



Development Of Bldc Motor With Field Oriented Control For Automotive Engine Cooling Fan

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Abstract: The paper expresses a review of Brushless DC (BLDC) motor control techniques and their applications in the automotive industry. BLDC motors characterized by their efficiency, reliability, and low maintenance requirements, have become increasingly prominent in automotive applications. This paper outlines the fundamental principles of BLDC motor operation, including the electronic commutation process and the role of sensors. It explores various control strategies, such as Hall sensing control, field-oriented control (FOC), current controller. The discussion includes practical challenges in automotive applications, such as thermal management, noise reduction, and the integration of BLDC motors into complex automotive systems. Through this review, the paper aims to provide insights into the current state of BLDC motor control technology and its critical role in advancing modern automotive domain.

Keywords : Brushless DC motor , Hall sensor, Field Oriented control, current controller, Drive, Automotive application

Introduction

DC motors have been substantially used for speed or position control applications due to ease of control as compared to the AC motors. However, due to the necessity of frequent maintenance on brushes and commutators, their use is no longer very common in most motor drive applications, especially where the motor is required to run continuously and with improved reliability. To reduce this issue of DC motors, the brushless direct current motor was invented to quell the issues of DC motors. Electrical features of this motor are rather similar to those of the DC motor but at the same time, it has some additional advantages, namely the high reliability which comes together with the replacement of mechanical commutation with the electronic one. To effect the electronic commutation, BLDC motors employ the use of sensors as well as circuits for driving. The position of magnets on the rotor is sensed by the detectors appropriately named the sensors. With the help of the detected position of the magnet, the driving circuits energise a certain winding to drive the motor continuously. In the BLDC motors, to remove the brushes of the dc motors, the armature winding is fixed in stator side whereas the magnets are fixed in rotor side. Therefore, the configuration established in BLDC motors is in variance with that of DC motors. When designing to remove brushes, there is some degree of freedom in the motor configuration and consequently, there are a multitude of BLDC motor designs to satisfy the needs of a specific application or in this case a smaller or thinner configuration. The merits in using BLDC motors include the following; efficiency, power density, torque – inertia ratio, speed capability, easy to drive, and cheap. As a result, today these inverters are used in many cost-effective solutions in numerous small and medium motor drive applications, home appliances, industries, office items and small vehicles.

I. BLDC MOTOR FOR AUTOMOTIVE APPLICATION:

A brushless DC motor, is an advanced type operates using a direct current power source. Unlike traditional brushed DC motors, which rely on brushes and commutators to transfer electrical power to the rotor, brushless DC motors utilize a different mechanism for generating motion.

At the heart of a brushless DC motor is its construction, which eliminates the need for brushes and commutators. Instead, BLDC motors feature a more complex internal structure that includes permanent magnets on the rotor and a series of electromagnets on the stator. These electromagnets are energized in a specific sequence by an electronic controller.

The primary advantage of brushless DC motor is soft starting. Because they lack the friction and wear associated with brushes and commutators, BLDC motors experience less energy loss and heat generation during operation. This results in higher overall efficiency, making brushless DC motors ideal for applications where energy conservation is important.

The electronic control system used in brushless DC motors also provides greater flexibility and precision in motor control. By adjusting the timing and intensity of the current provided to the stator windings, the electronic controller can precisely regulate the motor's speed and torque, making brushless DC motors suitable for a wide range of applications with varying performance requirements.

Overall, brushless DC motors offer a compelling combination of efficiency, reliability, and controllability, making them a popular choice for numerous applications across industries such as automotive, aerospace, robotics, and consumer electronics. Their advanced design and performance characteristics make brushless DC motors well-suited for demanding tasks where precision, reliability, and efficiency are paramount.

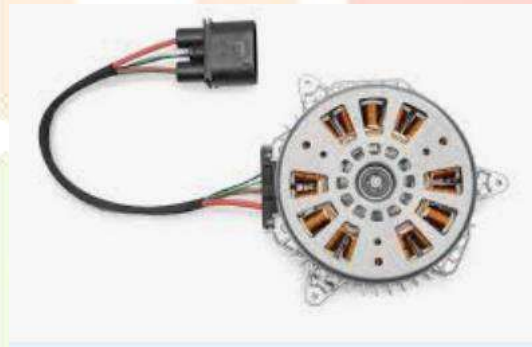


Fig.1: BLDC Motor

AUTOMOTIVE APPLICATION

The integration of BLDC motors using the control techniques has transformed automotive engineering, supporting the industry's shift towards more sustainable and efficient transportation solutions. In electric vehicles (EV) and hybrid electric vehicles (HEV), advanced control methods like FOC enable superior performance, energy efficiency, and driving comfort. Hall sensing and current control techniques are pivotal in auxiliary systems, enhancing functionality and reliability.

BLDC MOTOR IN AUTOMOTIVES

BLDC motors are increasingly used in automotive applications due to their efficiency, reliability, and ability to provide precise control.

- **Electric Power Steering :** BLDC motors provide the required torque and responsiveness for power steering systems, improving vehicle handling and fuel efficiency compared to hydraulic systems.



Fig.2: Power Steering

- **Electric and Hybrid Vehicle Drivetrains :** BLDC motors are commonly used in the propulsion systems of electric vehicles and Hybrid electric vehicles due to their high efficiency, reliability, and excellent torque characteristics.
- **Cooling Fans:** Used in engine cooling and HVAC systems, BLDC motors offer quiet operation and efficient performance, contributing to better thermal management and passenger comfort.



Fig.3: Cooling Fans

- **Fuel and water Pumps:** BLDC motors drive fuel pumps and water pumps in modern vehicles, offering precise control and reduced energy consumption.
- **Window Regulators and Seat Adjustments:** They are also used in electric window regulators and seat adjustment mechanisms, providing smooth and reliable operation.
- **Electric Parking Brake:** BLDC motors are used in EPB systems to automatically engage and release the parking brake, improving safety and convenience.
- **Actuators:** Various actuators, such as those for throttle control, turbochargers, and exhaust gas recirculation valves, utilize BLDC motors for precise and reliable operation.

II. CONTROL TECHNIQUES OF BLDC MOTOR

BLDC motors are commonly controlled using several techniques:

- Trapezoidal Control :** This method is based on powering the motor phases in a sequence that creates a trapezoidal back EMF waveform. It involves using six-step commutation, where the current is supplied to two phases at a time in a predetermined sequence. Hall effect sensors are commonly used for rotor position detection in trapezoidal control.
- Sinusoidal Control :** Sinusoidal control aims to approximate a sinusoidal back EMF waveform for smoother operation and reduced torque ripple. It requires more complex algorithms to calculate the required current vectors for each phase, usually using Park and Clarke transformations. Sinusoidal control often leads to higher efficiency and quieter operation compared to trapezoidal control.
- Field Oriented Control :** FOC decouples the control of torque and flux, allowing for independent control of these parameters. It involves transforming the stator currents from the stationary frame to a rotating frame to simplify control. FOC requires precise knowledge of the rotor position, often obtained using encoders or sensorless techniques.
- Direct Torque Control :** DTC directly controls the torque and flux of the motor without requiring transformation to a synchronous reference frame. It operates by selecting the optimal voltage vector based on the error between the actual and desired torque and flux. DTC offers fast dynamic response and good robustness to parameter variations.
- Sensorless Control:** Sensorless control techniques estimate the rotor position without the need for Hall effect

sensors or encoders. Methods include back EMF integration, observer-based techniques, and sensorless FOC. Sensorless control reduces cost and complexity but may be less accurate at low speeds or under dynamic conditions.

III. BLDC MOTOR DRIVE

The electronic controller circuit picks up the right motor winding and turns transistor or the other solid state switch to make the motor run all the time. The following is showing the simple BLDC motor drive which has MOSFET bridge, electronic controller, hall effect sensor and the BLDC motor.

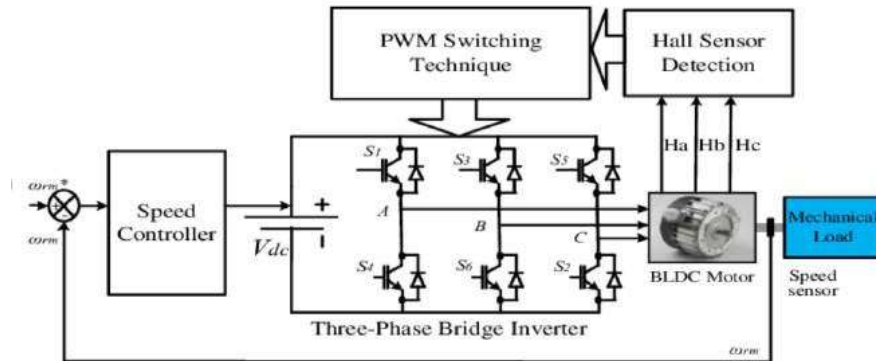


Fig.4: Circuit Diagram of BLDC motor drive

In most electric bicycles, position, and speed feedback, are made us of Hall effect sensors. The electronic controller in the mentioned figure can be a microcontroller unit (MU), microprocessor, DSP processor, FGPA unit or other controller. These signals are thereafter received by this controller, analysed and the control signals relayed to the MOSFET driver circuit.

Apart from the switching for a rated speed of the motor, other circuits that are installed change the speed of the motor according to the necessity of the application. These speed control units are normally incorporated with the PID controller for a more accurate control. I also believe that it is possible to get the four-quadrant operation out of the motor while having good efficiency at varying speeds using contemporary drives.

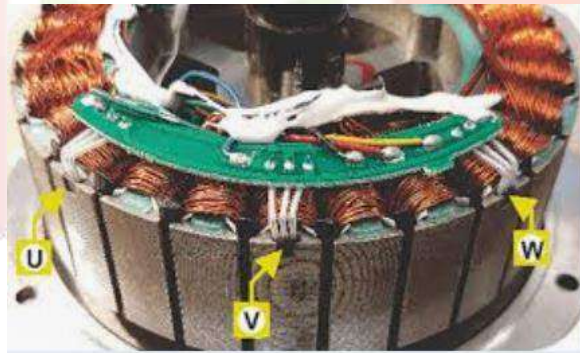


Fig.5: BLDC motor with Hall sensors

V HALL SENSING

Hall sensing is crucial technique used in Brushless DC motors for detecting the rotor position. This information is vital for the precise control of the motor's commutation.

BLDC motors typically use three Hall sensors embedded in the stator. These sensors are strategically placed to detect the magnetic field of the rotor magnets. As the rotor turns, the magnetic poles pass by the Hall sensors, which then produce a digital signal corresponding to the north or south pole of the rotor magnet.

The signals from the Hall sensors provide the electronic controller with the precise position of the rotor. This positional information is critical for timing the switching of the transistors in the inverter circuit that drives the motor. Accurate rotor position data ensures that the correct stator windings are energized to produce a rotating magnetic field, which in turn drives the rotor efficiently.

Commutation in BLDC motors is the process of switching the current in the motor windings to generate a continuous rotational motion. Based on the signals from the Hall sensors, the controller determines which winding to energize to keep the motor running smoothly. Each combination of Hall sensor states corresponds to a specific rotor position and commutation sequence.

MODELLING OF BLDC MOTOR

The Simulink in figure 6 is done in MATLAB 2021A version with ode45 solver. The discrete powergui with time constant of $1e-7$ is used to run the simulation and visualize the results. From the Simulink model the duty cycle has been obtained by sensing the hall signal from the motor and decoded. The rotor speed has been sensed and compared with the reference value and given to the PID controller. By performing the and operation of the above two feedbacks the gate signals have been given the driver to excite any two windings of the stator.

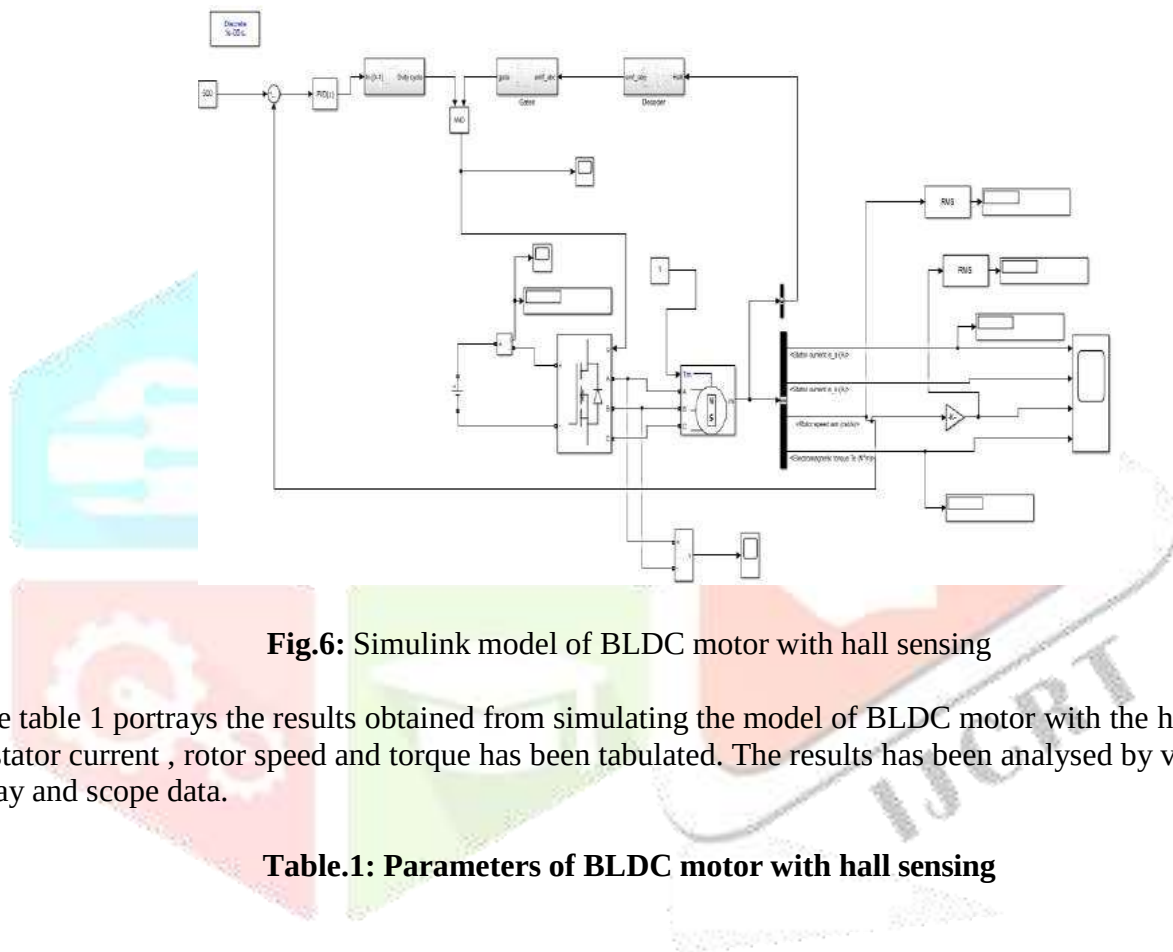


Fig.6: Simulink model of BLDC motor with hall sensing

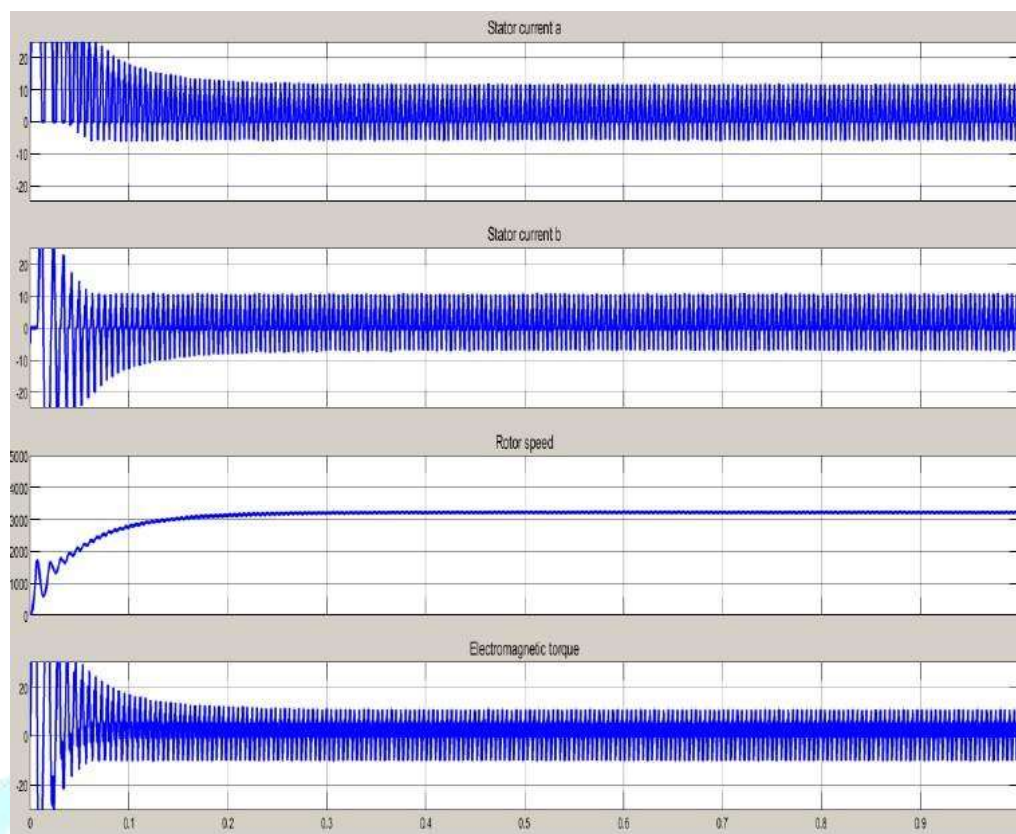
The table 1 portrays the results obtained from simulating the model of BLDC motor with the hall sensing. The stator current, rotor speed and torque has been tabulated. The results has been analysed by verifying the display and scope data.

Table.1: Parameters of BLDC motor with hall sensing

Parameters	Values
Stator current	4.627 A
Rotor speed	337.9 rad/sec
Rotor speed	3227 rpm
Electromagnetic torque	1.144 Nm
DC voltage	500V

The PWM Signals given to the driver of the BLDC motor to excite the windings appropriately. The PWM signals magnitude ranges between 0 to 1. The turn on and turn off time periods are estimated by comparing the feed back signals of rotor speed and hall signals.

The figure 7 showcases the resulting waveforms obtained from the simulation, the stator current indicates which two windings has been excited and its value is around 4.627 A. The rotor rotates around 3227 rpm. The electromagnetic torque obtained around 1.144 Nm.



rent a , Stator current b, Rotor speed, Electromagnetic torque of BLDC motor –Hall sensing

The figure 8 portrays the Inverter output voltage, the voltage obtained across the three phase inverter in 120° conduction mode as the driver. In driver circuitry for every 60° two windings has been excited in cyclic manner and the signals are used to rotate the rotor.

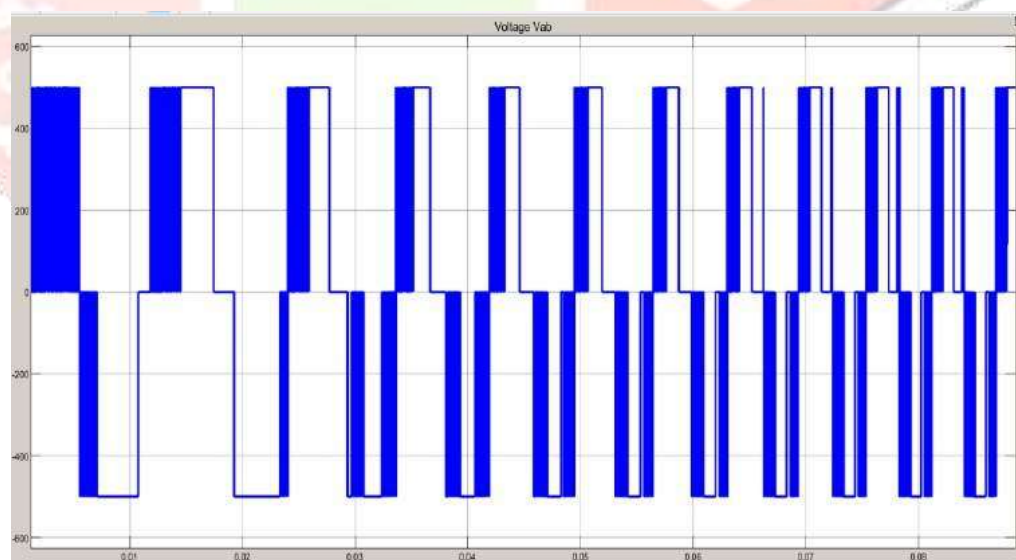


Fig.8: Inverter output voltage

APPLICATION

Hall sensors are easy to integrate and provide consistent performance under standard operating condition. However, they may lack the precision required for high-speed or dynamically demanding applications due to potential inaccuracies in position sensing and the limitations of discrete sensor placement.

Despite these limitations, Hall sensing is widely used in automotive applications such as fuel pumps, cooling fans, and electric power steering systems, where the balance between cost-effectiveness and sufficient performance is crucial. The method's straightforward implementation ensures dependable operation with minimal maintenance requirements, contributing to overall vehicle reliability.

VI FIELD ORIENTED CONTROL

Field –Oriented Control also known as vector control, is an advanced method used for controlling Brushless DC motors. It provides precise control over both the speed and torque by controlling the motor's magnetic field.

FOC aims to decouple the motor's torque and flux control, allowing for independent control of the magnetic field and torque-producing current. This decoupling is achieved by transforming the three-phase motor currents into a two-axis coordinate system, which simplifies the control of the motor.

d-q TRANSFORMATIONS

The figure 9 showcases the transformation equations to convert from one transformation form to the other transformation form.

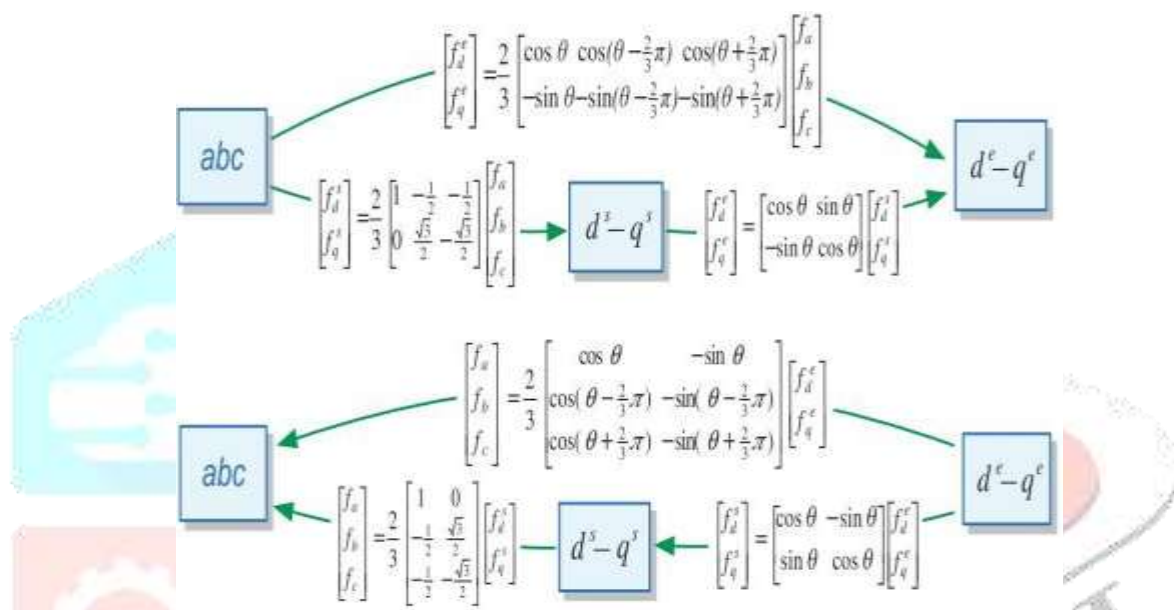


Fig.9: Transformations

IMPLEMENTATION STEPS

- **Current sensing :** Measure the three –phase stator currents (I_a, I_b, I_c)
- **Clarke Transformation:** Convert the three-phase currents into two-phase (I_α, I_β)
- **Park Transformation:** Convert the two-phase stationary frame currents to d- q frame currents.
- **PI Controllers:** Use Proportional-Integral (PI) controllers to regulate I_d and I_q according to the desired torque and flux.
- **Inverse Park Transformation:** Convert the controlled d-q currents back to two-phase currents.
- **Inverse Clarke Transformation:** Convert the two-phase currents back to three-phase currents (I_a, I_b, I_c).

MODELLING OF BLDC MOTOR WITH FOC CONTROL

In figure 10 modelling of BLDC motor with Field oriented control has been done in Plex sim platform. In this control the currents from the driver has been sensed and underwent Clarke transformation. In Clarke transformation the currents I_a, I_b, I_c are converted into I_{ds}, I_{qs} currents in stationary reference frame domain. In Park transformation the I_{ds}, I_{qs} are converted into I_{de}, I_{qe} currents in rotational reference frame domain. In inverse park transformation again the currents in rotational reference frame I_{de}, I_{qe} are converted into stationary reference frame I_{ds}, I_{qs} . In inverse Clarke transformation the currents in stationary reference frame I_{ds}, I_{qs} are again converted into three phase currents I_a, I_b, I_c .

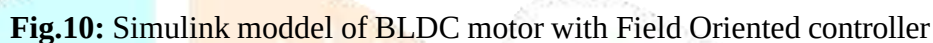


Table.2: Parameters of BLDC motor with Field Oriented controller

In figure 11 the waveforms of the simulation parameters are obtained from the scope data. The stator current of 5.0860 A , Back emf of 179.373 V, rotor speed of 448.20 rad/sec and electromagnetic torque of 4.0736 Nm are obtained from simulation results.

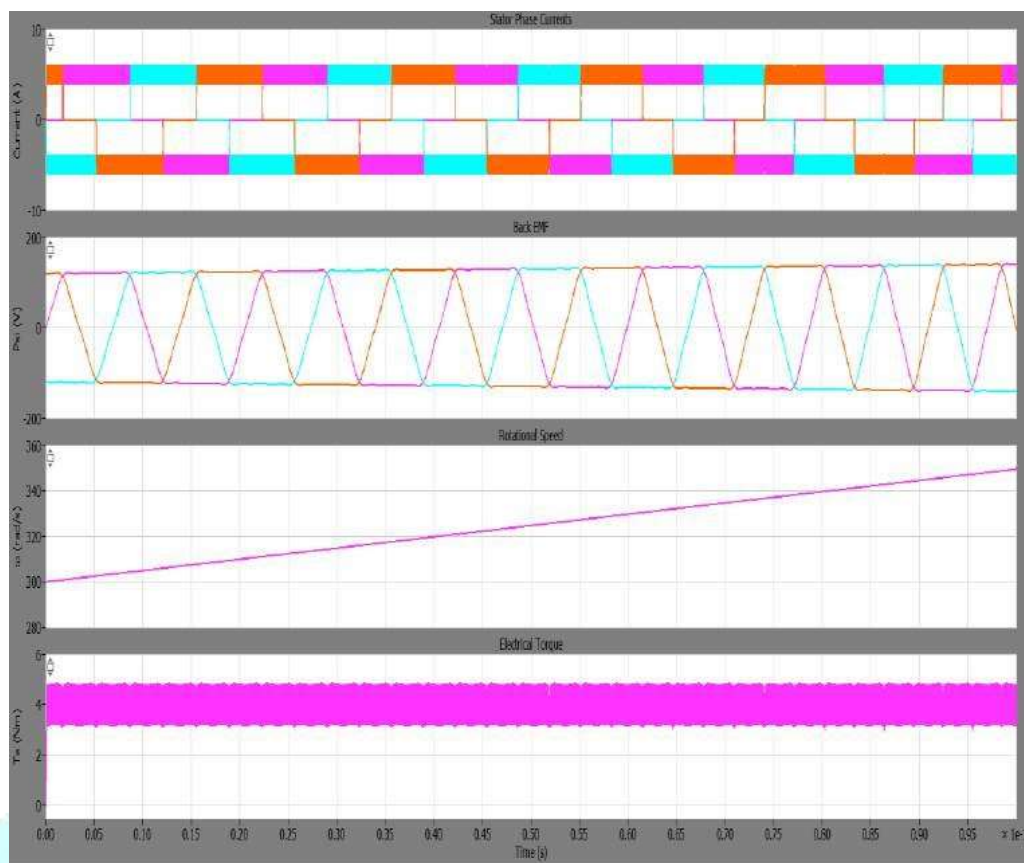


Fig.11: Stator currents , Back emf , Rotor speed, Electromagnetic torque of BLDC motor –FOC

The figure 12 portrays the Clarke transformation, Park transformation, Inverse Park transformation and Inverse Clarke transformation results.

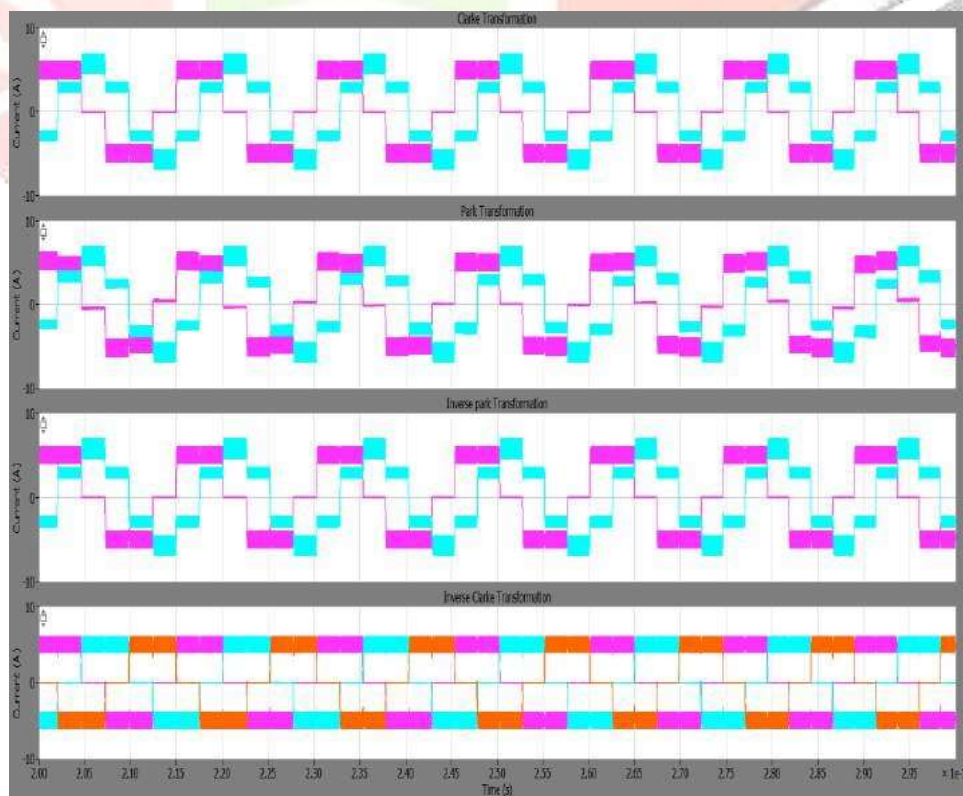


Fig.12: Transformations

FIELD ORIENTED CONTROL

Field Oriented control is a sophisticated technique that optimizes the control of BLDC motors by aligning the motor's magnetic field with the stator current vector. This alignment maximizes torque production and efficiency, allowing for precise and smooth motor operation across a wide range of speeds and loads. FOC's ability to decouple torque and flux control provides superior performance, making it highly effective for high-demand applications.

FOC requires advanced control algorithms and powerful processing capabilities, typically implemented using DSPs or high performance microcontrollers. This complexity translates to higher system costs and increased development effort, but the resulting benefits in performance and efficiency often justify these investments. In automotive applications, FOC enables refined motor control, contribution to smoother acceleration, improved energy efficiency, and enhanced driving experience in EVs and HEVs

VII MODELLING OF BLDC MOTOR WITH CURRENT CONTROLLER

In figure 13 the model of BLDC motor with current controller has been simulated in Plex Sim platform. The pulses for the driver has been obtained by comparing the three phase current with the reference current. The theta value has been obtained from the feedback of angle sensor.

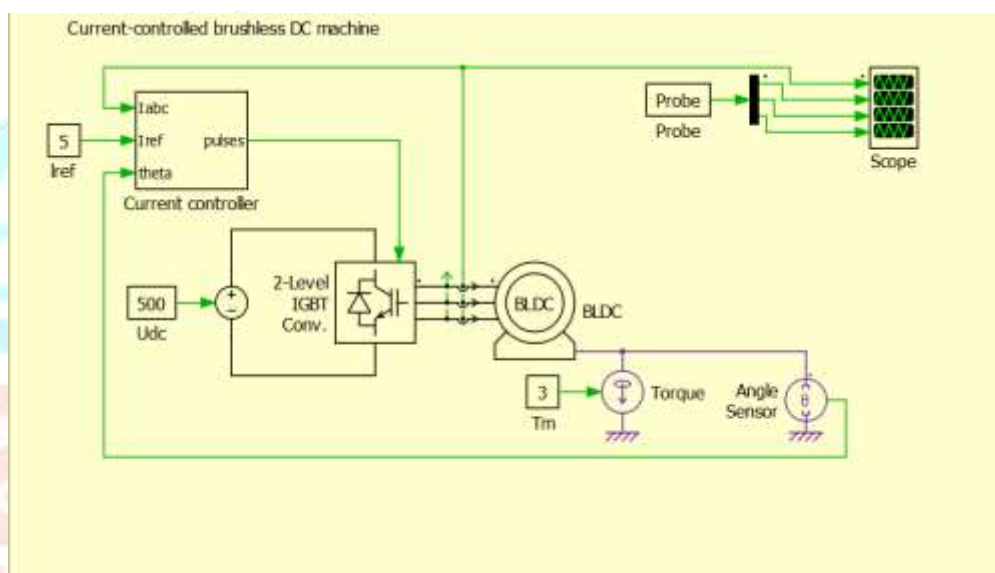


Fig.13: Simulink model of BLDC motor with current controller

The table 3 tabulate the simulation parameters such as stator current , rotor speed, back emf, electromagnetic torque obtained by simulating the simulation with a dc voltage of 500v.

Table 3: Parameters of BLDC motor with current controller

Parameters	Values
Stator current	5.0860 A
Rotor speed	448.207rad/sec
Back emf	179.373 V
Electromagnetic torque	4.0736 Nm
DC voltage	500V

The figure 14 depicts the results obtained from simulating the above circuit and from analysing the waveform its has obtained that stator current of 5.086 A and rotor speed of 448.207 rad/sec , Back emf of 179.373 V and Electromagnetic torque of 4.0736 Nm.

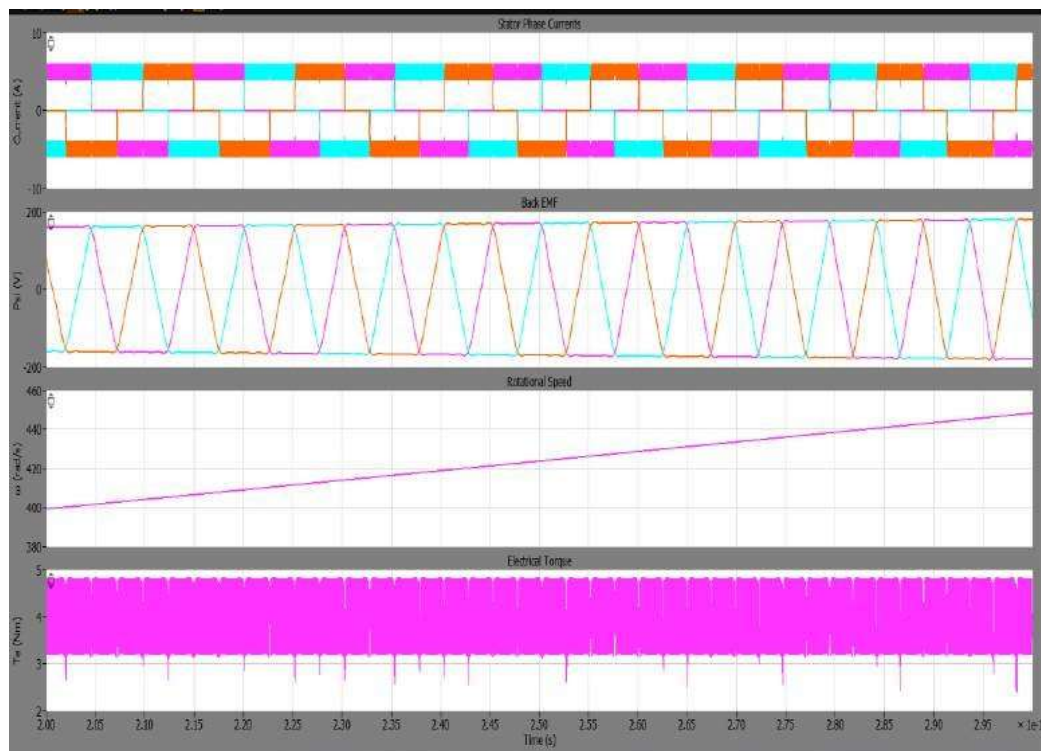


Fig.14: Stator currents , Back emf, Rotor speed, Electromagnetic torque of BLDC motor –Current controller

CURRENT CONTROL

Current control techniques, including direct torque control, focus on maintaining precise control over the motor's current to regulate torque and speed. These methods offer a balance between performance and complexity, providing rapid response to dynamic load changes and ensuring smooth operation. Current control strategies are essential for applications requiring stringent control over motor performance, such as advanced driver assistance systems, braking systems, and active suspension systems.

CONCLUSION

In most electric bicycles, position, and speed feedback, are made use of Hall effect sensors. The electronic controller in the mentioned figure can be a microcontroller unit (MCU), microprocessor, DSP processor, FPGA unit or other controller. These signals are thereafter received by this controller, analysed and the control signals relayed to the MOSFET driver circuit.

Apart from the switching for a rated speed of the motor, other circuits that are installed change the speed of the motor according to the necessity of the application. These speed control units are normally incorporated with the PID controller for a more accurate control. I also believe that it is possible to get the four-quadrant operation out of the motor while having good efficiency at varying speeds using contemporary drives.

In the automotive industry, the integration of BLDC motors using these control techniques leads to enhanced vehicle performance, improved fuel efficiency and reduced emissions. They are pivotal in applications ranging from main traction drives in EVs to auxiliary functions such as power steering, air conditioning, and advanced driver assistance systems.

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