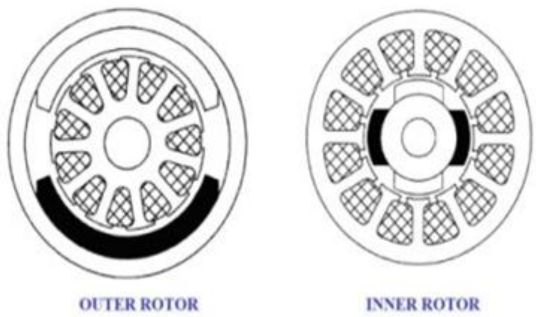


Fig4. a

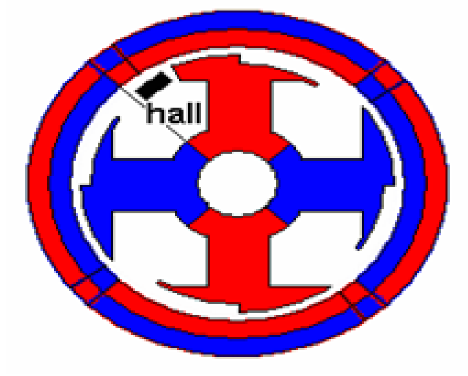
2.3 Position Sensors(Hall Sensors)

Since there are no brushes in a BLDC Motor, the commutation is controlled electronically. In order to rotate the motor, the windings of the stator must be energized in a sequence and the position of the rotor (i.e. the North and South poles of the rotor) must be known to precisely energize a particular set of stator windings.

A Position Sensor, which is usually a Hall Sensor (that works on the principle of Hall Effect) is generally used to detect the position of the rotor and transform it into an electrical signal. Since the commutation of BLDC motor is controlled electronically, the stator windings should be energized in sequence in order to rotate the motor. Before energizing a particular stator winding, acknowledgment of rotor position is necessary. So the Hall Effect sensor embedded in stator senses the rotor position .Most BLDC Motors use three Hall Sensors that are embedded into the stator to sense the rotor's position. Hall sensor provides the information

to synchronize stator armature excitation with rotor position

Each sensor generates Low and High signals whenever the rotor poles pass near to it. The exact commutation sequence to the stator winding can be determined based on the combination of these three sensor's response. Fig 5.a), shows the position of the sensor in the BLDC motor.



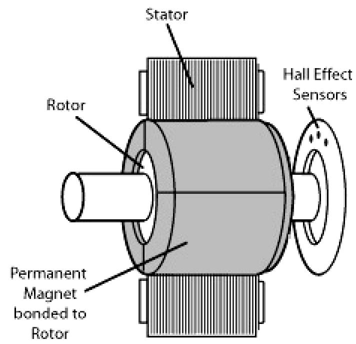
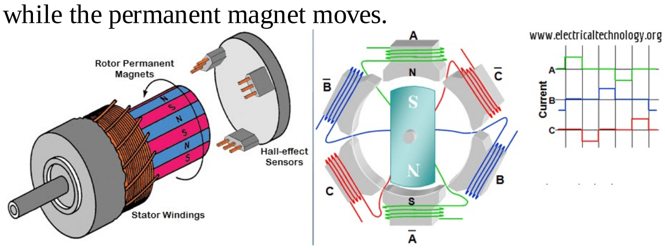


Fig.5.a)

Working of BLDC Motor

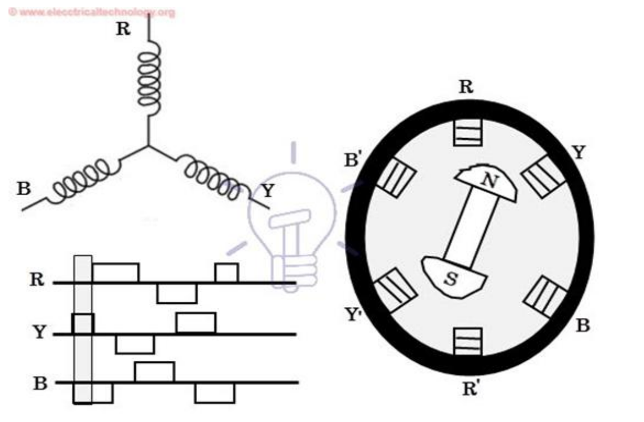
BLDC motor works on the principle similar to that of a conventional DC motor, i.e., law which states that whenever a current carrying conductor placed in a magnetic field it experiences a force. As a consequence of reaction force, the magnet will experience an equal and opposite force. In case BLDC motor, the current carrying conductor is stationary while the permanent magnet moves.



Construction, Working Principle & Operation of BLDC Motor (Brushless DC Motor)

When the stator coils are electrically switched by a supply source, it becomes electromagnet and starts producing the uniform field in the air gap. Though the source of supply is DC, switching makes to generate an AC voltage waveform with trapezoidal shape. Due to the force of interaction between electromagnet stator and permanent magnet rotor, the rotor continues to rotate.

Consider the figure below in which motor stator is excited based on different switching states.



Switching Sequence BLDC Motor

With the switching of windings as High and Low signals, corresponding winding energized as North and South poles. The permanent magnet rotor with North and South poles align with stator poles causing motor to rotate.
Observe that motor produces torque because of the development of attraction forces (when North-South or South-North alignment) and repulsion forces (when North-North or South-South alignment). By this way motor moves in a clockwise direction.

Here, one might get a question that how we know which stator coil should be energized and when to do. This is because; the motor continuous rotation depends on the switching sequence around the coils. As discussed above that Hall sensors give shaft position feedback to the electronic controller unit.

Based on this signal from sensor, the controller decides particular coils to energize. Hall-effect sensors generate Low and High level signals whenever rotor poles pass near to it. These signals determine the position of the shaft.

4. Comparison between BLDC Motors with Other conventional Motors.
Compared to brushed DC motors and induction motors, BLDC motors have many advantages and few disadvantages. Brushless motors require less maintenance, so they have a longer life compared with brushed DC motors. BLDC motors produce more output power per frame size than brushed DC motors and induction motors. Because the rotor is made of permanent magnets, the rotor inertia is less, compared with other types of motors. This improves acceleration and deceleration characteristics, shortening operating cycles. Their linear speed/torque characteristics produce predictable speed regulation. With brushless motors, brush inspection is eliminated, making them ideal for limited access areas and applications where servicing is difficult. BLDC motors operate much more quietly than brushed DC motors, reducing Electromagnetic Interference (EMI). Low-voltage models are ideal for battery operation, portable equipment or medical applications. Table 1 summarizes the comparison between a BLDC motor and a brushed DC motor. Table 2 compares a BLDC motor to an induction motor

TABLE 1: Comparison between A BLDC Motortoa Brushed DC Motor

Feature	Brushed type DC Motor	Brushless DC Motor (BLDC Motor)
Commutation	Brushed commutation	Electronic commutation based on Hall position sensors.
Efficiency	. Moderate.	High – No voltage drop across brushes
Output Power/ Frame Size	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size.	High – Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better.
Life	Shorter	Longer..
Speed/Torque Characteristics	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque	Flat – Enables operation at all speeds with rated load.
Speed Range	Lower – Mechanical limitations by the brushes	Higher – No mechanical limitation imposed by brushes/commutator.
Maintenance	Periodic maintenance is required.	Less required due to absence of brushes.
Electric Noise Generation	Arcs in the brushes will generate noise causing EMI in the equipment nearby	Low.
Cost of construction	Low.	Higher – Since it has permanent magnets, construction costs are higher.
Control Requirements	No controller is required for fixed speed; a controller is required only if variable speed is desired.	A controller is always required to keep the motor running. The same controller can be used for variable speed contro

Table 2 comparison between a BLDC motor to an induction motor

Features	AC Induction Motors	BLDC Motors
Output Power/ Frame Size.	Moderate – Since both stator and rotor have windings, the output power to size is lower than BLDC	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power.
Rotor Inertia.	High – Poor dynamic characteristics.	Low – Better dynamic characteristics
Speed/Torque Characteristics.	Nonlinear – Lower torque at lower speeds.	Flat – Enables operation at all speeds with rated load
Slip.	The rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the motor	No slip is experienced between stator and rotor frequencies
Starting Current.	Approximately up to seven times of rated – Starter circuit rating should be carefully selected. Normally uses a Star-Delta starter	Rated – No special starter circuit required
Control Requirements	No controller is required for fixed speed; a controller is required only if variable speed is desired.	A controller is always required to keep the motor running. The same controller can be used for variable speed control.

5. Advantages, Disadvantages and applications of Brushless DC Motors
5.1 Advantages

- It has no mechanical commutator and associated problems
- High efficiency due to the use of permanent magnet rotor
- High speed of operation even in loaded and unloaded conditions due to the absence of brushes that limits the speed
- Smaller motor geometry and lighter in weight than both brushed type DC and induction AC motors
- Long life as no inspection and maintenance is required for commutator system
- Higher dynamic response due to low inertia and

carrying windings in the stator
- Less electromagnetic interference
- Quite operation (or low noise) due to absence of brushes

5.2 Disadvantages
- These motors are costly since it requires Electronic controller
- electronic control solutions, especially for tiny BLDC motors
- Requires complex drive circuitry
- Need of additional sensors

5.3 Applications of Brushless D.C Motor
BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors.
Out of these, we can categorize the type of BLDC motor control into three major types:
• Constant load
• Varying loads
• Positioning applications

Applications with Constant Loads
Features:
These are the types of applications where a variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft.
For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly operating in open-loop.

Applications with Varying Loads
Features:
These are the types of applications where the load on the motor varies over a speed range. These applications may demand a high-speed control accuracy and good dynamic responses.
In home appliances, washers, dryers and compressors are good examples.
In automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these.
In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on.
These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

Positioning Applications
Features:
Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction. A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. These systems mostly operate in closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical encoder or synchronous resolvers are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions. Some of the important applications are
- Computer Numeric Controlled (CNC) machines
- Process controls,
- Machinery controls and
- Conveyer.

6. Low cost BLDC
In a research done by Tae-UkJung on Low Cost Design of Brushless DC Motor for Electric Water Pump Application ,a BLDC motor for a pump, in which the neodymium magnet is replaced with the Ferrite magnet, has been developed. In this paper the cost reduction design is studied to release the cost burden of BLDC motor for electric water pump using Nd-Fe-B material magnet. In order to minimize the material cost of permanent magnets, firstly, the magnet material is changed as ferrite magnet. By this, the air-gap length is largely reduced by the elimination of water proof capsulation of water pump. It helps the utilization of rotor magnet flux.
One of the pump motors is an IPM rotor type BLDC motor using the neodymium. However, the motors using neodymium magnets should have large air-gaps. This is because the composition of neodymium magnet is based on metal materials so the motors using this magnet should have larger air-gaps and waterproofing for rust. On the other hand, other motors using Ferrite magnets are able to have enough effective air-gaps because Ferrite magnet is not based on metal materials so the rotor using this magnet does not need to be waterproof. This point means that Ferrite type motors are able to utilize effectively the rotor flux by having enough effective air-gaps. The use of Ferrite magnet causes deterioration in the performance of the motor. This causes the decrease in the back-electromotive force (BEMF), the maximum power of the motor and the irreversible demagnetization characteristic of the magnet. In order to compensate for the lower performance, the SPM type structure is adopted. This paper presents the low cost design technology using optimal parameters and electromagnetic structure.
The conventional BLDC motor for water pumps is the 20W IPM motor using the neodymium magnet. The detailed design specifications are represented in Table 6.1. The concentrated windings are wound on 9 slots and the salient structural 6 poles with Nd-Fe-B magnet are in the IPM type

rotor. In this water pump structure, water can be leaked into inner part which rotor is placed. The urethane moulding waterproof insulation is applied to prevent the rust of NdFe-B magnet in the rotor. Therefore, the air gap length would be increased by the thickness of waterproof insulation. It causes the increase of magnetic resistance of air gap flowing flux. Therefore, the Nd-Fe-B magnet having high residual flux density is applied in the conventional water pump motor. Even though the material cost of rare earth Nd-Fe-B magnet is the great part of total material cost, the flux utilization of magnet is not efficient due to the long air-gap length. The proposed rotor structure is focused on this issue. The ferrite magnet instead of the rare earth magnet is applied to minimize the material cost of magnet. And the rotor structure is redesigned using ferrite magnet with the same stator core structure.

Employed material		
Magnet	Neodymium	NdFeB38H
		Br : 1.21 ~ 1.25 [T]
		-Hc : ≥ 899 [kA/m]
	Ferrite	NMF-7BE
		Br : 0.41~0.43 [T]
		-Hc : 286~326 [kA/m]
Steel Sheet		50A1300(S60)
		Non-oriented silicon steel sheet
		Density : 7.9 [g/cm²]
		Sheet thickness 0.5 mm

Table 6.1. Specifications of conventional water Pump

Some of the research details belowbriefly explained how low cost design is done keeping the similar level of driving efficiency.

Design procedure of BLDC motor :The proposed motor is the SPM BLDC motor using Ferrite magnet. Unlike in the IPM motor, the reluctance torque is not generated and only the magnetic torque is generated because of not having air-gap length changes. The aim of the present study is to design the SPM rotor in which the rare-earth magnet is replaced with the Ferrite magnet. The design for the stator shape in the proposed BLDC motor is carried out under the same conditions with the conventional BLDC motor. Table 6.(2) shows the comparison of the characteristics between the Ferrite magnet used in the proposed motor and the Nd-Fe-B magnet used in the conventional motor .as the characteristics of the core, a non-oriented silicon steel sheet is used

Design of thickness of ferrite magnet :The Ferrite thickness is designed to have safe in demagnetization for withstanding the magnetic field generated from the maximum current in the stator winding. The safety condition for demagnetization is U F m m + ≤ Hm m ·l , wherein the bend(curve, line) point of the demagnetization is Hm , and the magneto-motive force of the rotor surface by the stator current is Fm . The thickness of the neodymium magnet in the conventional motor is 1.2 [mm], and the demagnetization current is 14 [A]. The thickness in the case of Ferrite is 3.5 [mm]. Also, the final determination of the thickness should be made by the BEMF and the output characteristics.

Since the Ferrite magnet has weaker magnetic force than the neodymium magnet, the proposed motor should have narrow air-gaps. Therefore, the air-gap is designed as 1 [mm] through the capsulation removal.

Employed material		
Magnet	Neodymium	NdFeB38H
		Br : 1.21 ~ 1.25 [T]
		-Hc : ≥ 899 [kA/m]
	Ferrite	NMF-7BE
		Br : 0.41~0.43 [T]
		-Hc : 286~326 [kA/m]
Steel Sheet		50A1300(S60)
		Non-oriented silicon steel sheet
		Density : 7.9 [g/cm²]
		Sheet thickness 0.5 mm

Table 6.2. Property of material used for BLDC motor

Some of the experiment details given in the following tables. Table 6.3 shows comparison of output characteristics and Table 6.4 shows Material cost comparison

Unit	ConventionalIPM	Proposed SPM
Input DC Voltage [V]	12	
Speed [rpm]	3600	
Current [A]	1.52	1.34
Torque [mNm]	60	61.5
Output [W]	22.6	23
Efficiency [%]	42.1	42.8
Torque ripple [%]	12.2	9

Table 6.3 Comparison of output characteristics

Motor type	Items	Copper	Permanent magnet	Si-steel	Total cost (Won)
Conventional	Used weight (g)	27.8	3.8	27.8	1136.9
	Unit price (Won)	9.5	200.0 (Nd-Fe-B)	4.2	
	Cost (Won)	263.9	756	117	
	Cost rate (%)	23.2	66.5	10.3	100
Proposed	Used weight (g)	35.2	8.8	18.5	588.7
	Unit price (Won)	9.5	20.0 (Ferrite 9BE)	4.2	
	Cost (Won)	334.0	176.8	77.9	
	Cost rate (%)	56.7	30.0	13.2	100

Table 6.4The comparison of material cost composition

II. CONCLUSION

In conclusion, BLDC motors have advantages over brushed DC motors and induction motors. They have better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, rugged construction n and so on. Also, torque delivered to the motor size is higher, making it useful in applications where space and weight are critical factors. With these advantages, BLDC motors find wide spread applications in automotive, appliance, aerospace, consumer, medical, instrumentation and automation industries.

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