Performance Analysis of BLDC Motors and its Various Control Strategies

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ABSTRACT:

Brushless direct current (BLDC) motors are frequently used in dynamic applications. A Brushless DC Motor is similar to a Brushed DC Motor, except that as the names indicate, they are electronically commutated rather than using brushes for commutation. Brushes are utilized in conventional brushed direct current motors to transmit power to the rotor while they rotate in a fixed magnetic field. Small Brushless DC Motors have flourished as a result of current power electronics and microprocessor technology, both in terms of price and performance. This paper will discuss the history of BLDC motors, their different types, construction, operating principles, and several control mechanisms for driving BLDC motors in various industrial applications.

Keywords: BLDC Motor, Pulse Width Modulation (PWM), Hall Effect Sensors, Sensorless control, Rotor, Stator, Back Emf, Trapezoidal Control, Sinusoidal Control, Field Oriented Control

INTRODUCTION:

T. G Wilson and P.H. Trickey conducted several experiments before 50 years to run Direct Current (DC) motors with solid-state commutation, which created the basis for developing BLDC motors [1] based on Lorentz's force law. BLDC motors have been the center of extensive research in recent decades in order to promote the development of electric cars and UAV's etc. Because of their versatility, compact design, and low weight, BLDC motors are used in a diverse range of sectors, including avionics, automotive, pumping, and rolling [2]. Since demand for electric cars and unmanned aerial vehicles is predicted to rise over the next ten years, BLDC motors are likely to play a crucial role. The global market for BLDC motors is forecast to reach 15.2 billion USD by 2025, up from an estimated 9.6 billion USD in 2020, as shown in Fig.1. This machine's tremendous proliferation has enticed diverse applications [3].BLDC motors provides elevating, cutting, and bracing according to the purpose of the application, such as static or dynamic [4].

BLDC motors provide us with a rapid response especially compared to other types of motors. They must always be properly designed to have powerful electromagnetic linkage in order to be used for variety of purposes such as improved efficiency, higher torque to weight ratio, and lower operational noise [5]. The stationary flux between the rotor and stator in these devices primes the motor to run with a unity power factor. Electronically commutated motor drives are used to energize BLDC motors. A closed-loop controller drives each phase of the motor. A closed-loop controller is generally used to deliver a current pulse to the stator winding in order to regulate the speed and torque, which are complimentary phenomena in a motor [6]. Since BLDC motors are operated with such efficiency, they suffer from excessive wear and tear under load.

BLDC motors generally have an efficiency of 85 to 90 percent, whereas brushed type DC motors own an efficiency of 75 to 80 percent. There are several different types of BLDC motors available, ranging from low power ranges through fractional horsepower, integral horsepower, and enormous power ranges.

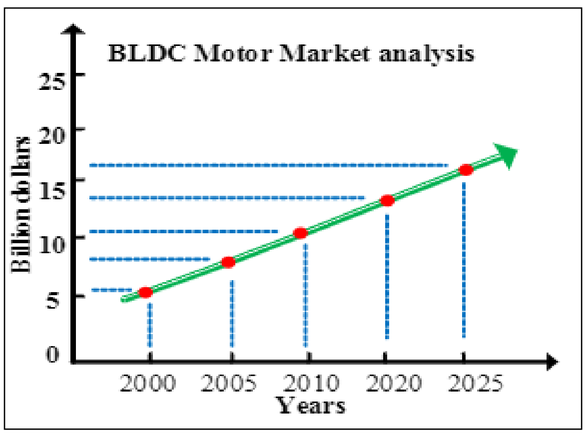

Fig 1:

BLDC Motor Market Analysis

A few circuits utilize Hall Effect sensors to directly detect the rotor's position, while few others, known as sensor-less controllers, detect the back electromotive force within the non-driven coils to gather the rotor's location. A generic hall sensor fixed BLDC motor comprises three dual-directional outputs which are controlled by a digital logic circuit [7].

Several sensor-less controllers are designed to measure the winding current flow generated by magnet direction to determine the rotor position and estimate parameters such as back electromotive force (EMF) and flux [8]. Despite the fact that indirect control (sensor-less) delivers less ability to respond than direct control (with sensor) and increases structural complexity, indirect controls are prioritized in many high-power automotive applications such as electric trains, aircraft, UAV's and so on. Sensor-less control is accomplished in three principles namely (i) EMF method with zero-crossing, (ii) observer-based EMF method, and (iii) magnetic anisotropy method [28].

The EMF mechanism with the zero-crossing principle is frequently utilized [9]. The other two principles are difficult to control and are not advisable for low-speed operations. The speed of the motor and the commutation logics are regulated in the drive for efficient control by aggregating inputs from both the drive and the motors such as rotor position or rotor angle, stator currents, hysteresis band current, and so on. The correct rotation of the motor is ensured by proper control of switching of multiple switches in motor drives [10].

While there are other techniques for regulating the current harmonics in drive supply, we opt to use the Pulse Width Modulation (PWM) technology [29]. Specifically, everyone likes space vector PWM (SVPWM) control among PWM approaches. Current control techniques using PWM and hysteresis controllers are significant for optimizing motor drive performance. Among the PWM approaches, everyone likes space vector PWM (SVPWM) control. Current control schemes using PWM and hysteresis controllers are significant in increasing the efficiency of motor drives.

Technologically advanced unipolar PWM control techniques might well be classified as follows: I H-PWM-L-ON, (ii) H-ON-LPWM, ON-PWM, (iii) PWM-ON, (iv) PWM-ON-PWM, (v) H-PWM-L-PWM modes [11].

TYPES OF BLDC MOTOR:

The physical construction of a BLDC motor is divided into two sections stator and rotor. Figure 2 represents the categorization of BLDC motor types. In inner rotor the rotor is located at the center of the motor. In outer rotor the location of the rotor surrounds the windings that are present in the core of the motor. The motor is manufactured in a range of designs, incorporating inner and outer rotors. The outer rotor-designed BLDC motor is described in [12]. The rotor's permanent magnet is embedded on the outside, while the stator windings are kept stationary on the inside. The outer rotor BLDC enhances the motor's output torque and power density.

The BLDC outer rotor motor is mostly utilized in electric cars, drones, variable drive applications, water pumping, and home electronics. The air gap radius between stator and rotor is decreased in [13] outer rotor BLDC motor design. As a result, the torque capability per unit length and current is increased. In [14], structural features have been added to optimize the rotor's stability. They enhance motor attributes in turbulent environments. The ferrite bonded magnet BLDC motor is analyzed using finite element analysis.

Experimentation shows that the inner rotor motor has appropriate power characteristics under dynamic situations. In [15] outlines a basic algorithm for a high-speed ferrite-based BLDC motor. Mechanical limits are adjusted to optimize magnetic flux components.

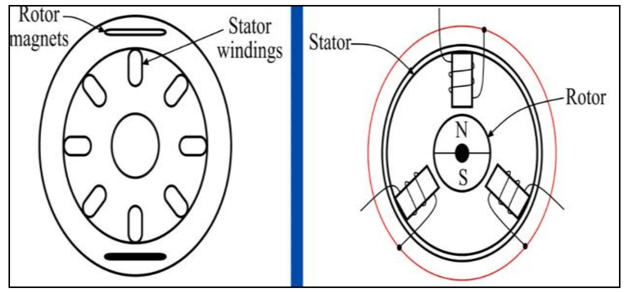

Fig 2: Outer and Inner Rotor

Table I covers the comparison of inner rotor and outer rotor BLDC.

Rotors in BLDC motors are generally made up of permanent magnets as well as a shaft, depending on the design of the PM rotor. Permanent magnets in motors are categorized into three types based on their cross-section: (i) surface mounted magnets [16], (ii) inserted magnets [17], and (iii) buried or embedded type rotor magnets [18-19]. In this case, the embedded type is more productive than the other types.

These BLDC motor drives are incorporated in many ways depending on the customer's expectations, such as magnetic field path, radial and axial flux. Axial flux motors exceed radial flux motors in terms of power output. The attributes of an axial flux type BLDC motor are examined in [20] adopting flux linkage methodology. The twin rotor technique enhances the mechanical stability of the BLDC motor.

BLDC motor physical design	Inner Rotor	Outer rotor
Stator	• Iron less core stator winding outside.	• Iron cored stator winding inside.
Speed	• High-speed motors are available.	• Low and medium speed motor available.
Inertia	• Low inertia	• High inertia
Noise	• Quickly changing direction makes noisy.	• Noise less.
Maintenance	• Less maintenance.	• High maintenance.
Efficiency	• High efficiency.	• Less efficiency compares to the inner rotor.
Torque	• Minimum torque.	• Produce more torque.
Power to weight ratio	• Compare to outer run less.	• High.
Gear box	• Gear box required.	• No gear box required.
Advantage	• Rotating shaft moment of inertia is small. • Heat dissipation efficiency high. • Reduce the downsize unit. • Compact size. • High output power.	• Increasing the torque capability and current. • Reducing heat dissipation. • Low cogging force. • Large airgap. • Increase torque.
Disadvantage	• Requires high magnetic flux density. • Need high-performance magnet. • High cogging force.	• Complex to design rotor embedded with magnets. • Mechanical stability. • Cooling stator winding.

Table I: Comparison of the inner and outer rotor features

In [21] examines and evaluates three distinct types of radial flux motors. In accordance with the results of the investigation, the dual rotor type offers good dynamic characteristics. Table II compares the axial and radial flux characteristics.

Furthermore, the categorization of BLDC motors based on stator components is reviewed. The number of phases, laminated core types, and back EMF of a BLDC stator can each be characterized. The number of phases of operation in a BLDC stator can be categorized.

Single-phase and three-phase motors are usually deployed in static applications. For dynamic applications such as electric cars, three-phase, five-phase, and seven-phase motors are favored.

Magnetic flux direction	Axial flux	Radial flux
Flux direction strength	• Flux-path is shorter.	• Flux-path is longer.
Magnetic field	• Strong	• weak
Efficiency	• High	• Compare to axial low.
Power density	• High	• Minimum.
Direction	• Flux unidirectional path.	• 2D dimensional path.
Iron loss	• Decreasing iron loss.	• Iron loss maximum.
winding	• Minimum heat conductivity.	• Low thermal conductivity.
diameter	• High	• Medium
Active length	• Minimum	• High
Mass	• Low	• High
Output voltage	• High	• Low.
Outer rotor	• High torque.	• Less torque.

Table II: Electromagnetic axial and radial flux path difference

Stator structure	Slotted	Slotless
Advantages	• Uneven magnetic pull. • High power density. • Higher order spatial harmonics. • Easier to protect.	• High power density. • Low cogging torque • Better overload capacity. • Limit the operational noise. • Increase operating frequency.
Disadvantages	• Volume of the machine size is big. • Poor overloading. • High cogging torque. • Enables to operate at high speed. • Less efficiency. • Increasing noise and vibration.	• Low inductance to control motor is challenging. • Not suitable for harsh environmental conditions.

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Table III: Comparison of slotted and spotless features.

A multiphase BLDC motor is proposed in [22] using an overlapping winding method. Utilization of an overlapping approach optimizes flux linkage between the coils. Multiphase motor topologies significantly enhance fault tolerance and torque characteristics. The stator coil winding is connected in a star or delta configuration. Depending on the application, various winding models are preferred. For high torque low-speed applications, a star connection is favored, even though a delta connection is chosen for low torque low-speed applications. The number of poles in the rotor increases as the speed increases.

Laminated iron cores are categorized into slotted and slotless cores. The slotted stator usually creates high-order spatial harmonics in [23] due to the reaction of the PM flux with the fluctuating permeance of the stator. This produces a slight vibrating torque on the shaft, known as cogging torque. As a consequence, it minimizes operational noise, which is essential for slotless machines. Furthermore, slot-less machines have lower rotational eddy loss, which enables the motor to operate at greater velocity. Table III compares slotted and slotless features.

The stators are also categorized based on their back emf waveforms, which are sinusoidal and trapezoidal. The interconnection between the stator windings and the air gap distance influence the shape of the back emf. As compared to trapezoidal back emf, BLDC motors are more efficient. These motors are somewhat more costly than trapezoidal back EMF BLDC motors [24-26] owing to the use of extra copper windings.

CONSTRUCTION AND WORKING OF BLDC MOTOR:

The BLDC motor operates on the same principle as a typical Dc motor, namely the law that states that if a current carrying conductor is placed in a magnetic field, it experiences a force. The magnet will feel an equal and opposite force as a response of the reaction force. In the case of a BLDC motor, the current carrying conductor is stationary while the permanent magnet moves.

As the stator coils are electrically switched by a power supply, it converts into an electromagnet and begins to generate a continuous field in the air gap. Regardless of the fact that the power supply is DC, switching yields an AC voltage waveform with a trapezoidal shape. The rotor continues to rotate due to the force of contact between the electromagnet stator and the permanent magnet rotor.

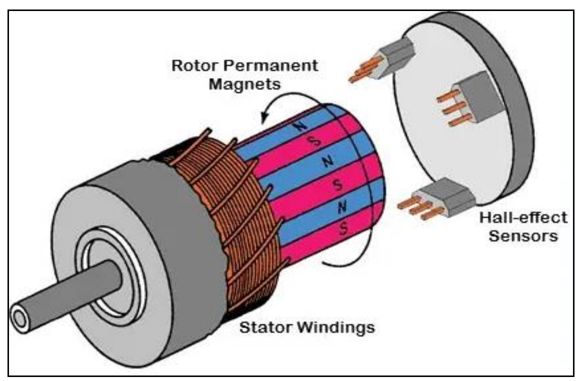

Fig 3: Construction of BLDC Motor

Windings are energized as North and South poles when they are swapped as High and Low signals. The motor will rotate so because permanent magnet rotor's North and South poles align with the stator poles. Understand how a motor generates torque as a result of the creation of attraction forces (whether aligned North-South or South-North) and repulsion forces (when North-North or South-South alignment). In this manner, the motor rotates clockwise.

Here, one might wonder how we know which stator coil should be powered and when. This is owing to the fact that the motor's continuous spinning is reliant on the switching sequence around the coils. As stated previously, Hall sensors provide shaft position feedback to the electronic controller unit.

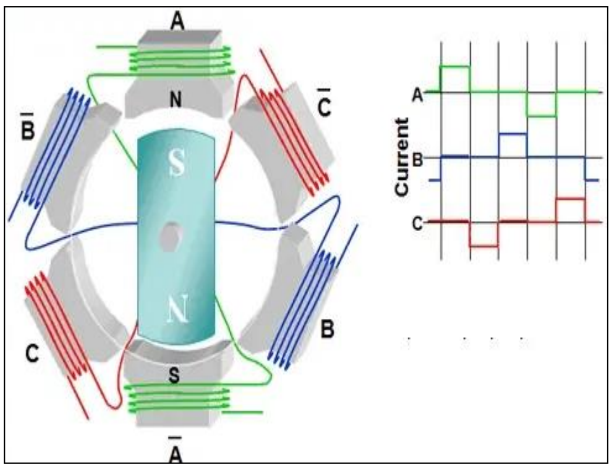

Fig 4: Operating Principle of BLDC Motor

The controller controls which coils to energize based on the sensor signal. As rotor poles pass close to a Hall-effect sensor, it produces Low and High level signals. These signals control the shaft's location.

CONTROL TECHNIQUES:

(a) Trapezoidal control:

Trapezoidal Control is one of the most basic and widely used techniques for controlling Brushless DC motors (BLDC). The stator is made up of three stator windings that serve as terminals. Current is regulated through two terminals at a time in this approach, with the third terminal electrically isolated from the source. Hall Effect sensors are typically embedded in motors to detect rotor position. A current of appropriate magnitude is flowing in two of the coils at any one moment, while the third is zero. As a result, the current space vector can flow in any of six alternative directions. [27].

Even though only one phase current needs to be monitored, this approach is very simple and inexpensive to deploy. As a consequence, it is suitable for low-cost applications that do not require significant performance. Because only one phase current needs to be controlled, this method is very simple and affordable to implement. As a consequence, it is appropriate for low-cost applications that do not require high performance.

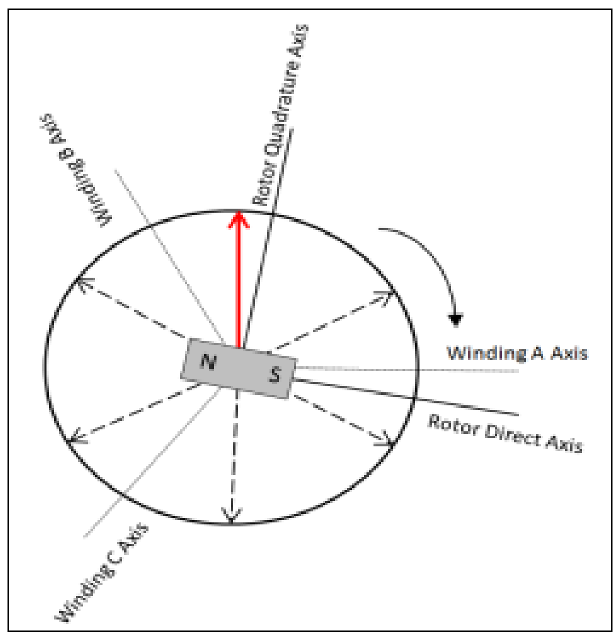

Fig 5: Possible directions of current space vector in trapezoidal control

(b) Sinusoidal control:

The Sinusoidal Control approach is to drive all three motor windings with currents that fluctuate smoothly and sinusoidally as the motor rotates. This requires regulating the three winding currents to ensure that the resultant space vector is always in quadrature with respect to the rotor and has constant magnitude.

To accomplish this, accurate rotor position measurements are necessary, which may be given by Resolver or Quadrature Pulse Encoders. Since the windings are connected in a star configuration, the current in one of these is the negative sum of the currents in the other two windings. As a consequence, a current control loop is necessary for the first two windings in this architecture. A typical sinusoidal control system block diagram. [28].

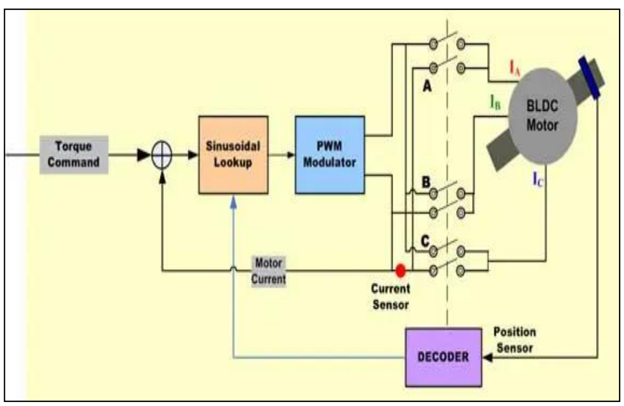

Fig 6: Sinusoidal Control

Sinusoidal Control eliminates Torque Ripple and provides smooth rotation with improved efficiency at low speeds, overcoming some of the disadvantages of Trapezoidal Control.The sinusoidal control is mainly used in PMSM-BLDC motors for drone applications in order to get the sinusoidal back emf for controlling the rotation and position of the motor.

(c) Field- oriented control

The Field Oriented Method of control is quite equivalent to Sinusoidal Control. But so far, due to some fundamental differences, it has become more effective at high speeds. The fundamental limitation of Sinusoidal Control is that it strives to controls motor currents whose amplitude and direction fluctuate over time. Due to their constrained bandwidth, PI controllers becoming incapable of handling the operation as the speed and frequency rise. This challenge may be resolved by describing and regulating the current space vector along the two dimension d-q.

The FOC algorithm can provide several benefits. High efficiency, smooth operation at high and low speeds, resulting in a wide speed range, transformation of a complicated and linked AC model into a simple linear system and fast dynamic response and good transient and steady state performance.

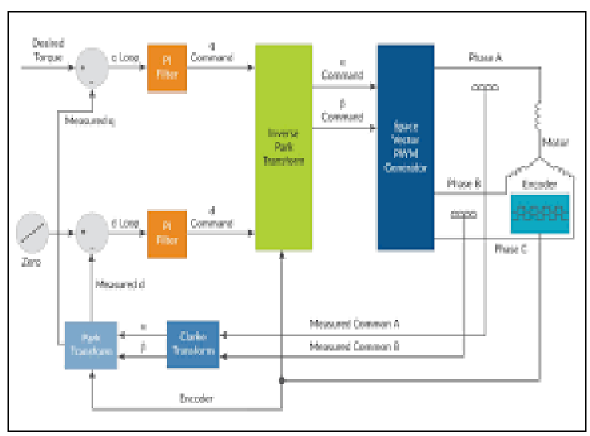

Fig 7: FOC Control Method

(d) PWM control method:

While also different control strategies are discussed in [29,] there are essentially two methods for controlling a PMBLDC motor. They have sensors control, as well as sensor-less control. Sensor-less techniques include position encoders and back EMFs. In sensor-based solutions, hall sensors and optical sensors are employed.

The PWM duty cycle control approach improves the efficiency and functionality of the Brushless DC motor by providing even more flexible control and unique cyclic operation, as well as improved motor protection schemes.

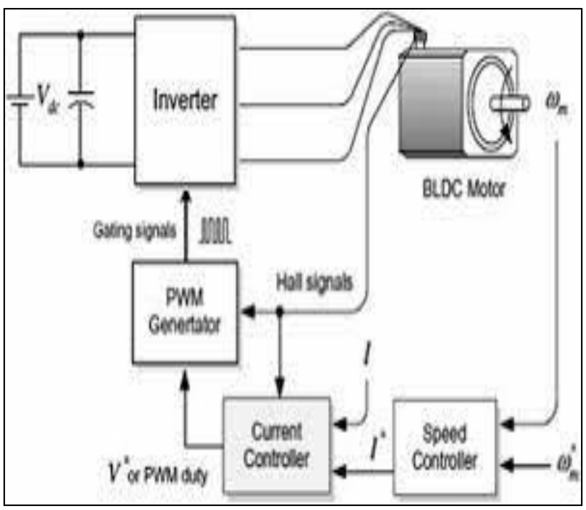

Fig 8: PWM Control

CONCLUSION:

This paper reviews about different types of BLDC motors, their construction and working principles. According to the study the outer rotor is having better performance than inner rotor motor and it is widely used for several commercial applications. According to the different types of control strategies of ESC trapezoidal control is simple and provides smooth operation at high speeds, but creates torque ripple at low speeds. While Sinusoidal Control minimizes torque ripple and enables efficient operation at low speeds, the constraints of a PI controller make it unsuitable for high-speed applications. Field Oriented Control (FOC) combines the greatest features of the preceding two approaches, providing smooth and economical operation as well as quick dynamic response at low and high speeds. Finally, the challenges in BLDC motor for different types of current control techniques and performance of BLDC motor with sensor and sensorless techniques are the future work according to this paper.

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