A REPORT

ON

TRACTION MOTOR AND INVERTER FOR TWO-WHEELER APPLICATIONS

BY

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AT

HERO ELECTRIC

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BML MUNJAL UNIERSITY

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CERTIFICATE

This is to certify that Practice School Project of <u>JANAPAREDDI SAI PRAVEEN</u> titled <u>TRACTION MOTOR AND INVERTER FOR TWO-WHEELER APPLICATIONS</u> to the best of my knowledge is a record of Bonafede work carried out by him under my guidance and/or supervision. The contents embodied in this report, to the best of my knowledge have not been submitted anywhere else in any form for the award of any other degree or diploma. Indebtedness to other works/publications has been duly acknowledged at relevant places. The project work was carried during <u>15-02-2021</u> to <u>18-06-2021</u> in <u>HERO ELECTRIC PVT LTD</u>

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BML MUNJAL UNIVERSITY
PRACTICE SCHOOL – III JOINING REPORT

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On the very outset of this report, I would like to extend my sincere & heartfelt obligation towards all the personages who have helped me in this endeavour. Without their active guidance, help, cooperation & encouragement, I would not have made headway in the project.

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At last, but not least gratitude goes to all of my friends who directly or indirectly helped me to complete this project report.

Any omission in this brief acknowledgement does not mean lack of gratitude.

ABSTRACT

This project targets to design a Traction Inverter module for 2-wheeler electric vehicle with certain specifications. In this, first the appropriate motor was selected for the application and then inverter module. After motor selection, proper algorithm or control technique was selected to significantly improve the performance and the efficiency of the vehicle. Along with the selection of algorithm, commutation logic was developed to control the on-off cycle of MOSFETS, and the load profile/Indian driving cycle profile was loaded into the system to validate the performance at some standard level.

After the development of the circuit for Trapezoidal control method and FOC control method, all the necessary data was provided as input to the system and outcome of both the methods were compared.

The final outcome of FOC is notably better than that of Trapezoidal control method and in FOC, the torque profile was smooth which is a significant parameter of performance.

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A brief introduction of the organization’s business sector

The organization we are working with is HERO Electric Private Ltd. which comes under 2-wheeler electric vehicle industry to be specific.

The electric vehicle industry in India is a growing industry. The central and state governments have launched schemes and incentives to promote electric mobility in the country and some regulations and standards are also in place. While the country stands to benefit in a large way by switching its transport from IC engines to electric motor-powered, there are challenges like lack of charging infrastructure, high initial cost and lack of electricity produced from renewable energy. By making the shift towards electric vehicles (EVs), India stands to benefit on many fronts: it has a relative abundance of renewable energy resources and availability of skilled manpower in the technology and manufacturing sectors. According to an independent study by CEEW Centre for Energy Finance (CEEW-CEF), the EV market in India will be a US$206 billion opportunity by 2030 if India maintains steady progress to meet its ambitious 2030 target. This would require a cumulative investment of over US$180 billion in vehicle production and charging infrastructure. Another report by India Energy Storage Alliance (IESA) projects that the Indian EV market will grow at a CAGR of 36 percent till 2026.

The Indian electric two-wheeler market is a highly competitive market with several regional and local players. A majority share of the market is captured by Hero Electric (Ather Energy), Ampere, Okinawa, and many others. To maintain a competitive edge in the market, the players are focusing on developing innovative products and increasing their product portfolio by making high R&D investments. Although the established players dominate the market, growth opportunities for regional and local players also exist. The competitive intensity is higher in the Northern and Southern regions of India due to growing technology and infrastructure projects in the electric two-wheeler market. Northern and Southern India states majorly contribute to the electric vehicle segment. In contrast, few states such as Maharashtra and Gujrat in Western India also contribute higher than other states of India. The National Electric Mobility Mission Plan, 2020 was launched by the Government of India in year 2012 with the aim of improving the national fuel security through the promotion of hybrid and electric vehicles. Auto industry contributes 22% to the manufacturing GDP. From the help of new Manufacturing Policy, contribution of manufacturing in overall economy will increase to 25% by year 2022.

Overview of the Organization

Brief history of the company

After finding success with Hero Cycles and Hero MotoCorp, the Munjal family started Hero Electric in 2007. Today, it has captured 65 percent of the market share in the Indian electric two-wheeler market and claims to have sold 50,000 electric bikes and scooters last year.

In the 1950s, India was still coming to terms with its new-found freedom. Foundations were being laid for various industries. One of the most significant sectors was the manufacturing of two-wheelers. This is where entrepreneur **OP Munjal** came into the picture. Munjal left Kamalia village, which is now in Pakistan, and went to Amritsar with his three brothers to start a bicycle spare parts business. This set the wheels in motion for the formation of the brand which is now synonymous with two-wheelers in India: **Hero**. Initially, the brothers set up **Hero Cycles** in Ludhiana in 1956. The business, which started small, went on to become the largest single bicycle maker in the world. Another Hero entity set up by them - **Hero MotoCorp** (formerly Hero Honda) - won over the motorcycle and scooter market in India. The company became the largest two-wheeler manufacturer in the world capturing 46 percent of India’s two-wheeler market. Looking beyond their success with bicycles and Internal Combustion Engine (ICE) vehicles, the family-run business saw a big opportunity in the electric two-wheeler segment.

Their market research gave them confidence that electric two-wheeler adoption in India will be possible in the long term. They started developing an electric two-wheeler business as early as 2000, and in 2007, they formally launched Hero Electric as a separate company.

According to an estimate, by 2019, Hero Electric captured 65 percent market share in the Indian electric two-wheeler market. The company claims to have sold 50,000 vehicles last year. Hero Electric is headquartered in Gurugram, Haryana, and has a manufacturing plant in Ludhiana, Punjab.

Hero Electric comes under the Hero Eco Group, a multi-company, multi-product, and multi-location enterprise with diversified interests in EVs, exports, bicycles, healthcare, and real estate. Vijay Munjal, a promotor of Hero Cycles and Hero Group, is now the Chairman of Hero Eco Group.

Business Size

Hero Electric is a privately owned company by Hero Eco Group. Hero electric has around 300 employs and it produced around 50,000 vehicles last year. The overall market size for two-wheelers has increased from 40,000 units in 2017 to 1.7 lakh units in 2020-21. Of this, Hero Electric accounted for 53,500 units. In the 14 years it has been in business, Hero Electric has sold 3.5 lakh electric scooters across the country.

Product Lines

Hero Electric Scooters price starts at Rs 39,990. Hero Electric offers total of 8 scooters of which 2 model is upcoming which include AE-75 and AXLHE-20. The Hero Electric Nyx is the most expensive among scooters of Hero Electric with a price tag of Rs 79,990.The most popular names in the line-up include Optima LA, Flash, NYX, Photon and Dash.

MODEL	EX-SHOWROOM PRICE
Optima LA	Rs. 44,990
Flash	Rs. 39,990 - 52,990
NYX	Rs. 63,990 - 79,990
Photon	Rs. 61,866 - 72,990
Dash	Rs. 50,000 - 62,000

Competitors

The major competitors for Hero Electric at present are-

- Ather Energy
- Twenty-Two Motors
- Bajaj Auto
- TVS
- Okinawa Scooters
- Ampere
- Techo Electra.

Plan of our internship program

On our internship program we are working with Hero Electric under Mr. Nagesh Sir who is head of the Research and Development department. And they assigned a project (traction motor and inverter for two-wheeler applications) to us, where we need to select a best motor for our EV application, and we have to design our own controller for the vehicle.

And this is 18 weeks internship program starts from 15-02-2021 to 18-06-2021.

Objectives of the work

1. Detailed study of traction motors, inverter controller and its applications in two-wheeler applications.
2. Study of different control algorithms for the inverter/controller and finalize the best suitable algorithm for our controller and implement it.
3. Simulate our model in the MATLAB and if simulation is perfect then we go with circuit diagram.
4. Simulate our circuit diagram in proteus and then convert the model into PCB design in proteus.
5. Development of prototype and testing

Traction Motor and Inverter for Two-Wheeler Applications

Detailed Weekly Work Plan

Week 1 :-

1. Detailed study of different types of traction motors used in 2 wheelers based on battery output requirements.
2. Study of Various Motors along with their specifications and required parameters to opt the best one.

Week 2 :-

1. Study of use of different speed sensors in motor speed control, DC to AC conversion techniques and use BLDC motor for two-wheeler applications.
2. Preparing a report/spreadsheet on practically available high efficiency motors.
3. Study of Dynamic characteristics and its variation.

Week 3 :-

1. Understanding of uninterruptible power supplies, cooling, and high-voltage DC control transmission, electric vehicle drivers, static VAR compensators.
2. Selection of different parameters for calculation of RPM, Power and Torque of the system.

Week 4 :-

1. Calculation of RPM, Power and Torque values, and representation of those obtained in graphical manner.
2. Study of the mapping and conversion techniques to convert our physical/mechanical terms into input data type.

Week 5 - 6 :-

1. Selection of a suitable algorithm that can best fit for Calculation
2. Designing of circuit diagram for the controller.
3. Discuss the feasibility and practicality of the selected algorithm with the faculty and industry mentors.
4. Development of the primary algorithm and data flow charts.
5. Simulation of our circuit using MATLAB Simulink.

<u>Week 7</u> :-

1. Collecting the appropriate, accurate practical data and statistics from the industry and testing it with the algorithm decided.
2. Understanding the problems that arise while testing and proposing different methods to solve the problem.

<u>Week 8 - 11</u> :-

1. Verifying, Validating, and testing the algorithm and data using MATLAB, Simpower or various simulation software to explore a wider range of operational and environmental conditions that would be difficult to reproduce with hardware testing.
2. Finalizing the algorithm by correcting it with necessary steps which could be best for practical testing.

<u>Week 12 - 17</u> :-

1. Designing of BLDC motor inverter on breadboard or any feasible setup.
2. Pairing of BLDC motor to the developed inverter controller.
3. Performing Practical hardware testing of the developed inverter controller and verifying its compatibility with the rest of the vehicle system.
4. Final implementation of the developed system.

<u>Week 18 :-</u>

1. Final report preparation and presentation to the industry panel.

Introduction

The project I am working on titled as “Traction Motor and Inverter for two-wheeler applications” in which our aim is to develop a controller/inverter for the selected motor type. The project initiated from the literature survey and comparative study of different types of available motors and after the selection of motor, the next step was to determine the target output or specifically saying the power estimation of the motor. For the control, we the Team had three options for the control logic- The Trapezoidal method, Sinusoidal Commutation method and FOC technique and as per our Industry and Faculty mentor’s suggestions now the team is working on all three algorithms, and will also simulate all the three on MATLAB and then the final control method will be finalized.

The complete motor controller consists of PWM, Invertor, Commutation Logic, Hall sensor signal processing and all these parts need to be designed separately. At first the input is given for acceleration or braking and in that a constant DC input is supplied to PWM and then that DC input is converted in 3 phase input supply by the help of PWM and Inverter, the invertor receives the commutation logic and supplies the current in correspondence to the rotor position which is determined by the hall sensors embedded in the motor.

The project target is to test the developed control technique on the bread board and once the final outcomes are satisfactory, then the team can go for final fabrication.

1. Various types of Electric Motors used in Electric Vehicles

1. DC Brushed Motor
2. Brushless DC Motor
3. Permanent Magnet Synchronous Motor (PMSM)
4. Three Phase AC Induction Motors
5. Switched Reluctance Motors (SRM)

1.1 DC Brushed Motor

In DC brushed motor, brushes along with commutators provide a nexus between external supply circuit and armature of the motor. Brushes can be made up of carbon, copper, carbon graphite, metal graphite and are mostly rectangular in shape [14]. Wearing of commutators due to continuous cutting with brushes is one of the main drawbacks of DC brushed motors. Also, friction between brushes and commutators, limits the maximum motor speed. DC brushed motors have the ability to achieve high torque at low speeds, which makes them suitable for traction system [29]. Depending upon power output and voltage rating, DC brushed motors can have two, four or six poles and the field winding may be series or shunt connected. Poor power density as compared to PMSM or BLDC motor is another drawback of brushed DC motor for use in electric vehicles.

High starting torque capability of the DC Series motor makes it a suitable option for traction application. It was the most widely used motor for traction application in the early 1900s. The advantages of this motor are easy speed control, and it can also withstand a sudden increase in load. All these characteristics make it an ideal traction motor. The main drawback of DC series motor is high maintenance due to brushes and commutators. These motors are used in Indian railways. This motor comes under the category of DC brushed motors.

1.2 Brushless DC Motors

It is similar to DC motors with Permanent Magnets. It is called brushless because it does not have the commutator and brush arrangement. The commutation is done electronically in this motor because of this BLDC motors are maintenance free. BLDC motors have traction characteristics like high starting torque, high efficiency around 95-98%, etc. BLDC motors are suitable for high power density design approach. The BLDC motors are the most preferred motors for the electric vehicle application due to its traction characteristics. You can learn more about BLDC motors by comparing it with normal brushed motor.

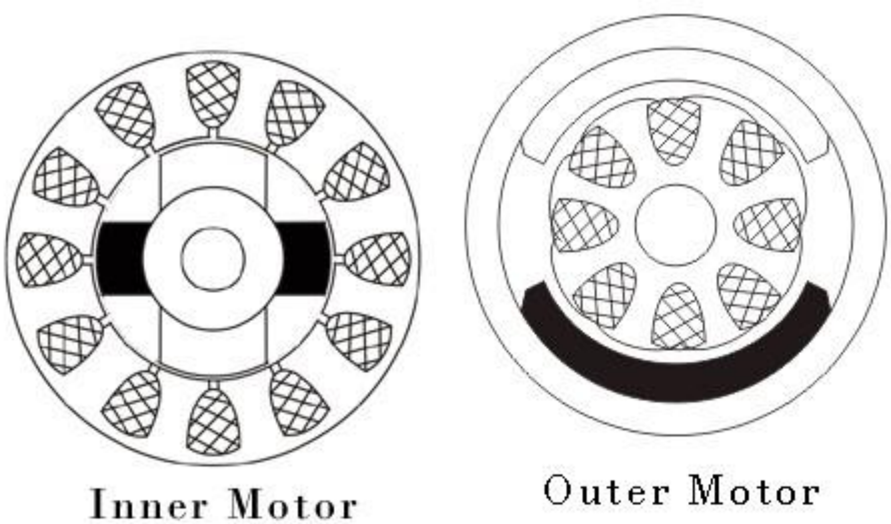
DC brushless motor provides certain advantages over DC brushed motor, like less maintenance and higher efficiency. Mechanical commutation as in brushed DC motor is replaced by equivalent electronic commutation (inverter circuit and rotor-position sensing element) circuit in DC brushless motor [2]-[29].

According to National Electrical Manufacturers Association (NEMA), BLDC motor is defined as rotating self-synchronous machine with a permanent magnet rotor and known rotor shaft positions for electronic commutation [28]. BLDC motor provides higher torque at the peak values of current and voltage as compared to other motors [2]. Due to better operating characteristics at higher speeds, these motors find their application in compressors, pump, and ventilation system.

BLDC motors further have two types:

1. Out-runner type BLDC Motor:

In this type, the rotor of the motor is present outside, and the stator is present inside. It is also called as Hub motors because the wheel is directly connected to the exterior rotor. This type of motors does not require external gear system. In a few cases, the motor itself has inbuilt planetary gears. This motor makes the overall vehicle less bulky as it does not require any gear system. It also eliminates the space required for mounting the motor. There is a restriction on the motor dimensions which limits the power output in the in-runner configuration. This motor is widely preferred by electric cycle manufacturers like Hullikal, Tronx, Spero, light speed bicycles, etc. It is also used by two-wheeler manufacturers like 22 Motors, NDS Eco Motors, etc.



BLDC motor types

2. In-runner type BLDC Motor:

In this type, the rotor of the motor is present inside, and the stator is outside like conventional motors. These motors require an external transmission system to transfer the power to the wheels, because of this the out-runner configuration is little bulky when compared to the in-runner configuration. Many three- wheeler manufacturers like Goenka Electric Motors, Speego Vehicles, Kinetic Green, Volta Automotive use BLDC motors. Low and medium performance scooter manufacturers also use BLDC motors for propulsion.

It is due to these reasons it is widely preferred motor for electric vehicle application. The main drawback is the high cost due to permanent magnets. Overloading the motor beyond a certain limit reduces the life of permanent magnets due to thermal conditions.

1.3 Permanent Magnet Synchronous Motor (PMSM)

This motor is also similar to BLDC motor which has permanent magnets on the rotor. Similar to BLDC motors these motors also have traction characteristics like high power density and high efficiency. The difference is that PMSM has sinusoidal back EMF whereas BLDC has trapezoidal back EMF. Permanent Magnet Synchronous motors are available for higher power ratings. PMSM is the best choice for high performance applications like cars, buses. Despite the high cost, PMSM is providing stiff competition to induction motors due to increased efficiency than the latter. PMSM is also costlier than BLDC motors. Most of the automotive manufacturers use PMSM motors for their hybrid and electric vehicles. For example, Toyota Prius, Chevrolet Bolt EV, Ford Focus Electric, zero motorcycles S/SR, Nissan Leaf, Hinda Accord, BMW i3, etc. use PMSM motor for propulsion.

In synchronous motors, rotor rotates at synchronous speed. The rotor is excited from a DC supply, while stator is connected to a three phase AC supply. Therefore, polarities of stator poles are continuously changing while rotor pole polarities are constant.
Consider that initially stator and rotor are having polarities. At this instant rotor S-pole is repelled by stator S-pole. Now, during another half-cycle, stator poles will change their polarities and now rotor S-pole will be attracted towards stator N-pole. Thus, rotor will experience pulsating torque and due to rotor inertia, it will not rotate in either direction. Therefore, synchronous motor does not have self-starting toque. Now, if the rotor is rotated by external means such that rotor poles are continuously under the influence of stator poles of opposite polarity even with continuously changing polarity, rotor will start rotating in one direction. Rotor S-pole and stator N-pole interlocked with each other and rotor rotating in clockwise direction. Now, even if external means are removed, rotor and stator poles are interlocked, and rotor will rotate with synchronous speed. Rotor should be rotated with such speed that it moves through a distance of pole pitch within half time period of supply. Due to its high efficiency and high torque density, synchronous motor finds its application in servo, wind turbine and electric vehicles.

1.4 Three Phase AC Induction Motors

The induction motors do not have a high starting toque like DC series motors under fixed voltage and fixed frequency operation. But this characteristic can be altered by using various control techniques like FOC or v/f methods. By using these control methods, the maximum torque is made available at the starting of the motor which is suitable for traction application. Squirrel cage induction motors have a long life due to less maintenance. Induction motors can be designed up to an efficiency of 92-95%. The drawback of an induction motor is that it requires complex inverter circuit and control of the motor is difficult.

Three phase induction motors are widely used in electric vehicles because of high efficiency, good speed regulation and absence of commutators. Three phase AC supply is connected to stator winding, due to which revolving magnetic field is established. This revolving magnetic field interacts with stationary rotor conductors and induced current flows through rotor conductors. Induced current establishes its own magnetic field. Interaction between revolving magnetic field and field due to induced currents gives rise to unidirectional torque [29]. As speed of rotor is different (less) than speed of revolving field (synchronous speed), these motors are also called as asynchronous motor.

In permanent magnet motors, the magnets contribute to the flux density B. Therefore, adjusting the value of B in induction motors is easy when compared to permanent magnet motors. It is because in Induction motors the value of B can be adjusted by varying the voltage and frequency (V/f) based on torque requirements. This helps in reducing the losses which in turn improves the efficiency.

Tesla Model S is the best example to prove the high-performance capability of induction motors compared to its counterparts. By opting for induction motors, Tesla might have wanted to eliminate the dependency on permanent magnets. Even Mahindra Reva e2o uses a three-phase induction motor for its propulsion. Major automotive manufacturers like TATA motors have planned to use Induction motors in their cars and buses. The two-wheeler manufacturer TVS motors will be launching an electric scooter which uses induction motor for its propulsion. Induction motors are the preferred choice for performance oriented electric vehicles due to its cheap cost. The other advantage is that it can withstand rugged environmental conditions. Due to these advantages, the Indian railways has started replacing its DC motors with AC induction motors.

1.5 Switched Reluctance Motors (SRM)

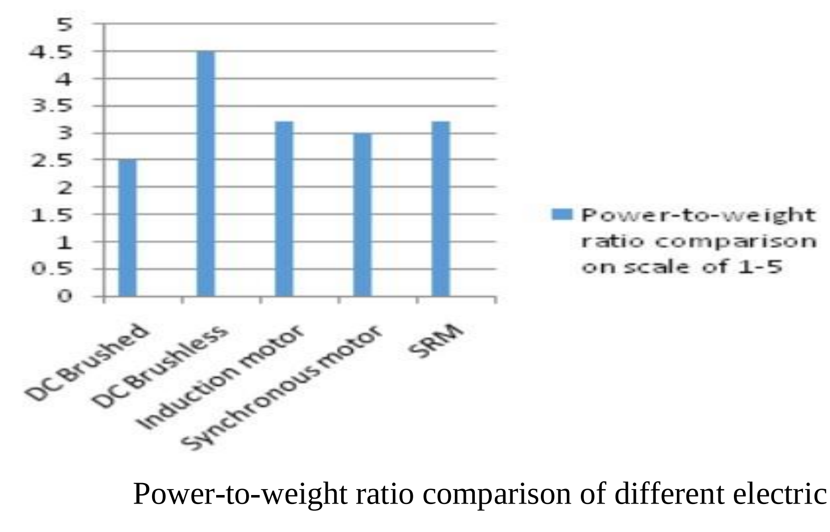
Switched Reluctance Motors is a category of variable reluctance motor with double saliency. Switched Reluctance motors are simple in construction and robust. The rotor of the SRM is a piece of laminated steel with no windings or permanent magnets on it. This makes the inertia of the rotor less which helps in high acceleration. The robust nature of SRM makes it suitable for the high-speed application. SRM also offers high power density which are some required characteristics of Electric Vehicles. Since the heat generated is mostly confined to the stator, it is easier to cool the motor. The biggest drawback of the SRM is the complexity in control and increase in the switching circuit. It also has some noise issues. Once SRM enters the commercial market, it can replace the PMSM and Induction motors in the future.

Switched reluctance motor produces torque by variable reluctance method. When stator coils are energized, variable reluctance is set up in the air gap between the stator and the rotor. Rotor tends to move to a position of least reluctance thus causing torque. Switched Reluctance motor has characteristics like high starting torque, wide speed range and good inherent fault-tolerance capability, which makes it suitable for electric vehicle application. Some parameters that must be considered while comparing above motors for choosing a best suited motor for required electric vehicle application are power-to weight ratio, torque-speed characteristics, efficiency, cost of controller, cost of motor.

2. Different Study Parameters: -

2.1 Power-to-Weight Ratio

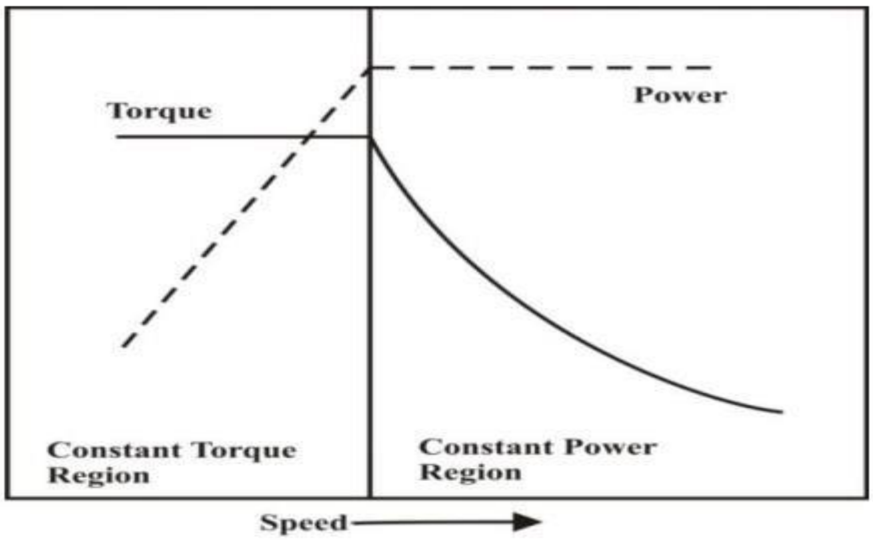
Power-to-weight ratio for electric motors is usually calculated using the peak power of motor. Power-to-weight ratio for an electric motor is obtained by dividing the peak power output of motor in KW by weight of motor in Kg. Unit of power-to-weight ratio of motor is KW/Kg. A motor with higher power-to-weight ratio is more suitable for EV application. Same type of motor with same ratings is designed and manufactured differently by different electric motor manufacturers and hence there can be a slight difference in their weights. Here, we will consider mean weight of motor to calculate their power-to-weight ratios. Now, if we consider different types of electric motors with same power, voltage, and speed ratings.



Power-to-weight ratio comparison of different electric motors

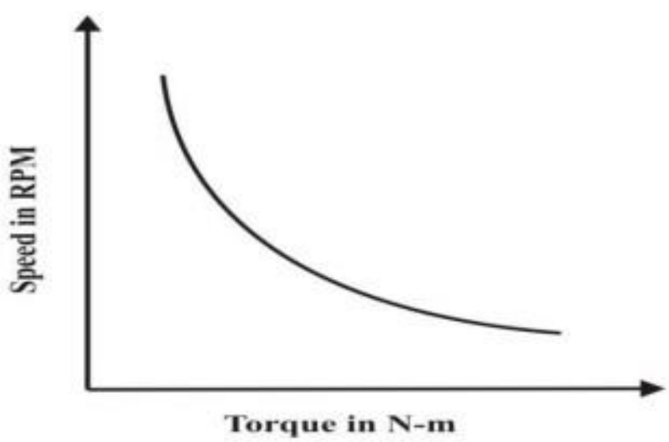
2.2 Torque-Speed Characteristics

The performance and suitability of an electric motor for a particular application can be decided by its torque-speed characteristics. Torque-speed characteristics are also called as mechanical characteristics. The ideal mechanical characteristics of an electric motor for electric vehicle application are as shown in Figure.

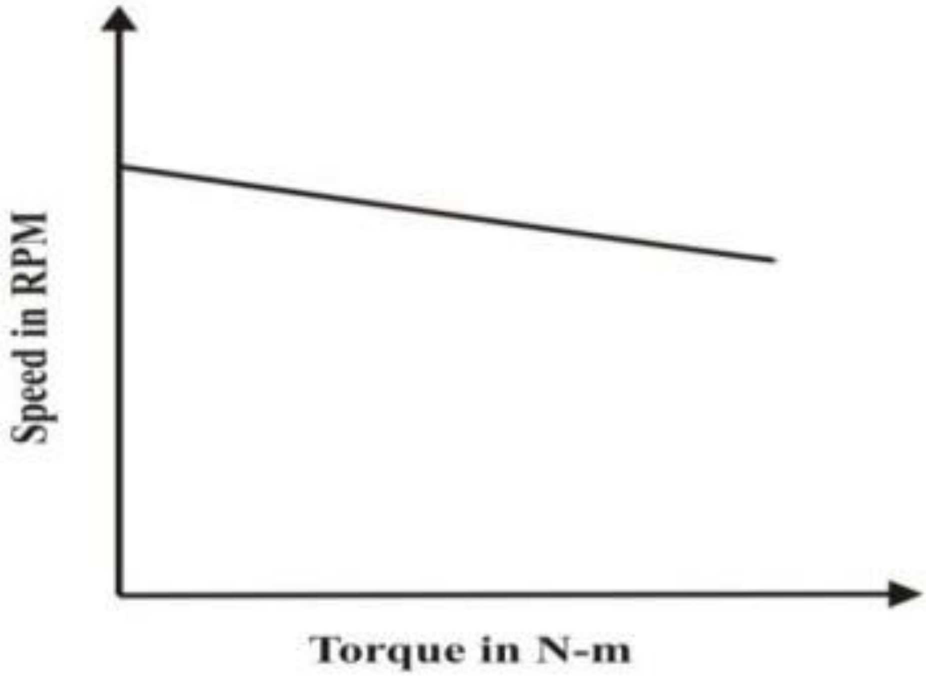


Ideal mechanical characteristics of electric motor in EV

When electric vehicle is used where frequent staring/stopping is required, motor is operated in constant torque region, while at high speed; it is operated in constant power region. DC series wound motor has high starting torque. Also, speed decreases with increase in torque. DC shunt motors have medium staring torque, but speed decreases slightly with increase in torque. Therefore, DC shunt wound motors are used in constant speed application.

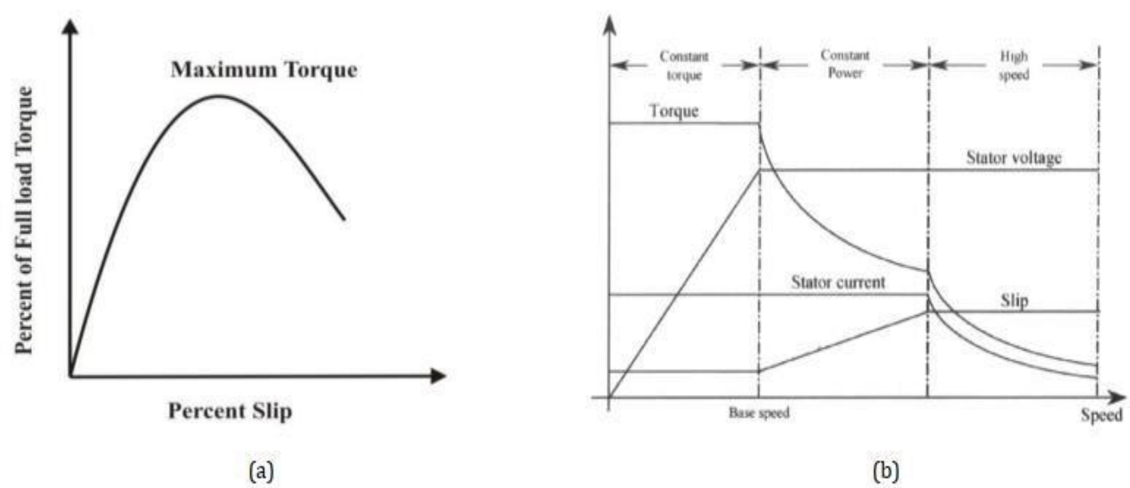


Torque versus speed characteristics of DC Series Wound Motor



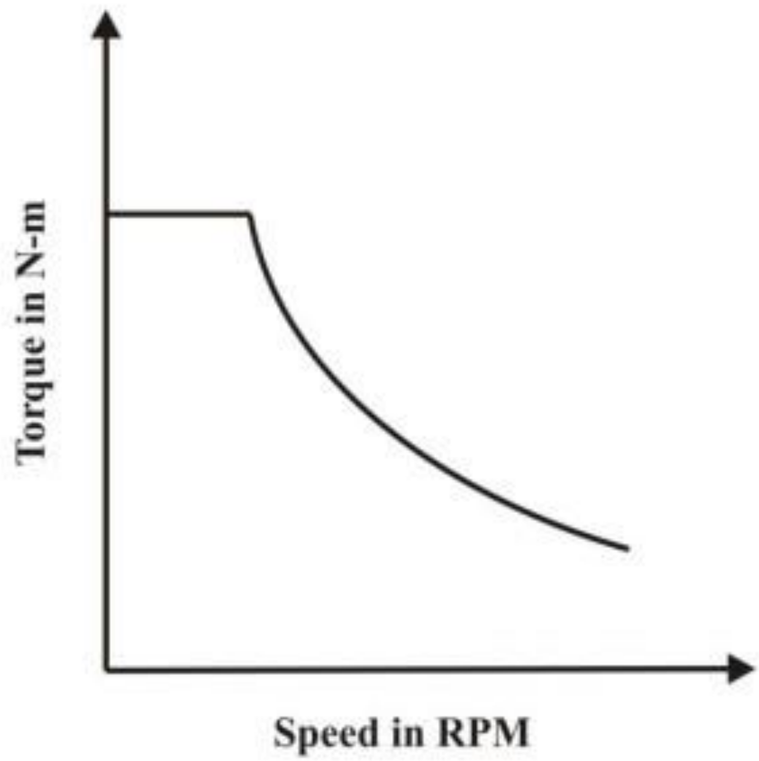
Torque versus speed characteristics of DC Shunt Wound Motor

Torque-speed characteristics of brushless DC motor is more drooping than that of DC shunt motor. Torque-speed characteristics of an induction motor slightly differ with different values of rotor resistance. Due to presence of breakdown torque, constant power operation is limited in induction motor. Torque-speed characteristic for medium value of rotor resistance is as shown in Figure.



(a) Torque slip characteristics of three phase Induction Motor (b) Different characteristics of induction motor

Synchronous motor operates at synchronous speed only and this speed of motor is independent of variation in load. Therefore, synchronous motors are used in vehicle where constant speed is required. The speed at which back emf is equal to bus voltage is called as base speed. For switched reluctance motor, torque below base speed is controlled by Pulse Width Modulation (PWM) of current while above base speed torque control is possible only through control of phase turn-on and phase turn-off angles. Torque-speed characteristic of Switched Reluctance Motor is as shown in Figure.



Torque versus speed characteristics of Switched Reluctance Motor

2.3 Efficiency

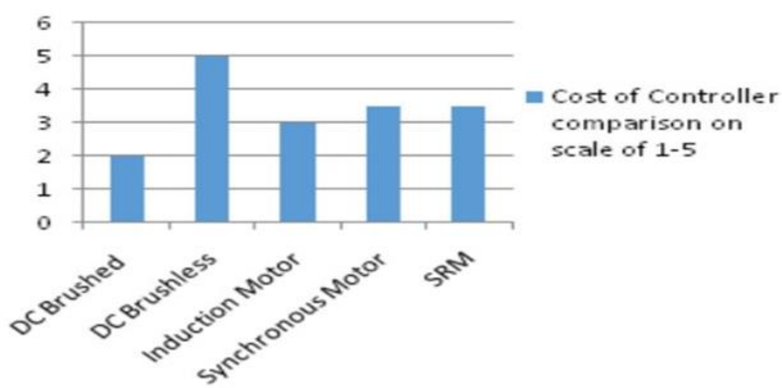
Motor is an electromechanical device which converts electrical energy into mechanical energy. Whole of input electrical energy is not converted into mechanical energy but is lost due to various factors. Electrical efficiency of an electric motor gives us relation between electrical input and useful mechanical output of motor and is generally given by ratio of shaft power output and motor input power. Generally, all electric motors are designed to operate at maximum efficiency at rated output of a motor. When an electric motor is used in electric vehicle, motor will be operated at different loads. Therefore, peak efficiency and efficiency at different loads of a motor must be considered before choosing it for an electric vehicle application. Efficiencies of different electric motors at peak load and at 10% load are tabulated below [27].

Efficiency Comparison of Different Electric Motors

Motor Type	Peak Efficiency (Percent)	Efficiency at 10% load (Percent)
DC Brushed Motor	85-90	80-85
DC Brushless Motor	>95	70-80
AC Induction Motor	>90	>90
Synchronous Motor	>92	80-85
Switched Reluctance Motor	<95	>90

2.4 Cost of Controllers

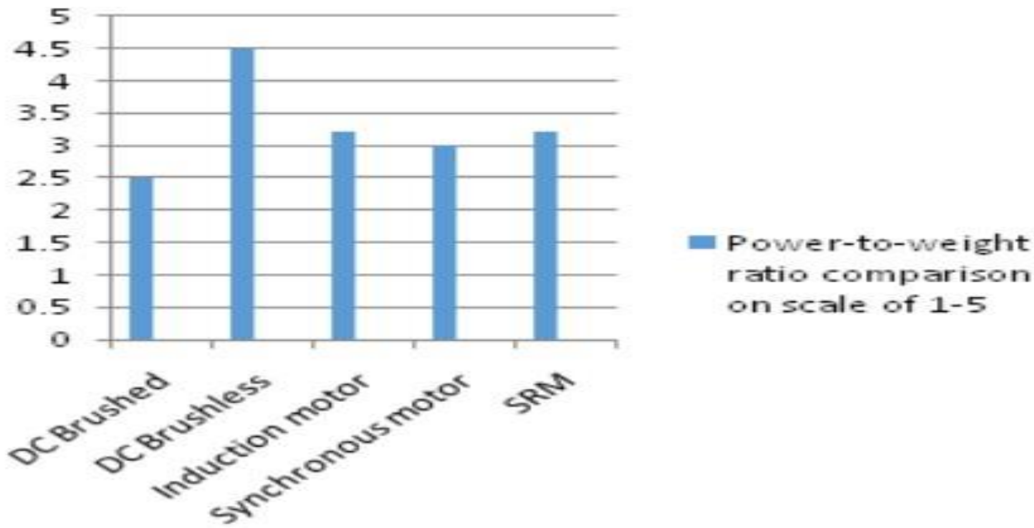
Motor controllers are an important part of drive system of an electric vehicle. Motor controller in electric vehicles offers improved performance, efficiency, and controllability. If an electric vehicle manufacturer wants to build a low-cost electric vehicle, then choosing a low-cost controller would eventually affect his choice for motor. For low voltage electric motor widely used in electric vehicle cost of controllers of different electric motors with same voltage and output power ratings, is as shown below.



Cost of Controller Comparison for Different Electric Motor

2.5 Cost of Motors

One of the important challenges ahead of electric vehicle manufacturers is to provide consumer with an electric vehicle which is as good as gasoline vehicle but within an affordable price. Cost of different electric motors with same voltage and output power ratings are compared as shown below.



Cost of motor Comparison for Different Electric Motor

3. Lithium iron phosphate battery (LiFePO4)

Advantages and Disadvantages

- LFP batteries are cheaper battery alternative to other lithium-ion battery types due to the safer iron phosphate chemistry as manufacturers do not have to spend more money to recycle the materials.
- LFP batteries have long term stability and performance which reduces the frequency of battery replacement indicating that the cycle life of LFP battery is high.
- These batteries do not catch fire making it the safest alternative available for mobility.
- Wide operating temperature range makes it suitable for automobiles in different climatic conditions.
- Fast charging capability of LFP batteries will decrease waiting time in case of full battery discharge during journey and in case of emergencies.
- The battery performance is affected when the temperatures drop below 0° C.
- Other disadvantages are similar to that of lithium-ion batteries i.e., aging effect on the performance of battery, deep discharge with aging, etc.
- LFP batteries require minimum to no maintenance and cuts down maintenance costs to the customer.

- These batteries have low self-discharging characteristics, hence the energy stored in the battery is not lost to the environment easily.
- LFP batteries are slightly heavier than the lithium-ion batteries and therefore are mostly used in stationary applications.

4. Evaluation of different Electric motors for EV Applications [4]

Parameters	DC	IM	SRM	BLDC
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	3	3.5
Controllability	5	5	4	4
Reliability	3	5	4	5
Technological Maturity	5	5	4	4
Cost	4	5	3	4
Total	**22**	**27**	**23**	**24**

Note:- All the grading is done on 1 – 5 scale, where 1- worst, 2- acceptable, 3- Average, 4- Good and 5- Best.

4.1 Conclusion for EV motors

The induction motor is the best candidate for the EV applications because they are robust, less costly, mature in technology and need less maintenance [4]. But, since we are performing the motor selection specifically for Electric Two-Wheelers, size of the motor acts as an important factor, it is demonstrated that the brushless DC motors have high efficiency around 95%, less energy consumption and more power to volume ratio which makes them attractive for Two-wheeler EV applications.

5. The Brushless DC Motor (BLDC Motor) in Electric Vehicles Detail:

Before the latest incarnation of electric vehicles, cars already used BLDC motors for windshield wipers, CD players, and power windows. Today's automakers use three different types of electric motors in green cars: the BLDC motor, brushed DC motor, and AC induction motor.

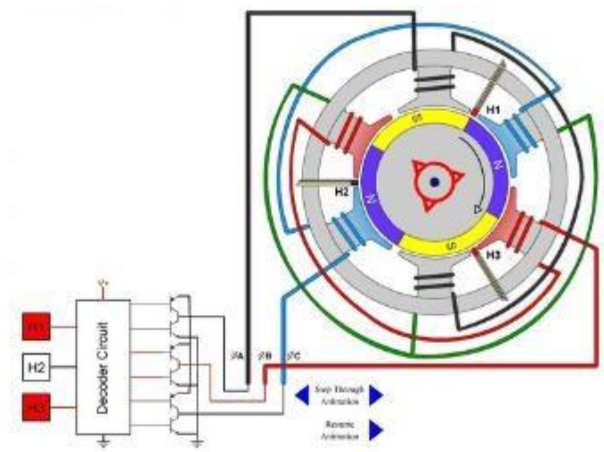
The BLDC motor has a permanent-magnet rotor surrounded by a wound stator. The winding in the stator gets commutated electronically, instead of with brushes. This makes the BLDC motor:

- Simpler to maintain
- More durable

- Smaller
- 85%–90% more efficient
- Able to respond faster and at higher operating speeds
- Simpler to control in regard to speed control and reversing
- Lighter
- Less prone to the failures that brushed motors experience
- Able to self-start

The composition of the BLDC motor also keeps the machinery inside a vehicle cooler and thermally resistant. Plus, because the motor is brushless, there is no dangerous brush sparking.

5.1 BLDC Motor Drive

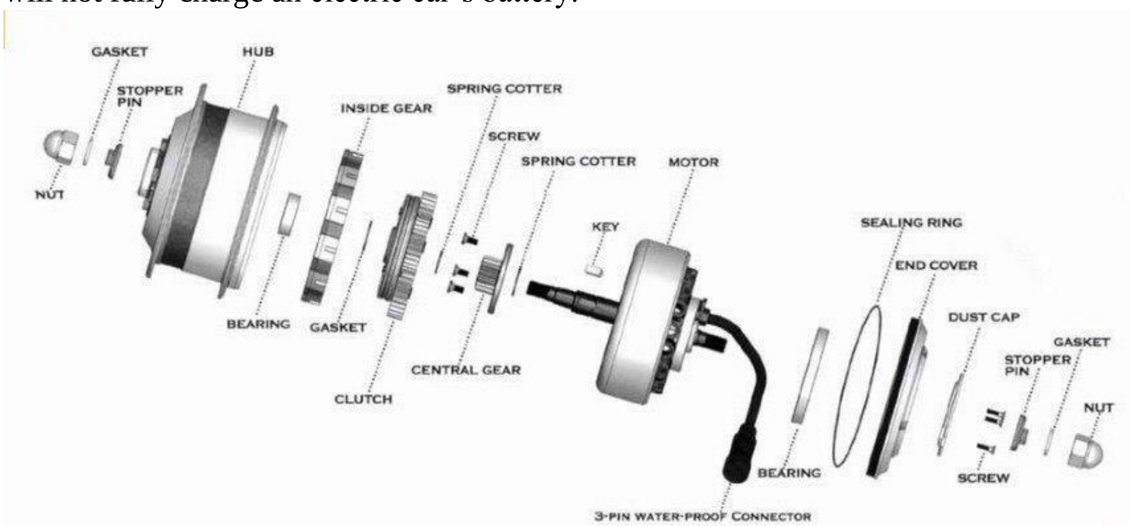


BLDC motor

A Brushless DC Electric Motor Powered by Direct Current Electric Supply and commutated electronically instead of brushes like conventional DC Motors. Primary efficiency is a most important feature for BLDC motors. Because the rotor is the sole bearer of the magnets and it does not require any power. i.e., no connections, no commutator, and no brushes. In place of these, the motor employs control circuitry. To detect where the rotor is at certain times, BLDC motors employ along with controllers, rotary encoders, or a Hall sensor.

BLDC hub motors

All of today's hybrid vehicles use a BLDC motor. Green car manufacturers often prefer BLDC motors over the alternatives because the peak point efficiency is higher and rotor cooling is simpler. The motors can also operate at "unity power factor," meaning the drive can operate at its maximum efficiency levels. Batteries and brakes. One of the most important components of the BLDC motor drive system is the batteries. In addition to supplying energy to the engine, they allow the electrical receivers to function. Therefore, it is important that the batteries in green cars be as efficient as possible. Whenever a battery gets used, an irreversible change in the chemical structure occurs. As a result, a rechargeable battery is most efficient when maintained close to full charge. Thanks to the permanent magnets in the brushless DC motor and the ability for the external torque to work as a generator, a person operating a green car can pulse-charge the battery by applying the brakes. It is important to note, that braking alone will not fully charge an electric car's battery.

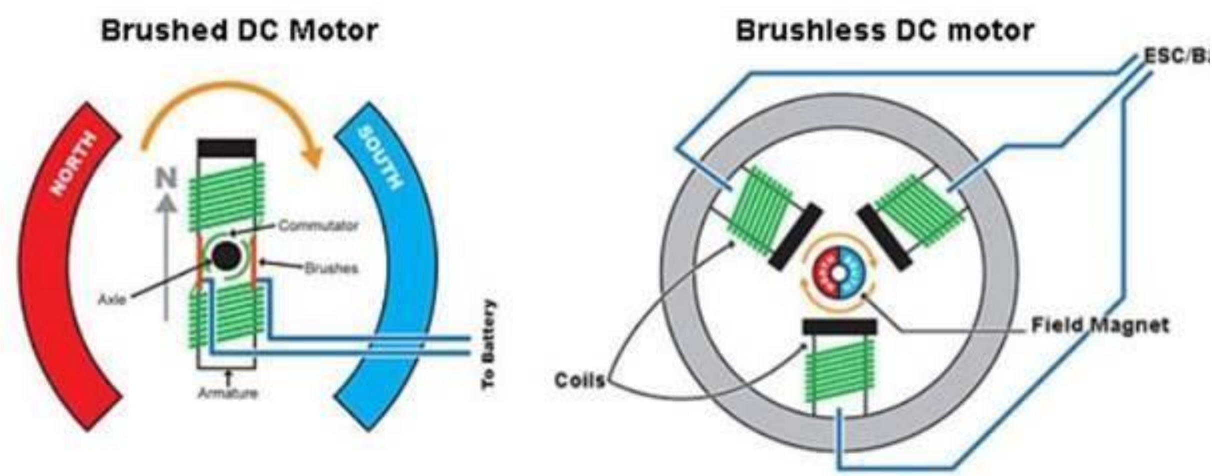


BLDC motor exploded view

Motor response. Green car manufacturers and entities like NASA prefer BLDC motors because of their fast motor responses. The high-performance, small-diameter magnetic rotors reduce the inertia of the armature, allowing high acceleration rates, a reduction in rotational losses, and smoother servo characteristics. This optimal motor response also allows for more constant speeds, instant speed regulation and a quieter drive system.

5.2 Differences between BLDC motors and Traditional Motors

BLDC Motor over The BLDC Motors proved to be more efficient and more compact than the traditional DC Motors. The long service life and better controllability also adds value to the BLDC Motors. The process that involves in rotating the BLDC rotor is little complex than a DC rotor which only requires supply of current through brushes. The BLDC Motors generally use inverter circuitry to implement smooth rotation of the motor. Typically, Hall sensors are used in BLDC Motors to know the position of the permanent magnet and allows the current to the rotor coils accordingly. While sensors offer obvious advantages, they come with disadvantages as well. Some sensors have low tolerance to dust and require regular maintenance. The role of coolant is also important in the long run of the rotor.



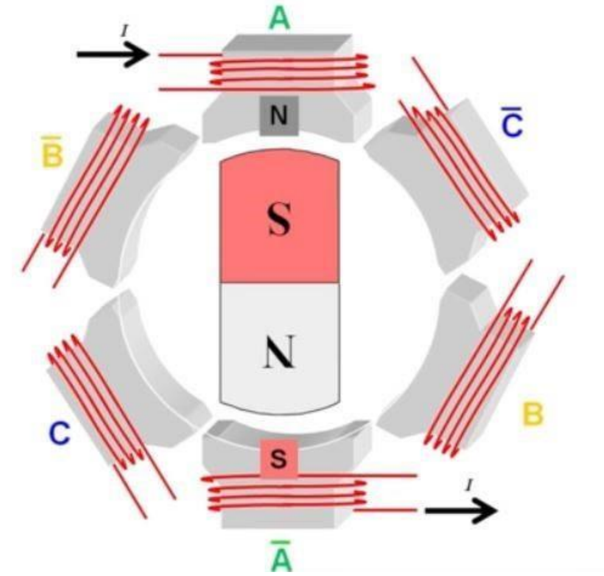
BLDC motor (Traditional Vs Brushless)

5.3 Voltage Control in BLDC Motors

A typical way to adjust the voltage is with pulse width modulation (PWM). In this approach, we alter the voltage by lengthening or reducing the pulse ON time, i.e., by varying the duty cycle. PWM can be implemented using MPUs equipped with dedicated PWM hardware.

5.4 How does BLDC Motor Operates?

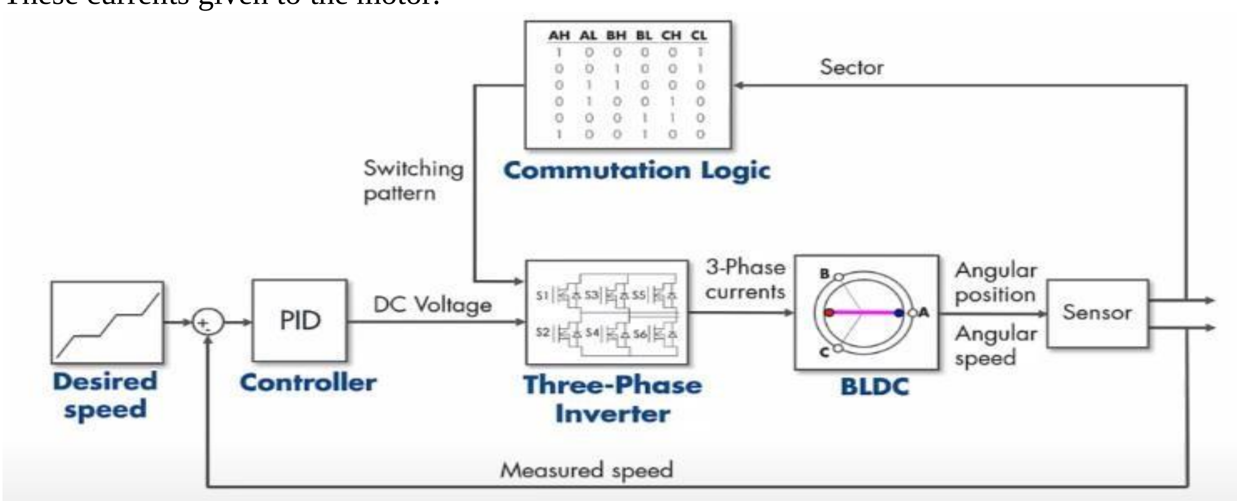
BLDC Motor runs on DC Power Input and its operation runs on interaction between permanent magnet and the stator coil. The Rotor always follows stator magnetic flux the entire time of the operation. After Every 180-degree rotation, the polarity of the coils are changed according to the polarity of the permanent magnet. So, the rotor follows the stator magnetic flux every time the motor is in ON State.



BLDC motor Internal structure

5.5 Control of BLDC Motor

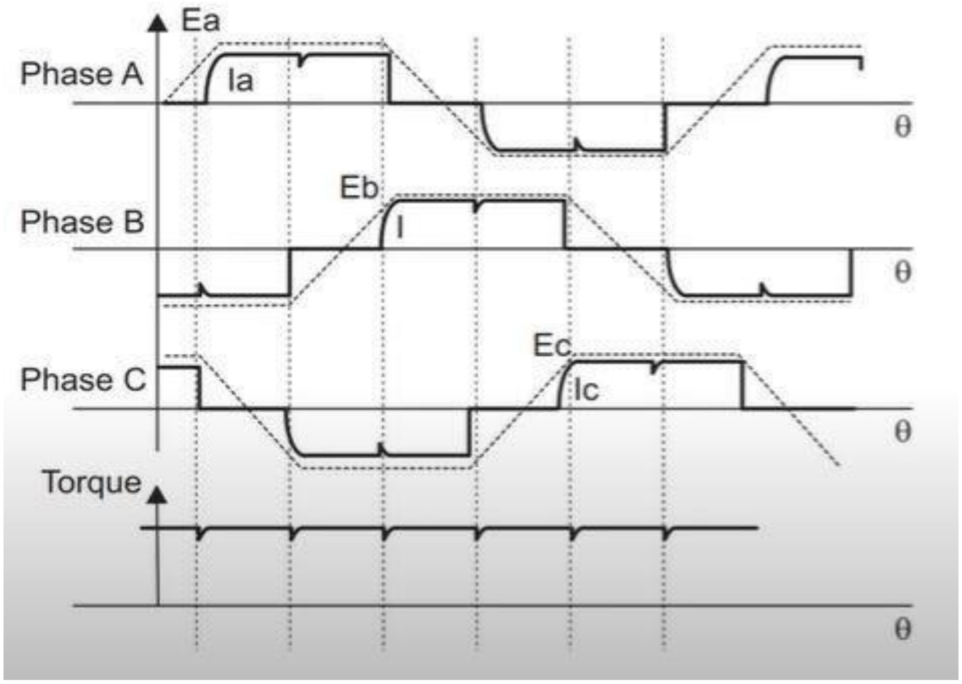
When an applied voltage is constant the motor turns at a constant speed due to the proportional relation between the voltage and speed. But if we want to control the motor at different speeds then we need to build a controller that will adjust the magnitude of the applied voltage. Here in the control of a motor DC voltage source that provides a constant voltage to the three-phase inverter which converts the DC power to 3 - phase currents.
These currents given to the motor.



BLDC Motor Control Mechanism

5.6 Commutation Logic in BLDC Motor

The six-step commutation. Each Motor phase terminal is electrically switched every 60 degree of rotation. As a result, the waveform of each phase winding changes at 60 degrees starting at zero, to positive current state, back to zero and to negative current state. The transient period at 60-degree rotation leads to ripples at the output motor torque. The current is injected into each motor terminal depending on the rotor's position. The rotor's position can be determined by using sensored Techniques with hall sensors.



Wave forms of the three coil windings and the motor torque output

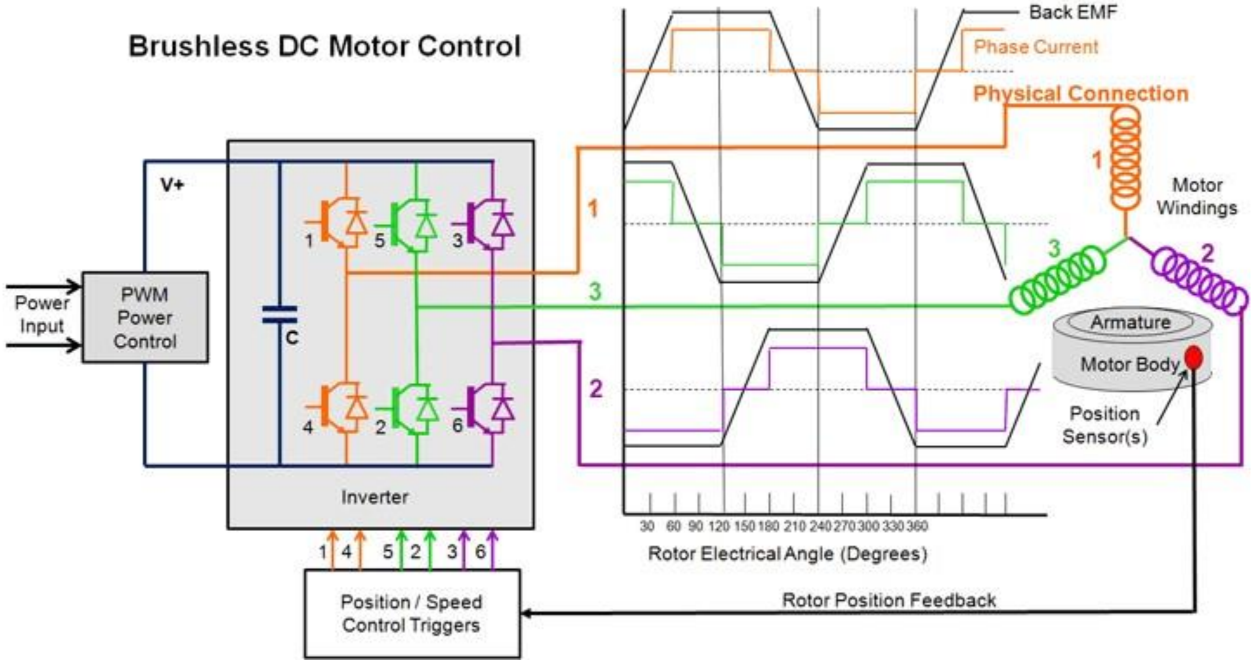
To control our motor first we need to measure the angular position and speed by using Hall sensor. We have to determine when to commutate the motor. But we don't know which two out of three Phases to commutate. The correct phases are specified by a commutation logic shown in the above picture. That commutation logic computes the switching pattern for 3-phase inverter. This commutation logic is belonging to the control algorithm.

5.7 Speed and Torque Characteristics in a BLDC Motor

The speed and torque characteristics in the BLDC motor are very important to study the gear mechanism in electric vehicles. The Torque is proportional to the armature current. As the motor speed increases, the back EMF is produced more resulting in the decrease of armature current. This concludes that increase in speed results in decrease of torque and vice-versa. High speed in the motor is also dangerous to the equipment because when we suddenly stop a motor, the back EMF disappears and there will be a sudden spike in voltage and current which leads to heat. So, proper voltage controlling mechanism is needed to avoid excess heat.

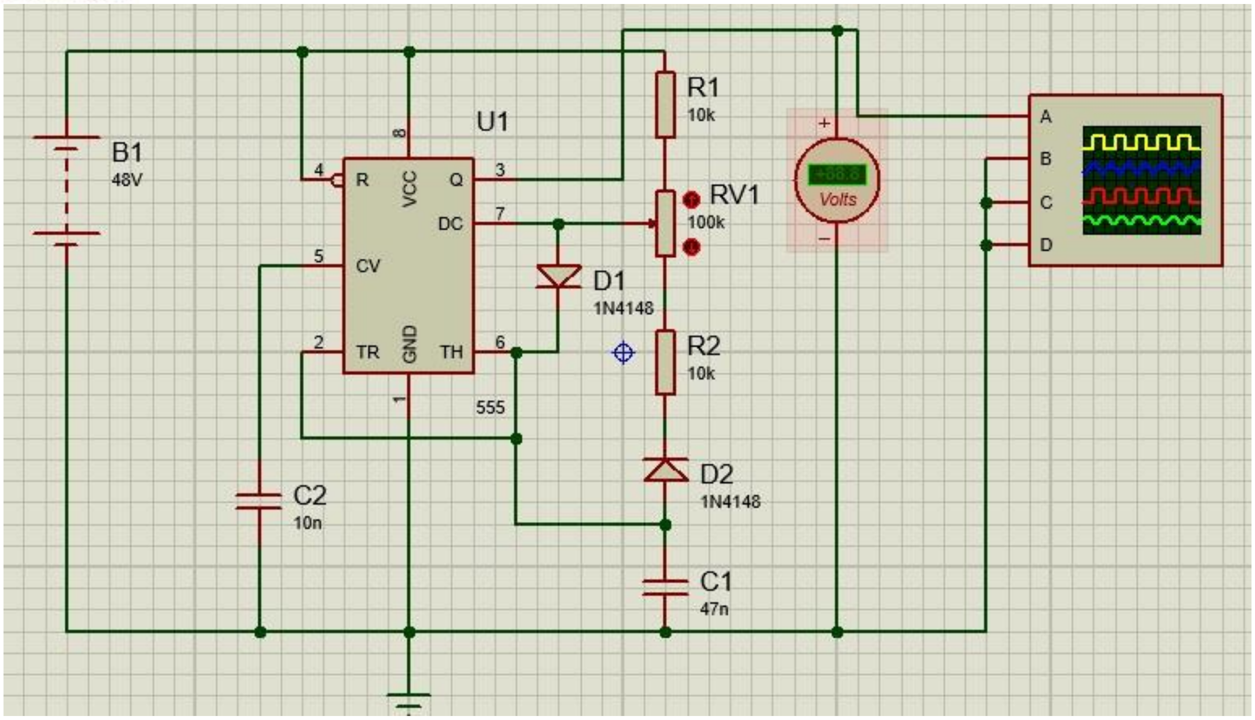
5.8 Speed Control of BLDC motor

In reality the DC voltage is a fixed voltage source which we need to modulate, so for modulation we use PWM (Pulse Width Module) technique.



BLDC motor Control Circuit

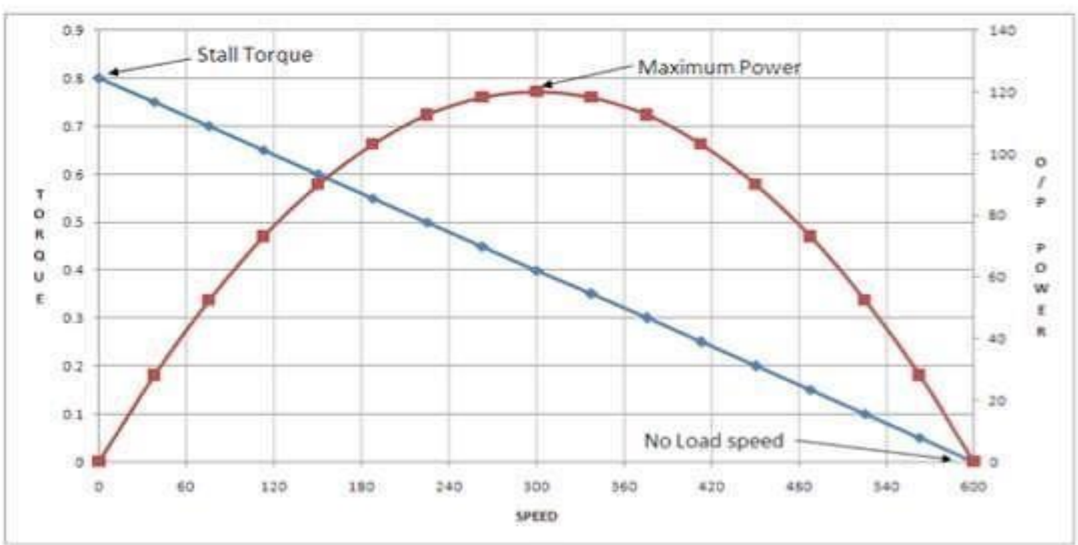
Here PWM acts like a switch that takes DC voltage and apply it to the motor with a series of on and off pauses at a certain frequency. When we increase the PWM frequency the voltage will be averaged out, which will improve the speed control.



PWM Technique

5.9 Torque Control

Torque can be controlled by adjusting the magnet flux. however, magnetic flux is dependent upon the current flowing through the windings. So, by controlling current, torque of motor can be controlled.



Speed-Torque-Power curve

5.10A Look to the Future aspects of BLDC Motors

The brushless DC motor is not without fault. It is currently more expensive to manufacture than its brushed counterparts. Also, the magnetic field produced by the permanent magnets is not adjustable. Scientists hope to make the strength of the magnetic field more adjustable so when an electric vehicle requires maximum torque, particularly at low speeds, the magnetic field will be at maximum strength.
As green vehicles continue to grow in popularity, automakers and scientists expect the brushless DC motor to dominate the market. With continuing innovations in electric car manufacturing, economists predict that by the year 2020, up to 33% of new car purchases worldwide will be for green cars.

6. Forces acting on a 2-wheeler

The major forces acting on a 2-Wheeler are Rolling Resistance, Climbing Force, Aerodynamic Force and Acceleration Force.
So, the Total traction force acting on the 2-wheeler is
$F_t = 0.5*\beta*C_d*A*V^2 + m*g*\mu + m*g*\sin\alpha$
Where, μ =Road Friction=0.013
α =Road Inclination =9 degrees
β=density of the medium= 1.2 kg/m2
Cd=Drag Coefficient=0.9
A=Cross sectional Area=0.5 sqm
V= Speed of the vehicle relative to the medium

7. Power Estimation for 2-wheeler

$P_t = F_t * V$ = 6713 W
Now, power on an inclined surface would be $m*g*\sin\alpha*V$ = 398.5*13.9 = 5540 W
So, traction power on a flat surface would be 6713 – 5540 = 1173 W
On an Inclined Surface, if we ride at 14kmph or 3.88 metres per second, the power required would be 398.5 * 3.88 = 1546 W.
Total Traction power= 1173+1546 = 2719 W
Kinetic Energy at 50kmph would be $0.5*m*V^2$
i.e., 0.5*260*13.9*13.9=25120 Joules
Power required would be E/t=1255 W
So, Our Motor Model requires about 1255 + 2719 = 3974 W power.
For the worst-case scenario, the motor requires about 4000 W power.
In 1 rotation, the vehicle moves about 1.57 m (radius of wheel=0.25 m)
In order to travel at 50kmph or 13.9mps, the vehicle Tyre must rotate at 13.9*60/1.57=532 rpm.

Taking Gear Ratio as 4:1, the motor speed would be 532*4=2130 rpm.
P=2*pi*N*T/60
Where p is max power
T= max torque
N= max rpm
T=4000*60/13376=17.9 Nm
For a linear surface, the max torque would be
T= (1173+1255) *60/13376= 10.89 Nm
We selected the below values for our simulation model
Pmax=4000 W
Tmax=10.89 W
Vdc=48V
Imax= 80A

8. Requirements of our Vehicle

1. Vehicle Max causing speed: 50 kmph
2. Vehicle weight: 110 kg
3. Rider weight (2 riders) 75 kg + 75 kg
4. Gradient capability: 9 degrees @ 15 kmph with 260 kg total weight

9. Speed Control of BLDC Motors Using Hall Effect Sensors

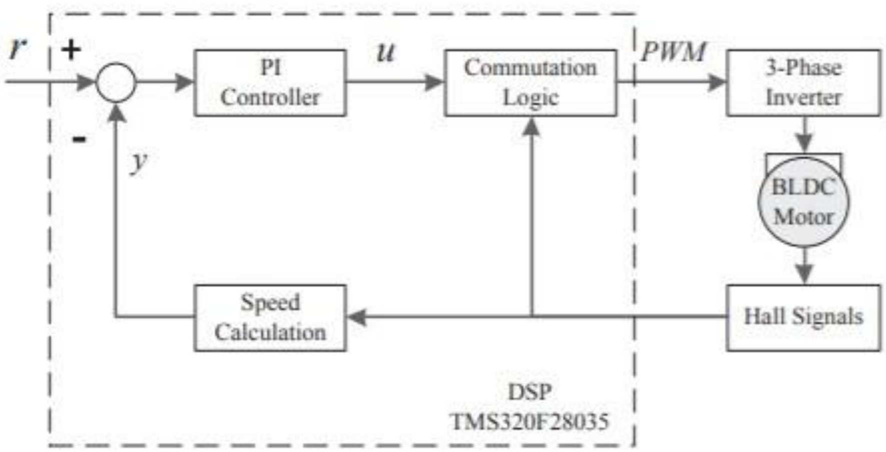
BLDC motor is high torque and also fits variable speed application. Without brushes, the motors generate less temperature and no mechanical wear. Combine all these benefits makes BLDC motors be more suitable option for industry. Although, the control algorithm is more complicated than DC brushed motor. BLDC needs to detect the rotor position data and make the correct commutation. They are considered in two ways: sensored and sensor less methods. Sensored method which is the easier way needs position sensors, like Hall effect sensors, to make the measure of proper timing to make rotor commutation. Sensor less method which means without any position sensor but require higher performance processor, more procedures in the program and more consumption of memory.

The sensor less methods also have the following Disadvantages:

a) Back-EMF needs motor to rotating at the minimum speed to generate, it causes sensor less method not suitable for applications with very low speed.
b) Rapidly motor load changes also generate the back-EMF, the driving loop may misrecognize it and cause out of lock.

A 3-phase BLDC with Hall effect sensors installed in the stators is driven by the medium voltage digital motor control (DMC) kit included with the gate IC and three phase invertors. According to the rotor position data from Hall effect sensors, a trapezoidal drive method is applied to switch the BLDC. The Digital Signal Processor (DSP) is the main control processor to implement the control scheme. Hall effect sensors are on the purpose of the initial rotor position data detection and manage the commutation after switching to close loop control. The current information is measured from the shunt resistor and conversion in the middle of the PWM duty cycle. The speed feedback comes from the position data from Hall effect sensors, since between two commutation signals are 60° mechanical degrees, it is possible to compute speed of motor with the passing mechanical degrees per elapsed time. The speed information is used as the feedback to the PI controller.
Before starting the motor, rotors position data as first input need to be gathered by Hall effect sensors. The switches sequence is followed accordingly

All the switches sequence must be controlled properly so that the current flow to the correct phase winding. As the six timing sequences, the trapezoidal control also called six steps control. The switches sequence and corresponding conduction phase of each winding is given in the above table. In this method, the PWM applied on high side and lower side, the PWM duty controls the quantity of the current flows to the DMC, the wider the PWM duty, the faster BLDC spinning. Proportional-Integral-Derivative (PID) controller is the most common way of using feedback in modern engineering system. It should strictly speaking be called PI controllers, if there is no derivative involved in the process.



Structure of PI controller [24].

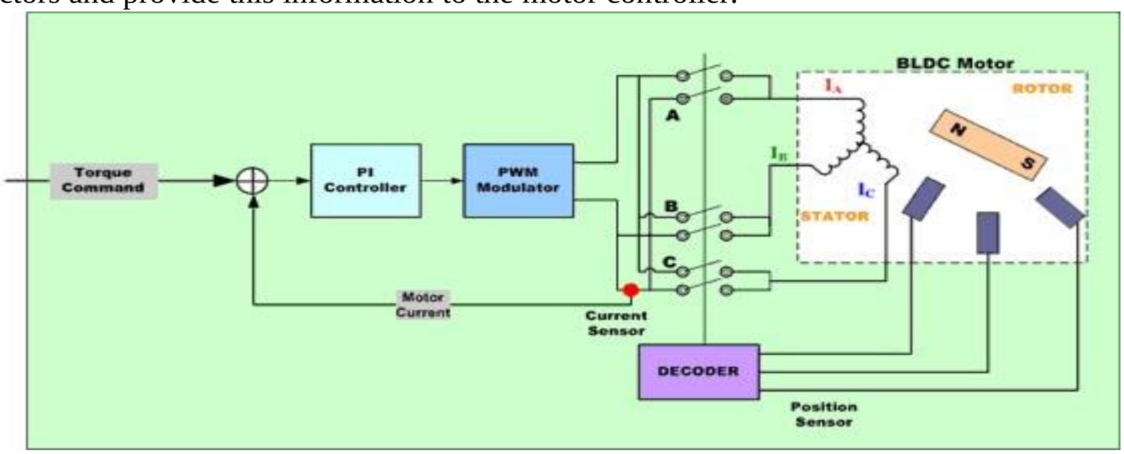
10. BLDC motor control algorithms

There are three types of algorithm or commutation control techniques available.

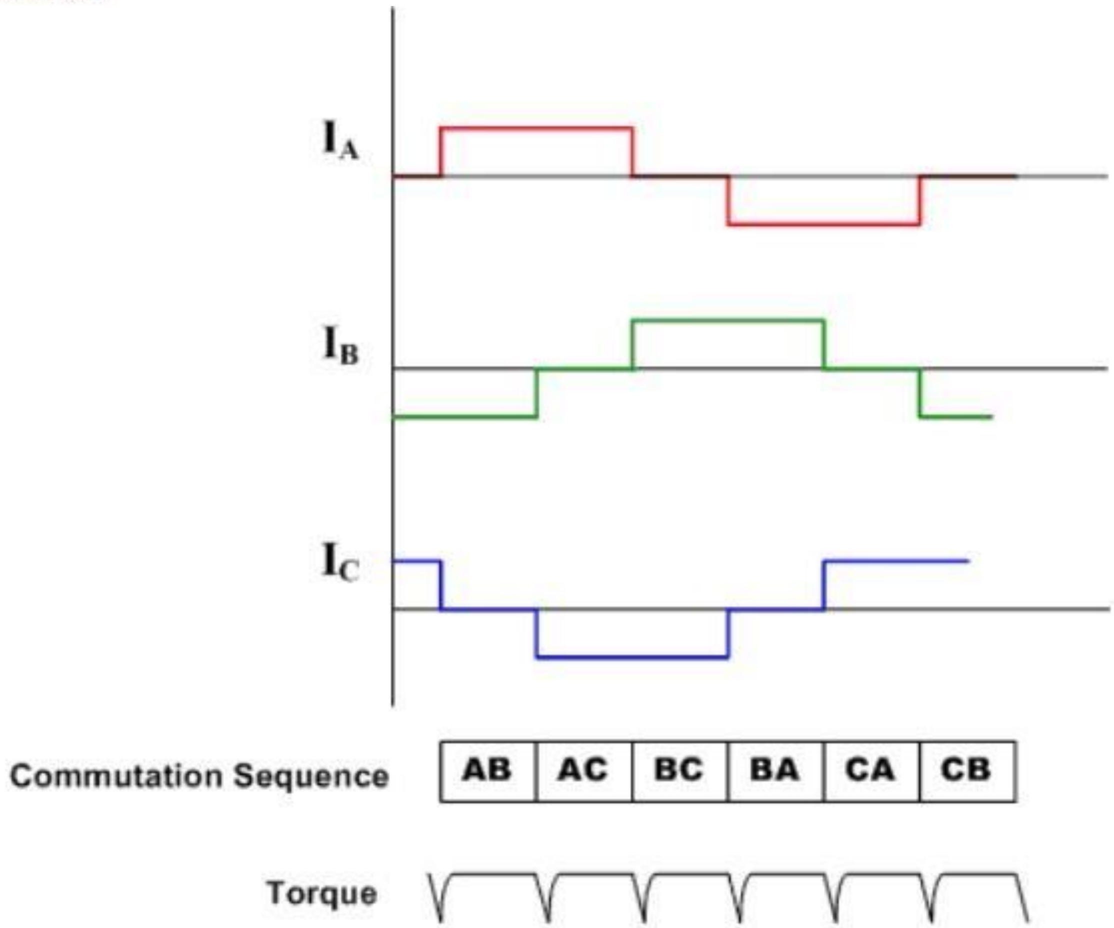
1. Trapezoidal Commutation Method
2. Sinusoidal Commutation Method
3. Field Oriented Control Method

10.1 Trapezoidal Commutation Method

Trapezoidal commutation is one of the simplest methods of control for DC brushless motor. Current is controlled through motor terminals one pair at a time, with the third motor terminal always electrically disconnected from the source of power. Three hall devices embedded in the motor are usually used to provide digital signals which measure rotor position within 60-degree sectors and provide this information to the motor controller.



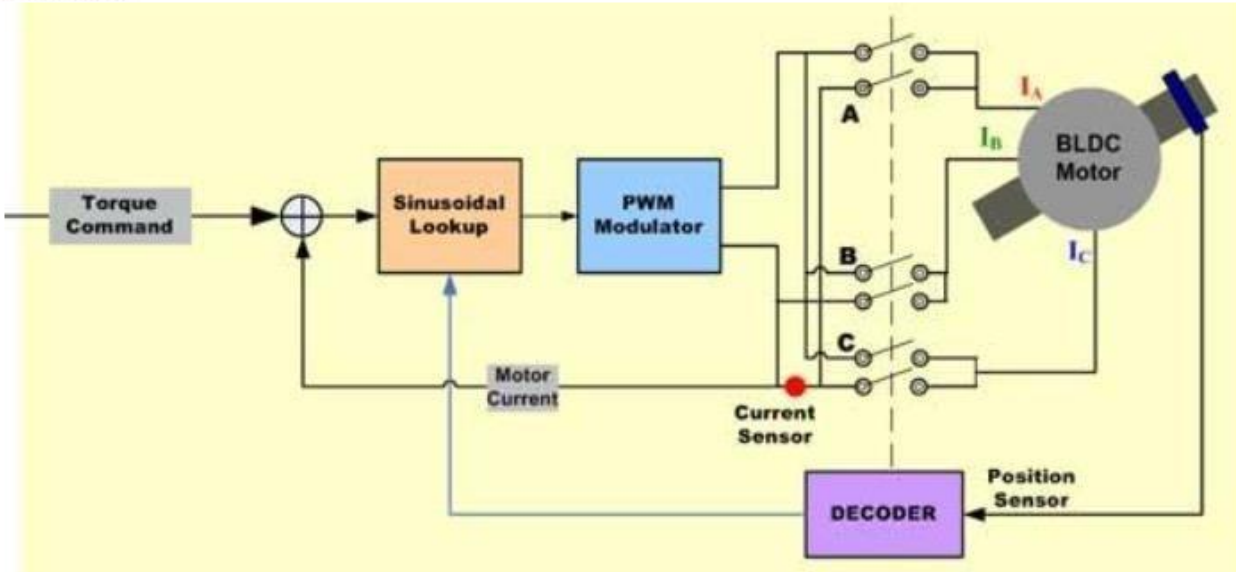
Block diagram of Trapezoidal controller for BLDC motor



Drive Waveforms and Torque at Commutation

10.2 Sinusoidal Commutation Method

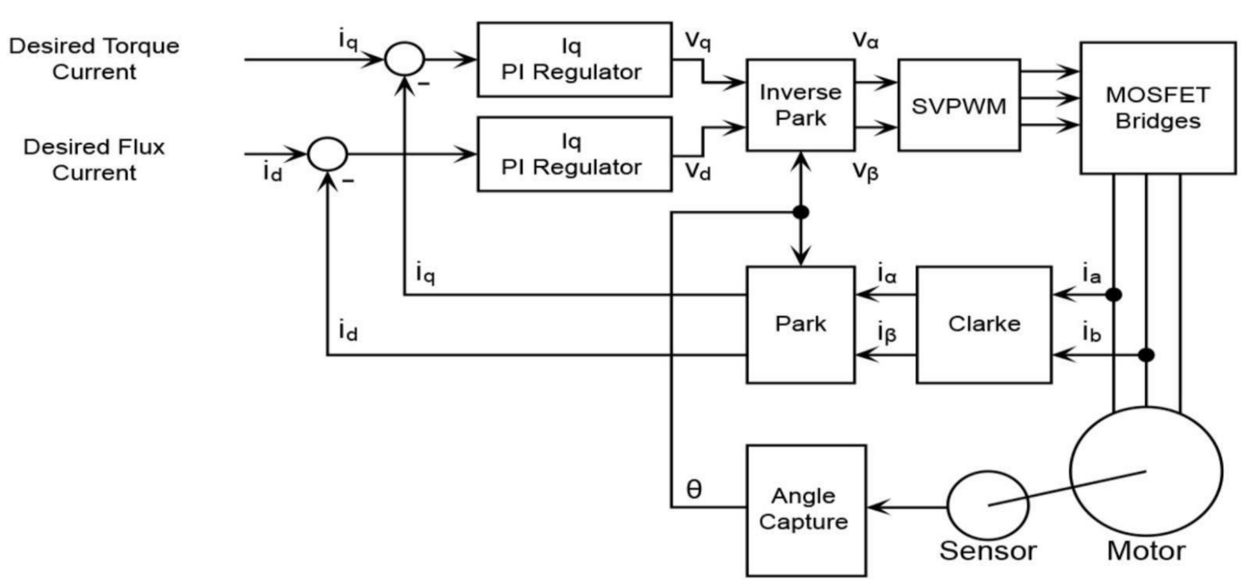
Sinusoidally commutated brushless motor controller attempts to drive the three motor windings with three currents that vary smoothly and sinusoidally as the motor turns. Trapezoidal commutations is inadequate to provide smooth and precise motor control of Brushless DC motor, particularly at low speeds. Sinusoidal commutation solves this problem. This is because the torque is produced in a three phase Brushless motor (with a sine wave back emf) is defined by some equations.



Block diagram of Sinusoidal controller for BLDC motor

10.3 Field Oriented Control Method Field Oriented Control Process

1. Micro Controller reads current sensor value (feedback current), read pedal output (reference output)
2. Find error between reference and feedback
3. Transforming 3-phase inputs to 2-phase inputs using Clarke and park Transforms
4. Setting the phasor angle of d and q vectors to 90 degrees to get maximum torque



Block diagram of Field-Oriented controller for BLDC motor

11. Hardware Required

Arduino UNO board
Brushless DC motor
6 x 06N03LA N-type mosfet
3 x IR2101 (or IR2101S) gate driver IC
LM339 quad comparator IC
6 x 33k ohm resistor
6 x 10k ohm resistor
6 x 10-ohm resistor
3 x IN4148 diode
3 x 10uF capacitor
3 x 2.2uF capacitor
10k ohm potentiometer
12V source
Breadboard
Jumper wires

12. SIMSCAPE MODEL OF THE DESIGNED MOTOR CONTROL SYSTEM

Field-Oriented Control (FOC), also known as vector control, is a technique used to control Permanent Magnet Synchronous Motor (PMSM) and AC induction motors (ACIM). FOC provides good control capability over the full torque and speed ranges. The FOC implementation requires transformation of stator currents from the stationary reference frame to the rotor flux reference frame (also known as d-q reference frame).

Speed control and torque control are the most commonly used control modes of FOC. The position control mode is less common. Most of the traction applications use the torque control mode in which the motor control system follows a reference torque value. In the speed control mode, the motor controller follows a reference speed value and generates a torque reference for the torque control that forms an inner subsystem. In the position control mode, the speed controller forms the inner subsystem.

FOC algorithm implementation requires real time feedback of the currents and rotor position. Measure the current and position by using sensors. You can also use Sensor less techniques that use the estimated feedback values instead of the actual sensor-based measurements.
According to the theory of FOC, and the hysteresis loss of permanent magnet synchronous motor is neglected, the voltage flux equations in D-q coordinate system which are based on the principle of power invariance, are obtained respectively as follows:

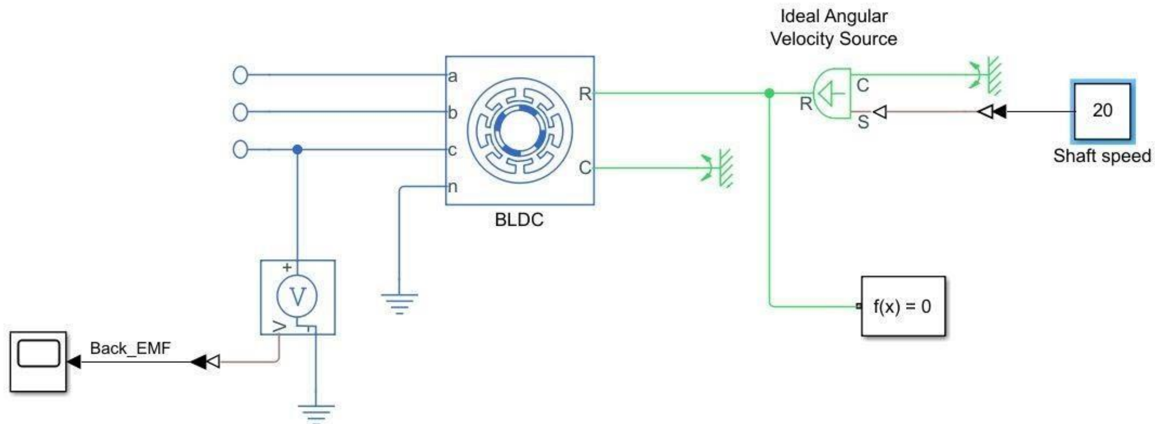
$$u_d = R_s i_s + L_d \frac{di_d}{dt} - w_e L_q i_q$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + w_e (L_d i_d + \varphi_f)$$

$$T_e = 1.5p[i_d \left(L_d - L_q\right) + i_q \varphi_f]$$

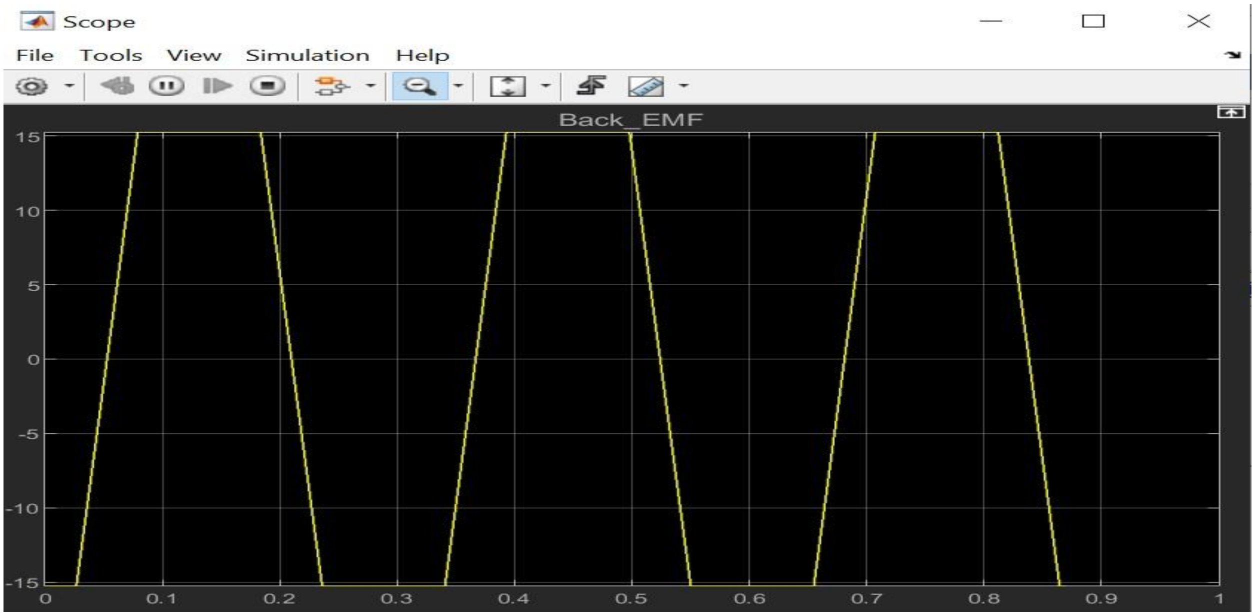
Ud and Uq is the dq-axis components of stator voltage. Rs is the resistance of three-phase winding. is is the current of stator three-phase winding. id is the current of d(q)-axis components. Ld and Lq is the dq-axis components of inductance. we is the electric angular velocity. Phi is the flux of permanent magnet. p is the pole pair numbers of motor.

12.1Back EMF Visualization in MATLAB Simulink



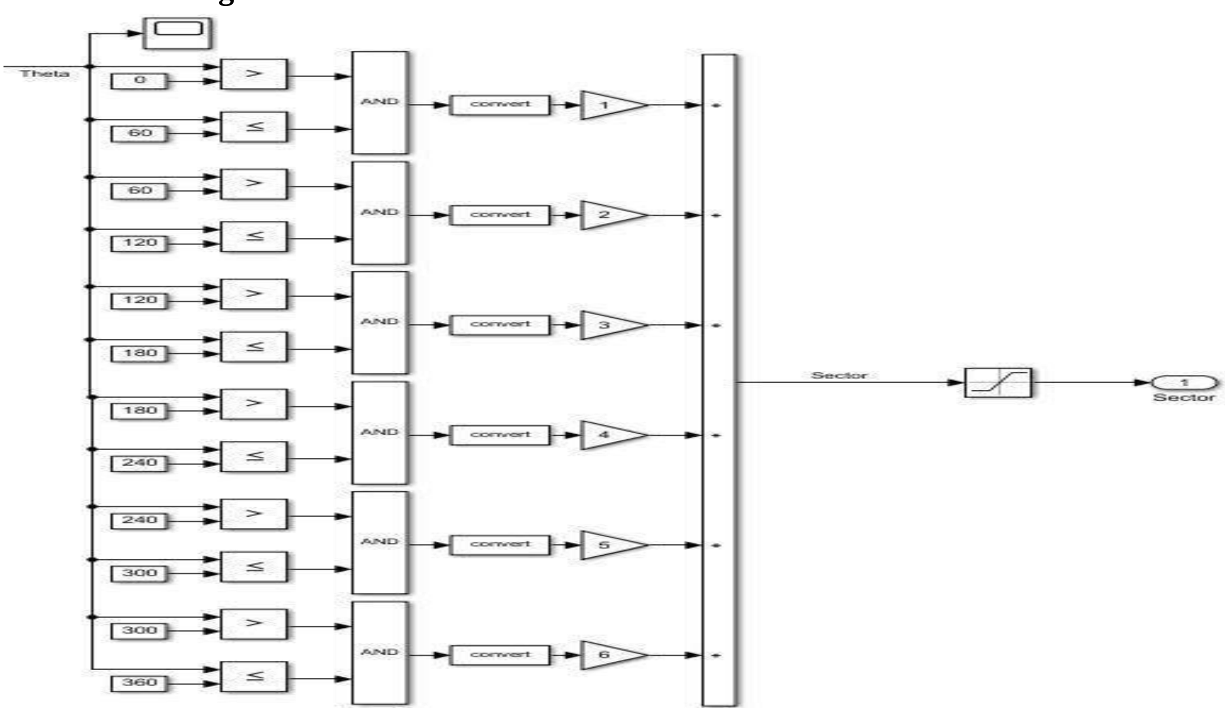
Back EMF in Simulink

12.2Trapezoidal EMF Structure



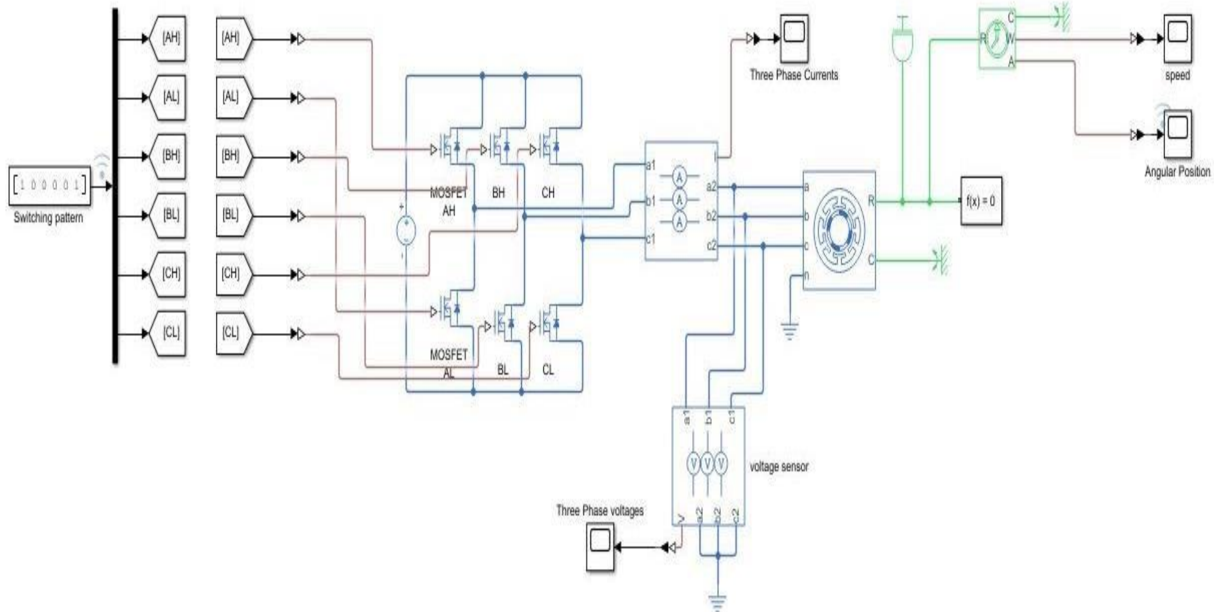
Trapezoidal EMF structure in MATLAB

12.3Hall Sensor Algorithm Structure in MATLAB Simulink



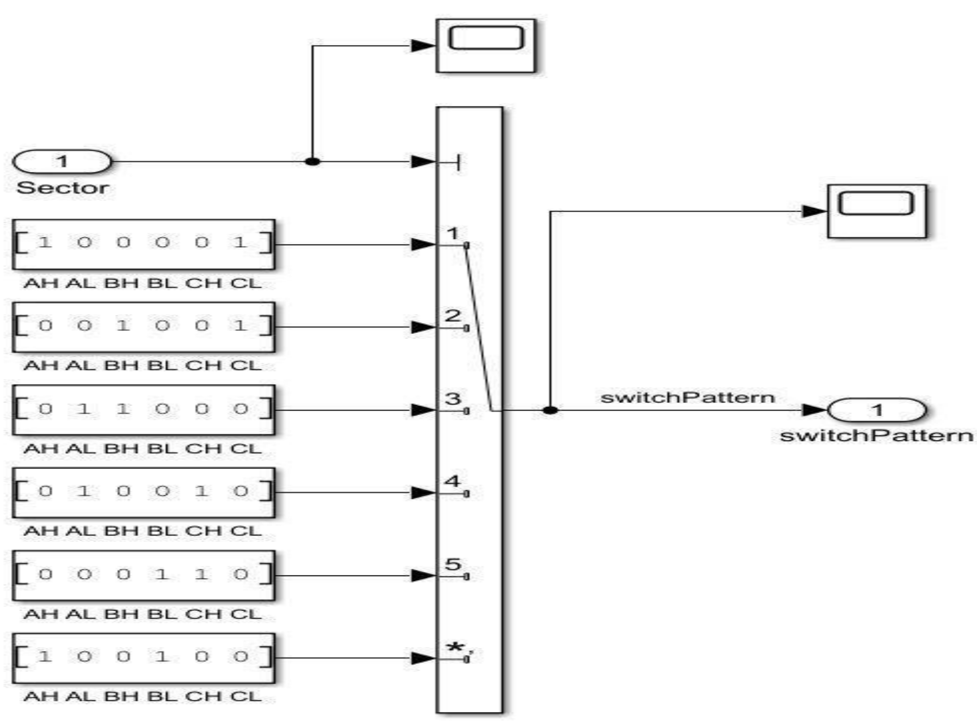
Hall Sensor Algorithm structure

12.4Inverter Model in MATLAB Simulink



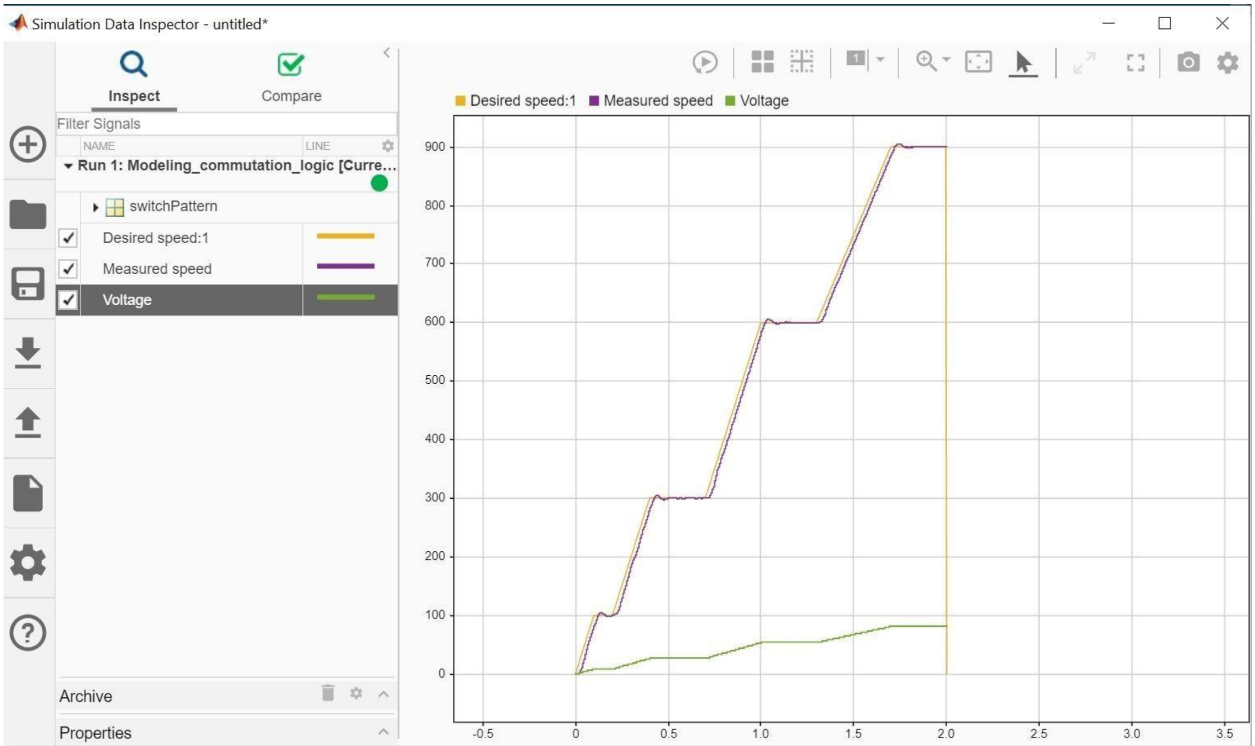
Inverter model in Simulink

12.5Selection of suitable input using the output of Hall sensor



Hall sensor output to input logic

12.6Graph depicting the Desired speed and Measured speed



Desired speed and Measured speed

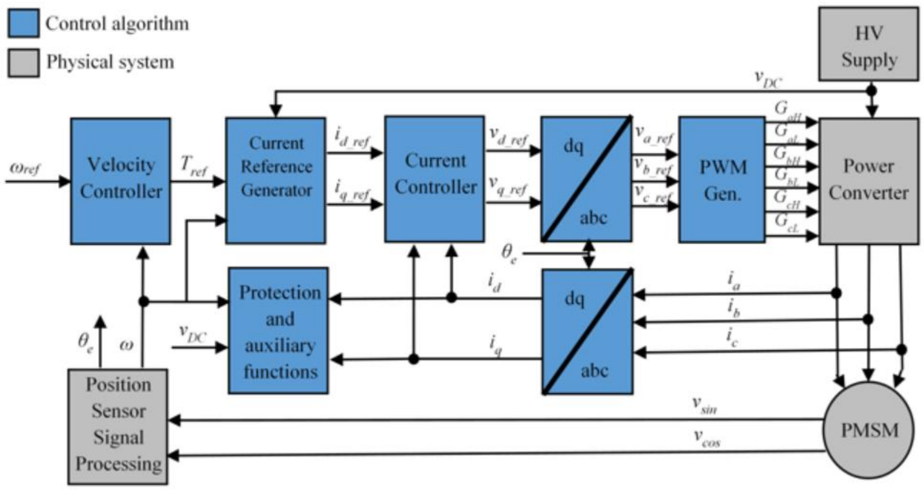
13. FOC architecture for a PMSM

At first, the reference speed, Wref, is compared with the measured speed, Wfb , and the error signal is fed to the speed PID controller. This regulator compares the actual and reference speed and outputs a torque command. The torque is related to the speed by the mechanical equation of the motor

T=J * dw/dt

J= Inertia of the motor

T=Load Torque

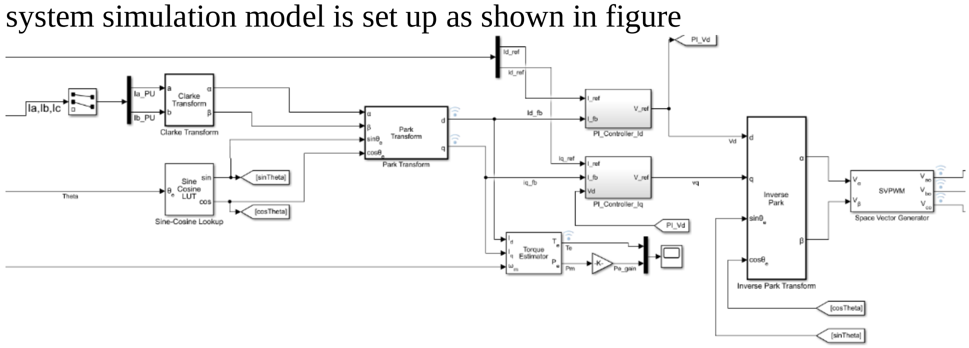


The PID outputs, Vdref and Vqref, are first transformed to abc domain by the use of inverse Park. Then, those reference voltages are used by the PWM unit to generate the inverter's command signals. A saturation block has been included to avoid exceeding the maximum torque and voltages allowed in the machine. When these limits are reached, the regulators control that the torque or voltage values do not overpass their maximum values.

The voltage supplied to the motor is transformed from d-q coordinate reference frame of the rotor to the three-phase static reference frame of the stator before it can be fed to Space Vector Pulse Width Modulation (SVPWM) to get PWM output. The implementation of vector based FOC which is built upon stator-flux oriented method gives a better steady state operation. In order to yield a high-performance system, the selection of the microprocessor is important.

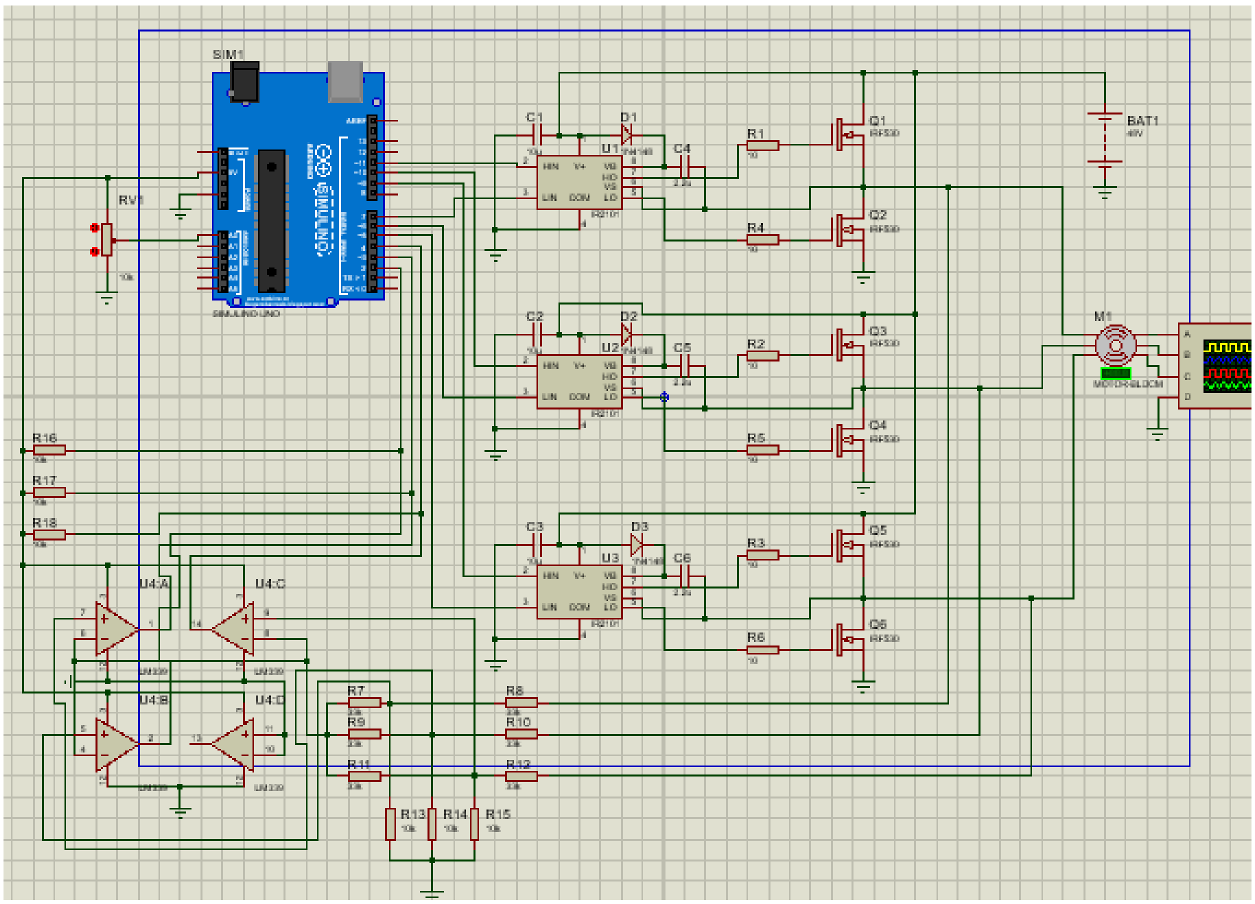
14. Software Simulation of the Control System

The control system of motor adopts closed loop control structure, which is a speed loop. The speed loop plays an important role in the whole regulation process. It can make the actual speed of the motor fast, follow the input given stably, realize the speed regulation without static check, and greatly reduce the steady-state error of the system. At the same time, because the speed loop is a closed-loop system, it has good immunity to the sudden change of load. The system simulation model is set up as shown in figure



The system consists of a speed PI regulator, a current PI regulator, a Park and Clark transform, a matrix converter, a motor model, a current detection device and a speed detection device. Both the speed PI regulator and the current PI regulator are regulators with finite amplitude.

15. Circuit diagram simulation on Proteus



The first three 33k (connected to motor phases) and the three 10k resistors are used as voltage dividers, the other three 33k resistors generate the virtual natural point.

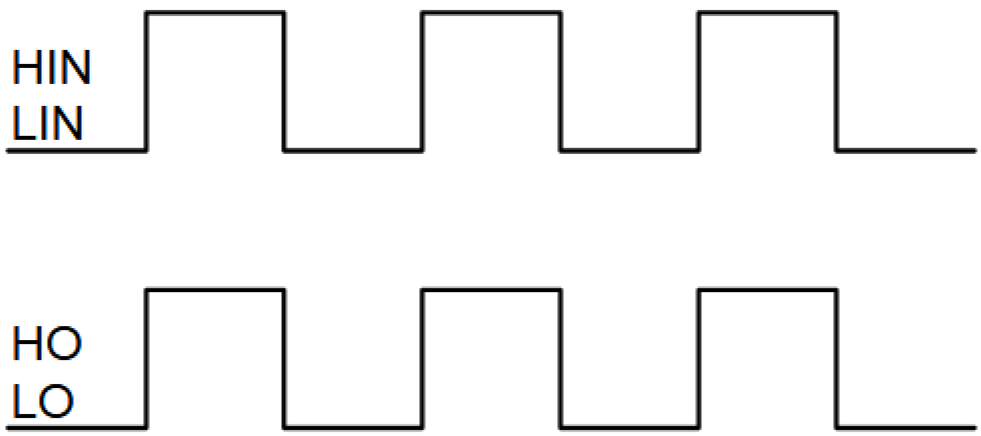
In this project we need 3 comparators to compare the BEMF of each phase with respect to the virtual natural point because we need to detect the zero crossing of each phase, here I used the LM339 quad comparator chip. The virtual point is connected to the inverting input (–) of the three comparators as shown in the circuit diagram above. BEMF A is connected to the non-inverting pin (+) of comparator number 1, BEMF B is connected to the positive terminal of comparator 2 and BEMF C is connected to the positive terminal of comparator 3. Comparator 4 is not used and its input terminals should be grounded.

As known the comparator output is logic 1 if the non-inverting voltage is greater than the inverting voltage and vice versa.

The LM339 outputs are open collector which means a pull up resistor is needed for each output, for that I used three 10k ohm resistors.

The outputs of the 3 comparators are connected to Arduino pins 2, 3 and 4 respectively for BEMF A, BEMF B and BEMF C.
Arduino UNO pins 2, 3 and 4 are ATmega328P microcontroller external interrupt pins PCINT18, PCINT19 and PCINT20 respectively.

The IR2101 chips are used to control high side and low side mosfets of each phase. The switching between the high side and the low side is done according to the control lines HIN and LIN. The figure below shows input and output timing diagram:



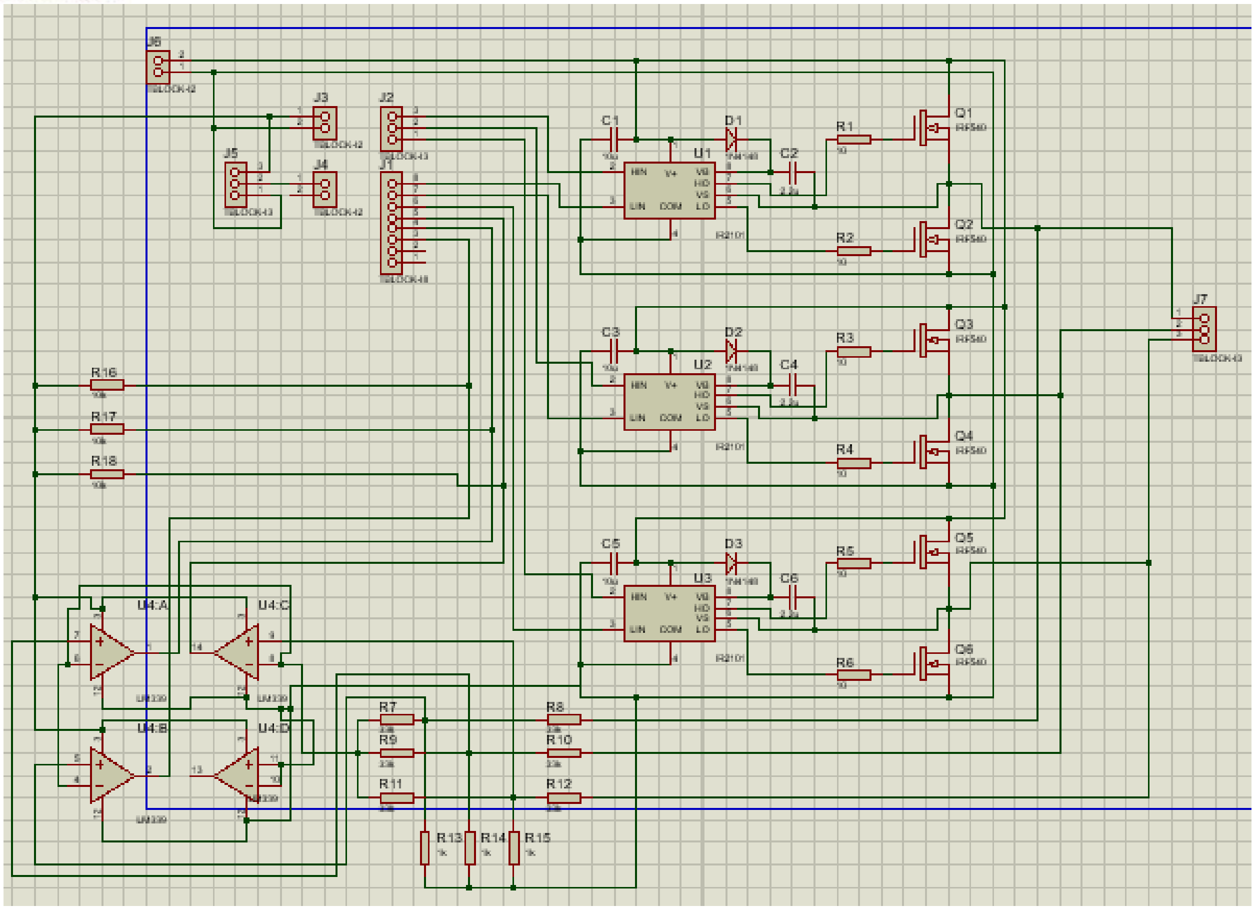
IR2101 input output timing diagram

The HIN lines of the three IR2101 are connected to pins 11, 10 and 9 respectively for phase A, phase B and phase C. The Arduino UNO can generate PWM signals on that pins where only high side mosfets are PWMed.
The LIN lines are connected to Arduino pins 7, 6 and 5 respectively for phase A, phase B and phase C.

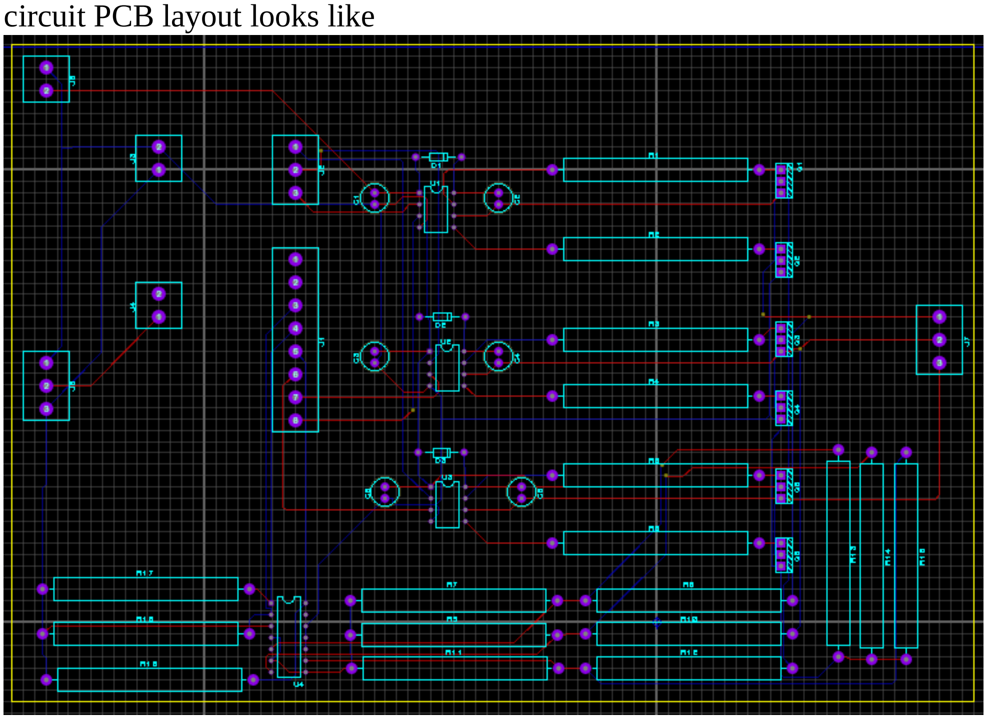
The 10k potentiometer is used to vary the speed of the BLDC motor, its output is connected to Arduino analog channel 0 (A0).

15.1PCB design of our circuit diagram

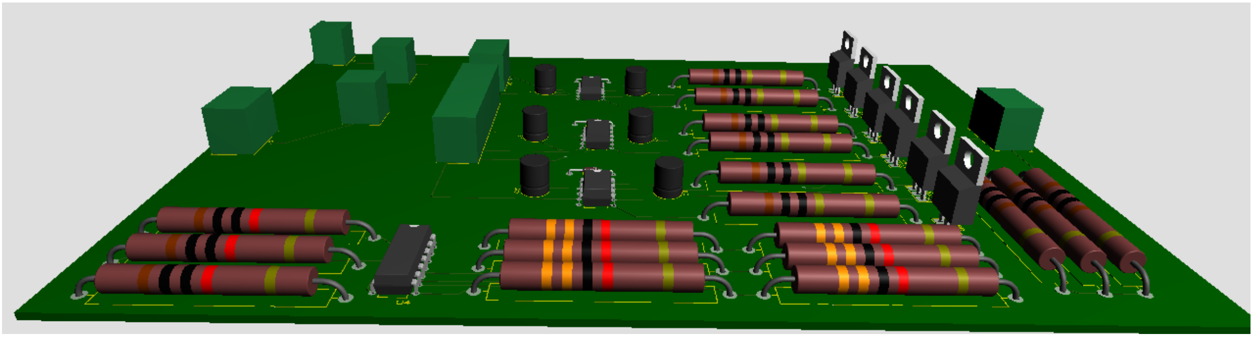
Here we change some of our components into T-blocks because those components do not have PCB preview in proteus.



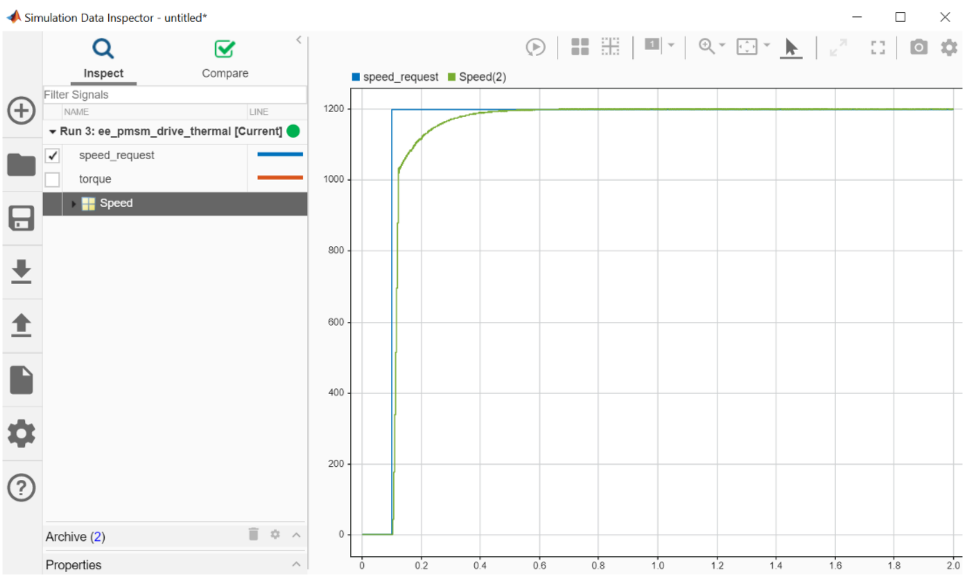
For this circuit PCB layout looks like



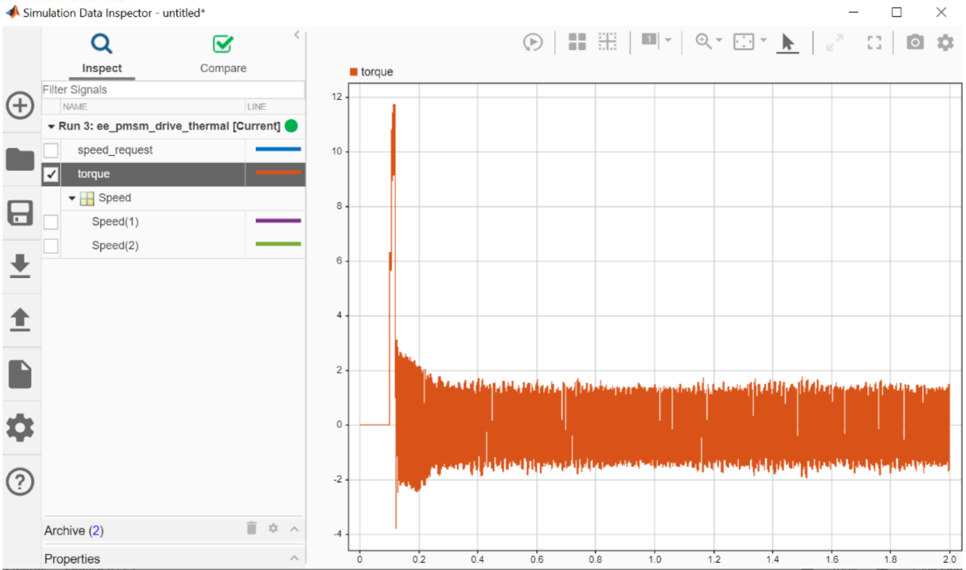
This is how our PCB looks like in 3D



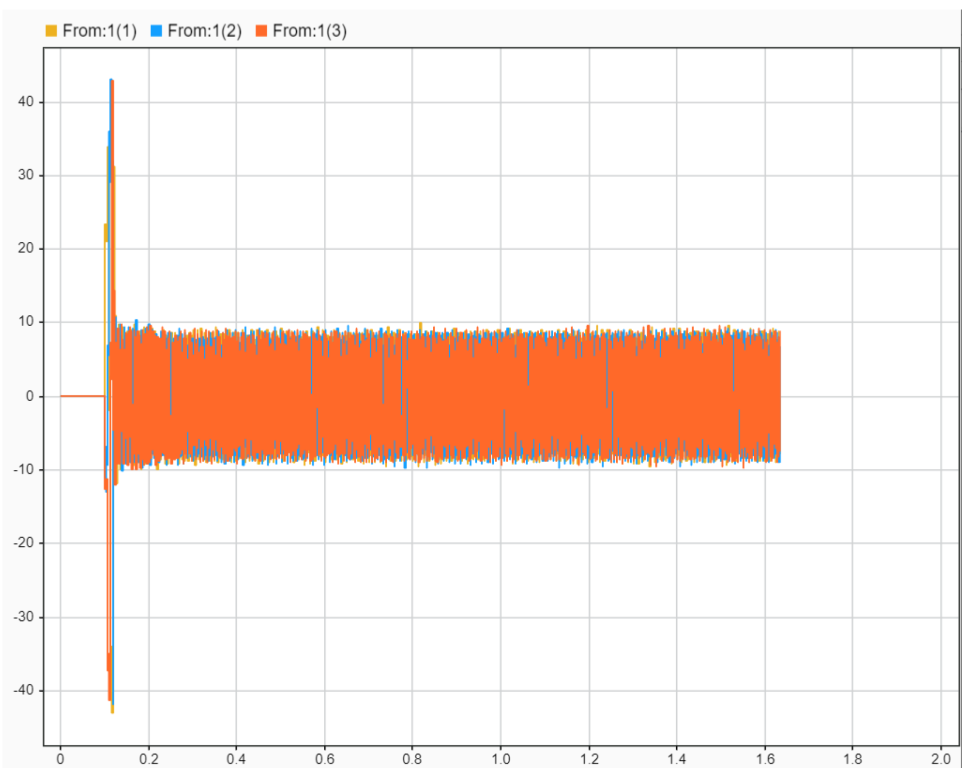
16. Results



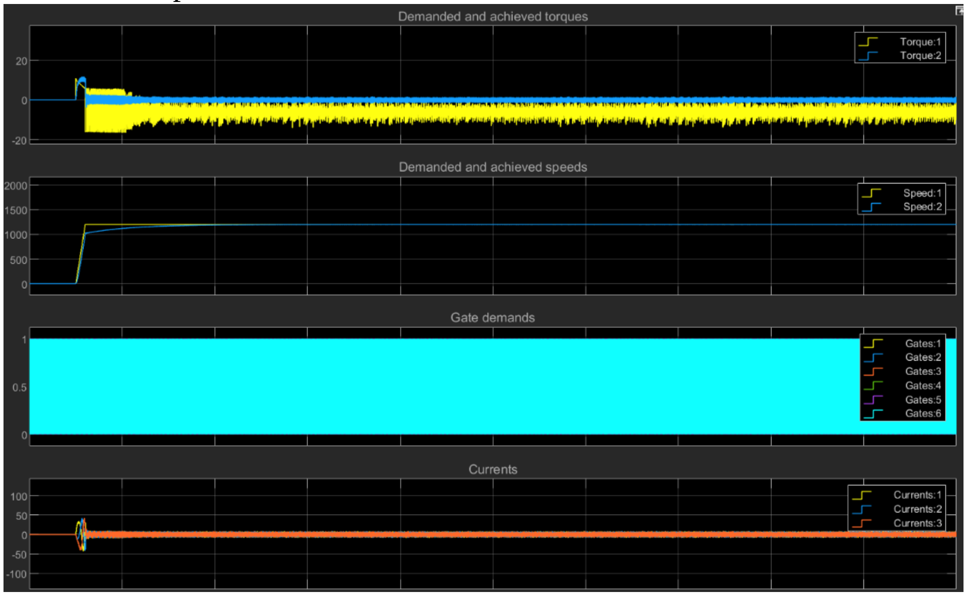
When a step signal of 1200 rpm is given to the controller, the Measured speed reached the target in about 0.4 sec. As the Desired speed increases, the time taken for reaching the required speed increases.



The Torque will be at a peak position as dw/dt will be constant in order to reach the desired speed. As soon as the motor reaches the speed, the torque required will be lowered close to zero as shown in the above figure.



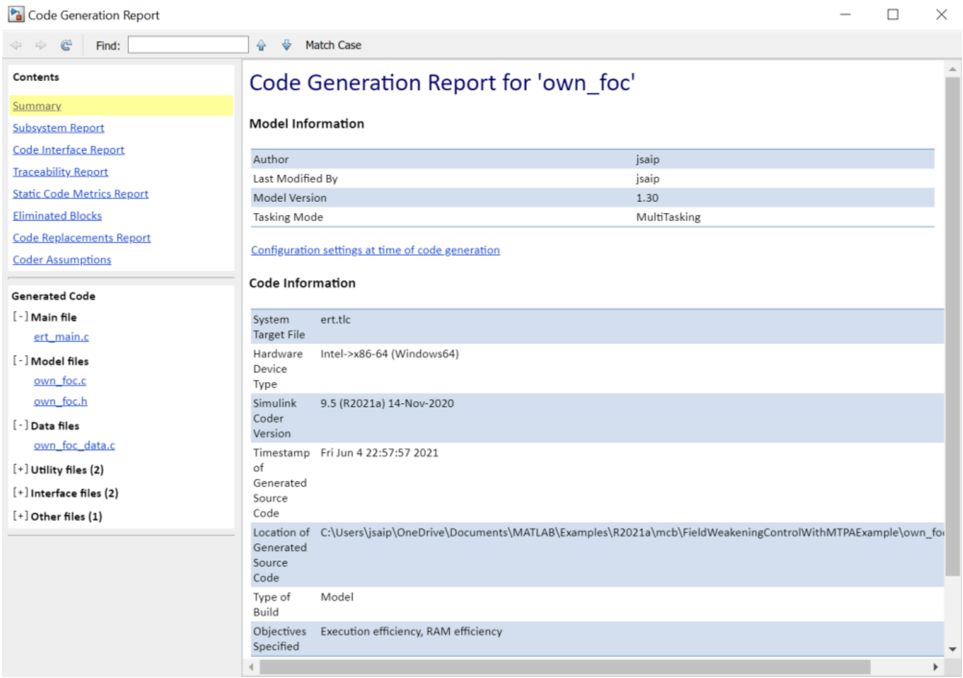
As Torque is proportional to the amount of current passing through the motor, the flow of three phase currents will be decreased after reaching the desired speed. At 1200 rpm, the motor runs close to 8 amps.



The above figure is the combined representation of the simulated model.

16.1Code Generation

The algorithm model can be compiled. After the completion of the code compilation, Matlab will transfer the code to the CCS, after which the program will automatically download to DSP and run. The code generation report is shown in the below figure. In the code generation report, you can see the code generation of each sub-module through the link, you can easily see the specific register configuration parameters, model parameters and model corresponding code.



16.2Brushless dc motor control with Arduino code:

Arduino pins 9, 10 and 11 can generate PWM signals where pin 9 and pin 10 are related to Timer1 module (OC1A and OC1B) and pin 11 is related to Timer2 module (OC2A). Both Timer modules are configured to generate a PWM signal with a frequency of about 31KHz and a resolution of 8 bits. The duty cycles of the PWM signals are updated when the ADC module completes its conversion by writing to registers OCR1A, OCR1B and OCR2A.

```
#define PWM_MAX_DUTY      255
#define PWM_MIN_DUTY      50
#define PWM_START_DUTY    100

byte bldc_step = 0, motor_speed, pin_state;

void setup()
{
  DDRD  |= 0xE0;
  PORTD  = 0x00;
  DDRB  |= 0x0E;
  PORTB  = 0x31;
  TCCR1A = 0;
  TCCR1B = 0x01;
  TCCR2A = 0;
```

```
  TCCR2B = 0x01;
  // ADC module configuration
  ADMUX  = 0x60;
  ADCSRA = 0x84;

  PCICR  = EIMSK = 0;

  pinMode(2, INPUT_PULLUP);
  pinMode(3, INPUT_PULLUP);
  pinMode(4, INPUT_PULLUP);
}

// pin change interrupt 2 (PCINT2) ISR
ISR (PCINT2_vect)
{
  if( (PIND & PCMSK2) != pin_state )
    return;
  // BEMF debounce
  for(byte i = 0; i < 20; i++)
  {
    if(bldc_step & 1){
      if(PIND & PCMSK2)     i -= 1;
    }
    else {
      if(!(PIND & PCMSK2))  i -= 1;
    }
  }

  bldc_move();
  bldc_step++;
  bldc_step %= 6;
}

// BLDC motor commutation function
void bldc_move()
{
  switch(bldc_step)
  {
    case 0:
      AH_BL();
      BEMF_C_FALLING();
```

```
      break;
    case 1:
      AH_CL();
      BEMF_B_RISING();
      break;
    case 2:
      BH_CL();
      BEMF_A_FALLING();
      break;
    case 3:
      BH_AL();
      BEMF_C_RISING();
      break;
    case 4:
      CH_AL();
      BEMF_B_FALLING();
      break;
    case 5:
      CH_BL();
      BEMF_A_RISING();
  }
}

void loop()
{
  SET_PWM_DUTY(PWM_START_DUTY);
  int i = 5000;

  // motor start
  while(i > 100)
  {
    delayMicroseconds(i);
    bldc_move();
    bldc_step++;
    bldc_step %= 6;
    i = i - 20;
  }

  motor_speed = PWM_START_DUTY;

  PCICR  = 4
```

```
  while(1)
  {
    ADCSRA |= 1 << ADSC;
    while(ADCSRA & 0x40);
    motor_speed = ADCH;
    if(motor_speed < PWM_MIN_DUTY)
      motor_speed = PWM_MIN_DUTY;
    SET_PWM_DUTY(motor_speed);
  }
}

void BEMF_A_RISING()
{
  PCMSK2 = 0x04;
  pin_state = 0x04;
}
void BEMF_A_FALLING()
{
  PCMSK2 = 0x04;
  pin_state = 0;
}
void BEMF_B_RISING()
{
  PCMSK2 = 0x08;
  pin_state = 0x08;
}
void BEMF_B_FALLING()
{
  PCMSK2 = 0x08;
  pin_state = 0;
}
void BEMF_C_RISING()
{
  PCMSK2 = 0x10;
  pin_state = 0x10;
}
void BEMF_C_FALLING()
{
  PCMSK2 = 0x10;
  pin_state = 0;
```

```
}

void AH_BL()
{
  PORTD &= ~0xA0;
  PORTD |=  0x40;
  TCCR1A =  0;
  TCCR2A =  0x81;
}
void AH_CL()
{
  PORTD &= ~0xC0;
  PORTD |=  0x20;
  TCCR1A =  0;
  TCCR2A =  0x81;
}
void BH_CL()
{
  PORTD &= ~0xC0;
  PORTD |=  0x20;
  TCCR2A =  0;
  TCCR1A =  0x21;
}
void BH_AL()
{
  PORTD &= ~0x60;
  PORTD |=  0x80;
  TCCR2A =  0;
  TCCR1A =  0x21;
}
void CH_AL()
{
  PORTD &= ~0x60;
  PORTD |=  0x80;
  TCCR2A =  0;
  TCCR1A =  0x81;
}
void CH_BL()
{
  PORTD &= ~0xA0;
  PORTD |=  0x40;
```

```
  TCCR2A =  0
  TCCR1A =  0x81;
}

void SET_PWM_DUTY(byte duty)
{
  OCR1A  = duty;  // set pin 9  PWM duty cycle
  OCR1B  = duty;  // set pin 10 PWM duty cycle
  OCR2A  = duty;  // set pin 11 PWM duty cycle
}
```

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