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Assessment of Forces and Powers and Control law of a brushless motor

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General Introduction

In the realm of electric motors, brushless motors have emerged as key components in diverse applications, ranging from consumer electronics to industrial machinery. The distinctive feature of brushless motors lies in their design, which eliminates the need for traditional brushes, resulting in reduced friction, lower maintenance, and enhanced efficiency.

The efficient operation of brushless motors hinges on the implementation of sophisticated control laws. Control mechanisms play a pivotal role in regulating the speed, position, and overall performance of these motors, ensuring they meet the stringent demands of modern applications. As technological advancements continue to push the boundaries of what is achievable, the importance of precise and adaptive control in brushless motor systems becomes increasingly apparent.

This report delves into the intricacies of the control law governing brushless motors, shedding light on the principles, methodologies, and applications that characterize their dynamic behavior. From the fundamental principles of PID control to the challenges and innovations in the field, the following sections provide a comprehensive exploration of the crucial role that control strategies play in optimizing the performance of brushless motors.

To facilitate a systematic understanding, the report is structured to cover key aspects of brushless motor control. Starting with an exploration of the fundamental principles of brushless motor operation, the report delves into various control laws, with a special focus on PID control. Concrete examples, case studies, and a discussion on challenges and innovations further enrich the narrative, providing a holistic view of the current state and future prospects of brushless motor control.

As industries continue to embrace the efficiency and versatility of brushless motors, a nuanced understanding of their control mechanisms becomes imperative. This report serves as a comprehensive guide, offering insights into the intricate world of brushless motor control.

Chapitre 1

Assessment of Forces and Powers

Introduction

The calculation of engine power holds paramount significance in the field of mechanical engineering, providing fundamental insights to assess an engine's performance across various operational contexts. This report aims to present a detailed analysis of the engine power calculation process, shedding light on the methods employed, collected baseline data, and the achieved results.

In the realm of engineering, understanding the power of an engine is essential for optimizing its operation, enhancing energy efficiency, and meeting specific requirements across diverse applications. Whether in the transportation sector, industrial production, or other domains, engine power is a key parameter directly influencing the overall system performance.

The primary objective of this report is to comprehensively describe the engine power calculation process, emphasizing the utilized methodology, relevant data, and the outcomes of this study. By analyzing these elements, we seek to provide valuable insights that can serve as a foundation for well-informed decisions in the realms of design, maintenance, and engine optimization.

The report will also address the practical implications of the obtained results, highlighting potential applications in real-world scenarios. Additionally, it will underscore any challenges encountered during the calculation process and discuss important considerations to ensure the reliability and accuracy of the results.
Through this study, we aim to contribute to the overall understanding of engine power calculation, thereby offering significant insights for engineering professionals, researchers, and anyone interested in the performance of mechanical systems..

1.1 Acceleration Calculation

The maximum speed imposed by the specifications is Vmax = 30 km/h. Converting this to meters per second, we get Vmax = 8.333333 m/s.

Assuming that our car starts from the origin at time t=0 and with zero initial velocity, after a duration of 15 seconds, our car reaches its maximum speed of Vmax = 8.333333 m/s.

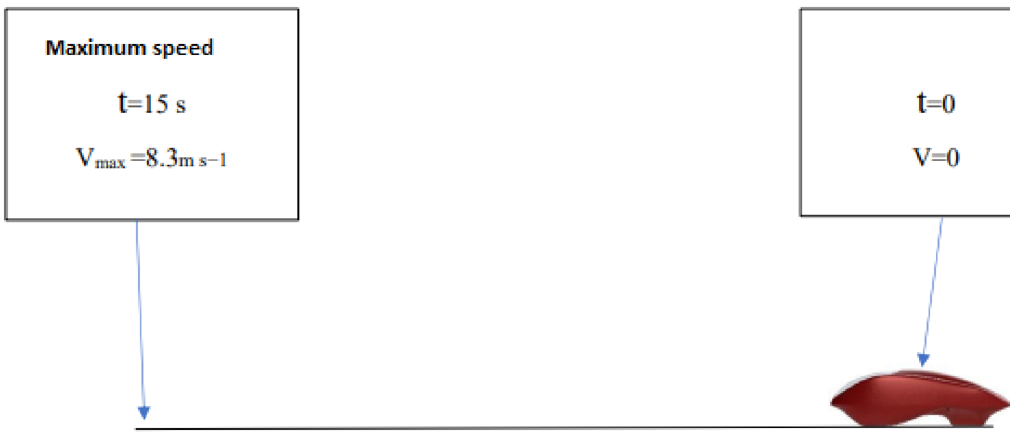

FIGURE 1.1 – explanatory diagram

$$\tau = \frac{\Delta V}{\Delta t} = \frac{8.3 - 0}{15 - 0} = 0.55\, m/s^2$$

Where :
- τ : Acceleration.
- ΔV : Change in velocity.
- Δt : Change in time.

1.1.1 Inertia Force

The car has 3 wheels, so the total mass needs to be divided among the 3 wheels. However, for calculation safety, we measure using the total mass (see Figure 2).

Let $M_total = M1 + M2 = VehicleMass + DriverMass$
Where M1 = 50 kg and M2 = 60 kg

$$F_1 = M_{total} \cdot \tau = 110 \cdot 0.55 = 61\,N$$

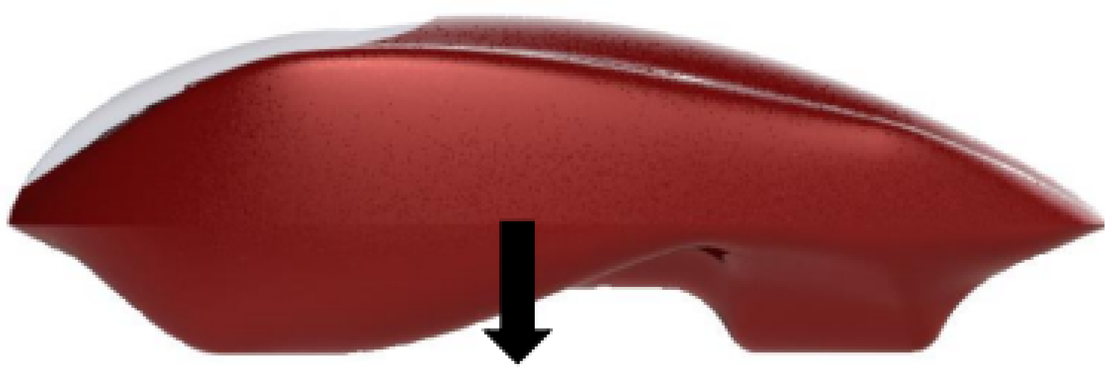

FIGURE 1.2 – Inertia Force

1.1.2 Rolling Resistance

The tire's rolling resistance is primarily associated with the deformation of the tire. Rolling resistance is one of the forces that opposes the forward movement of the vehicle.

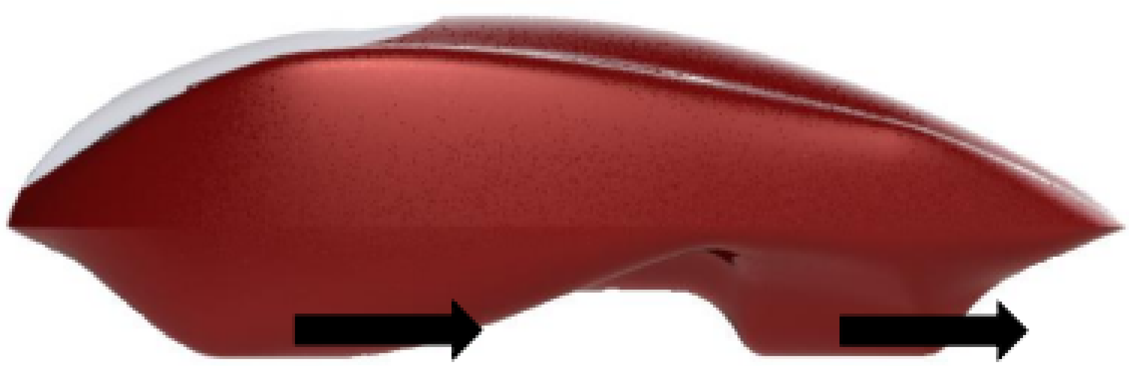

FIGURE 1.3 – Rolling Resistance

$$F_2 = \delta \cdot M_{total} \cdot g = 0.015 \cdot 9.8 \cdot 160 = 23.52\,N$$

Where :

- δ : Rolling resistance coefficient to be determined from Figure 3.

- M_{total} : Total mass.
- g : Acceleration due to gravity (approximately 9.8 m/s²).

C_{rr}	Description
0,000 3 à 0,000 4 [1]	Roue de chemin de fer en acier sur rail en acier (résistance au roulement pure)
0,001 à 0,001 5 [2]	Roulement à billes en acier durci sur acier
0,001 0 à 0,002 4 [3, 4]	Roue de chemin de fer en acier sur rail en acier. Wagon de passager environ 0.0020 [5]
0,001 9 à 0,006 5 [6]	Roues en fonte de véhicules miniers sur rails en acier
0,002 2 à 0,005 [7]	Pneus de bicyclette de production pour 8,3 bars et 50 km/h
0,002 5 [8]	Pneus spéciaux éco-marathon
0,005	Rails sales de tramway (standard) avec et sans virages
0,004 5 à 0,008 [9]	Pneus de grands camions
0,005 5 [8]	Pneus BMX de bicyclettes typiques pour voitures solaires
0,006 2 à 0,015 [10]	Mesure de pneus de voiture
0,010 à 0,015 [11]	Pneus de voitures ordinaires sur béton
0,038 5 à 0,073 [12]	Diligence (XIXe siècle) sur une route sale. Neige molle sur la route dans le pire cas
0,3 [11]	Pneus de voitures ordinaires sur sable

Le coefficient C_{rr} désigne le coefficient de résistance au roulement (anglais : *rolling resistance coefficient*). La force de résistance constante s'élève à

$F_R = C_{rr} \cdot m \cdot g$

où m est la masse du véhicule et g correspond à la gravité terrestre.

FIGURE 1.4 – Rolling Coefficient

1.1.3 Aerodynamic Force

The aerodynamic force or drag is given by :

$$F_3 = \frac{1}{2} \rho \cdot S \cdot C \cdot V^2$$

Where :
- ρ : Air density,
- S : Frontal area of our vehicle,
- C : Drag coefficient to be determined from Figure 4 (for a more aerodynamic shape, $C = 0.04$, but for safety, $C = 0.075$),
- V : Relative velocity.

$$F_3 = \frac{1}{2} \times 1.225 \times 0.3 \times 0.075 \times 8.32^2 = 0.95\, N$$

FIGURE 1.5 – Aerodynamic Force

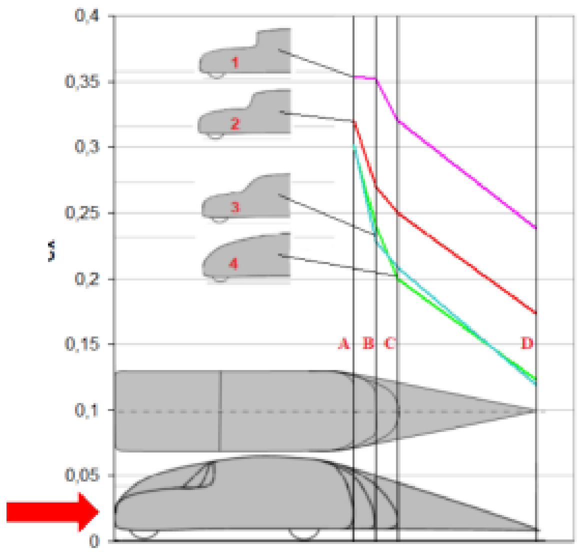

FIGURE 1.6 – Determination of Drag Force

1.1.4 Gravity Force

Gravity forces, F_g, come into play only when the traveled road has slopes. Gravity forces are more significant when the slope is steep, and the vehicle's mass is large.

$$F_4 = M_{total} \cdot g \cdot \sin(\alpha) = 110 \cdot 9.81 \cdot \sin(2°) = 38\,N$$

Where :

- M_{total} : Total mass in kilograms,
- g : Acceleration due to gravity (9.81 m/s^2),
- α : The angle of the slope in degrees.

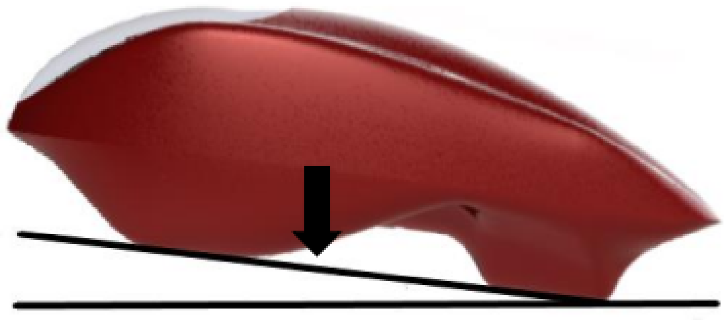

FIGURE 1.7 – Gravity Force

1.2 Force Summary

F1 : Vertical Mass Force = 61 N
F2 : Rolling Force = 23.52 N
F3 : Aerodynamic Force = 0.95 N
F4 : Gravity Force = 38 N

This force summary provides a comprehensive overview of the individual forces acting on the vehicle, highlighting their respective magnitudes in Newtons (N).

1.3 Power Calculations

$$P_1 = F_1 \cdot V = 61 \cdot 8.3 = 506.3\,W$$

$$P_2 = F_2 \cdot V = 23.52 \cdot 8.3 = 195.21\,W$$

$$P_3 = F_3 \cdot V = 0.95 \cdot 8.3 = 7.885\,W$$

$$P_4 = F_4 \cdot V = 38 \cdot 8.3 = 315.4\,W$$

$$P = \sum P_i = P_1 + P_2 + P_3 + P_4 = 506.3 + 195.21 + 7.885 + 315.4 = 1025\,W$$

*Conclusion :** The estimated maximum power is 1025 W.

Since the transmission system is a gear and chain (with efficiency $90\% < \eta < 95\%$), for $\eta = 90$

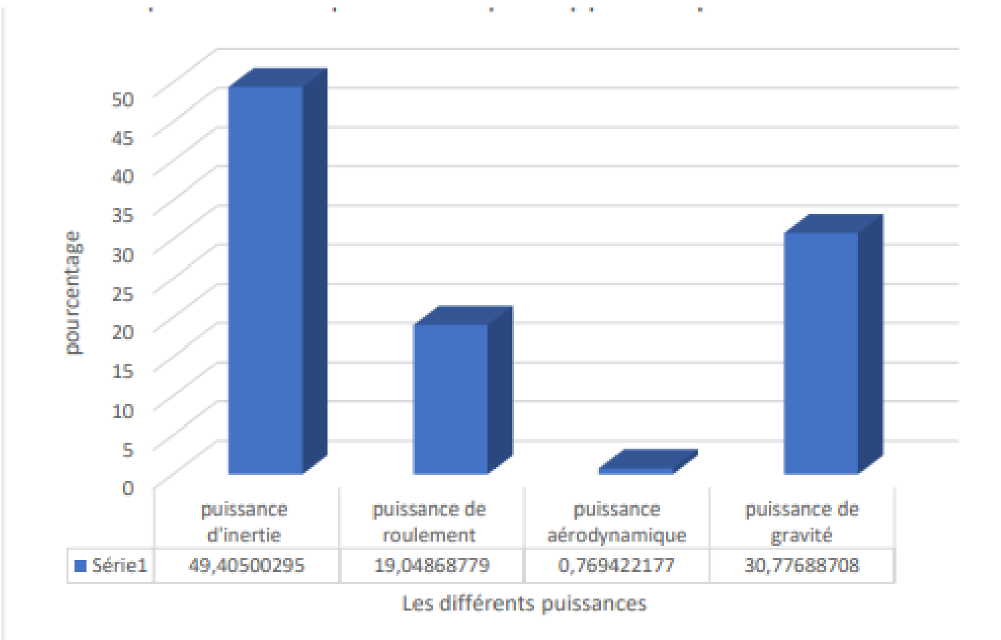

Figure 1.8 – The distribution of powers in relation to the total power

$$P_m = \frac{P_s}{\eta} = \frac{1025}{0.9} = 1139\,W$$

Therefore, a motor with a power rating of 1200 W is sufficient.

Conclusion

This chapter has facilitated a comprehensive analysis of the forces influencing the vehicle, shedding light on key aspects such as mass, rolling resistance, aerodynamic force, and gravity. Power calculations were performed to estimate the load required by the motor, and a conclusion was drawn regarding the minimum necessary power.

The results indicate that the estimated maximum power is 1025 W, with a safety margin taken into account for the transmission system. The choice of a 1200 W motor is deemed appropriate to meet the vehicle's requirements.

This chapter demonstrates the importance of understanding the associated forces and powers to design an efficient propulsion system. Considerations regarding rolling resistance, aerodynamic force, and gravity provide a solid foundation for the selection of motor components and the overall vehicle design. The methodology used offers a systematic approach to estimate power requirements, facilitating well-informed design decisions.

Chapitre 2

Control law of a brushless motor

Introduction

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

Even though they have been used for drives and power generation for a long time, the sub kilowatt range, which has been dominated by Brushed DC Motors, has always been a grey area. But the modern power electronics and microprocessor technology has allowed the small Brushless DC Motors to thrive, both in terms price and performance.

2.1 Principle of Brushless Motor Operation

2.1.1 Brief Explanation of How Brushless Motors Work

A Brushless DC Motor (BLDC) is similar to a Brushed DC Motor, but it doesn't use brushes for commutation. Instead, it is electronically commutated. In conventional Brushed DC Motors, the brushes are used to transmit the power to the rotor as they turn in a fixed magnetic field. BLDC motors have several advantages over brushed motors, including higher dynamic response due to low inertia and carrying windings in the stator, less electromagnetic interference, and low noise due to the absence of brushes. They are used in various applications, including electric vehicles, industrial robots, CNC machine tools, and washing machines, among others. The operation of a BLDC motor involves a stator with a stationary current-carrying conductor and a moving permanent magnet rotor. The field inside a brushless motor is switched through an amplifier, which is triggered by the electronic controller. The rotor alignment, power supply, magnetic fields interaction, and continuous rotation are the main steps involved in the operation of a BLDC motor. As mentioned earlier, a BLDC motor used electronic commutation and thus eliminates the mechanically torn brushes.

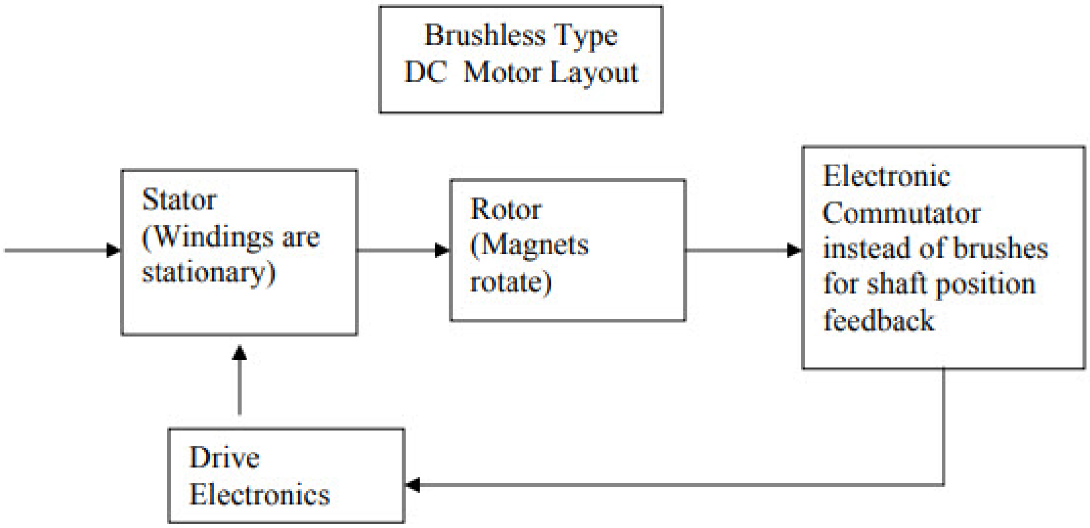

FIGURE 2.1 – Block diagram of BLDC motor

— Stator : The stationary part of the motor, which contains coils of wire that generate a magnetic field when an electrical current is passed through them.
— Rotor (or Armature) : The rotating part of the motor, typically consisting of permanent magnets or coils. Speed Controller (ESC) : This component plays a crucial role in brushless motor operation by electronically controlling the power supplied to the motor windings.

The operation of a brushless motor can be summarized in the following steps :
— Rotor Alignment : Initially, the rotor is in a specific position concerning the stator, known as the initial commutation state.
— Power Supply : An external power source, controlled by the ESC, energizes specific stator coils based on the rotor's position.
— Magnetic Fields Interaction : The energized stator coils create a magnetic field that interacts with the permanent magnets on the rotor, causing it to move.
— Continuous Rotation : As the rotor rotates, sensors (or in some cases, the back-EMF generated by the motor) feedback information to the ESC, allowing it to adjust the power supply to maintain a smooth and controlled rotation.

This process repeats, ensuring the rotor continues to follow the desired rotational path. The absence of brushes and commutators in brushless motors contributes to reduced friction, lower wear and tear, and enhanced reliability compared to brushed motors.

2.1.2 Construction of BLDC Motor

The primary distinction between brushed and brushless motors is the replacement of the mechanical commutator with an electric switch circuit. In the case of a Brushless DC Motor (BLDC), it is a type of synchronous motor, meaning that the magnetic field generated by the stator and the rotor revolves at the same frequency. Brushless motors are available in three configurations : single phase, two phase, and three phase, with the three phase BLDC being the most common. The absence of brushes in BLDC motors leads to several advantages, including higher dynamic response, less electromagnetic interference, and lower noise. These motors are used in a wide range of applications, such as automotive industry, industrial automation, aerospace, and consumer electronics.

The following image shows the cross-section of a BLDC Motor.

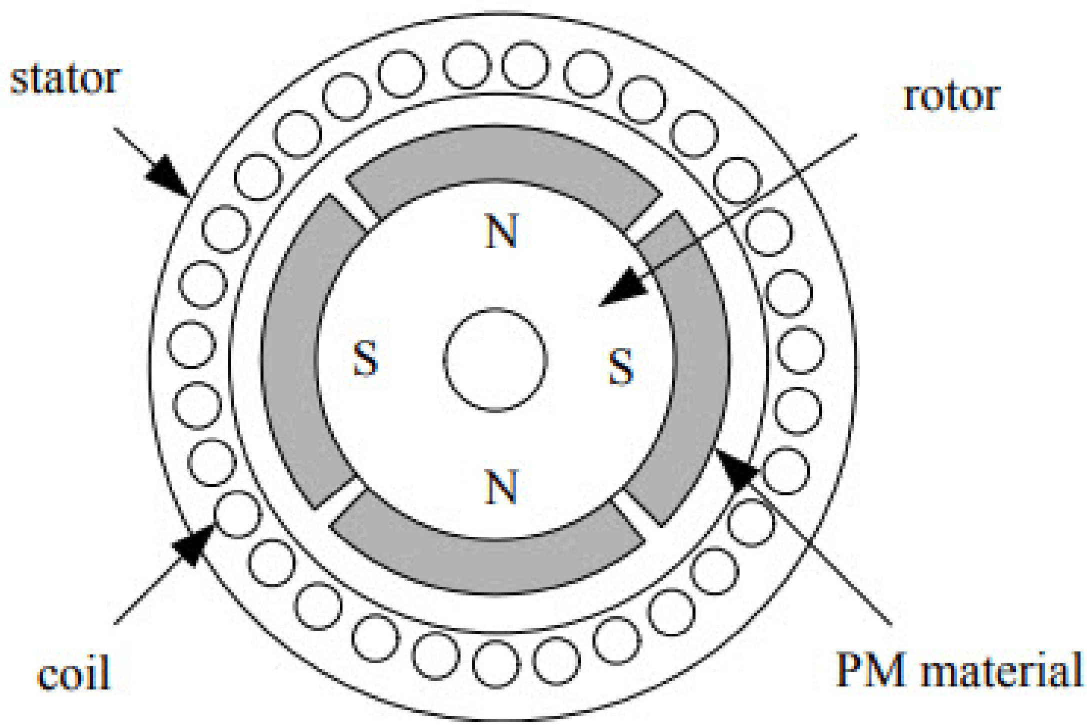

FIGURE 2.2 – cross-section of a BLDC Motor

As you can see in the image, a BLDC Motor consists of two main parts : a stator and a rotor

2.1.3 Advantages Over Brushed Motors

- Reduced Friction and Wear : Brushless motors eliminate physical contact between brushes and a commutator, leading to less friction and wear. This results in a longer lifespan and reduced maintenance requirements compared to brushed motors.
- Improved Efficiency : The absence of brushes reduces energy losses due to friction and sparking, making brushless motors more energy-efficient. They can deliver more power for the same input compared to brushed motors.
- Higher Power-to-Weight Ratio : Brushless motors often have a higher power-to-weight ratio, making them suitable for applications where weight is a critical factor, such as in aerospace and electric vehicles.
- Precise Speed and Position Control : The electronic control of brushless motors allows for precise control of speed and position, making them ideal for applications that require accuracy and responsiveness, such as robotics and automation.
- Reduced Electromagnetic Interference : Brushless motors produce less electromagnetic interference (EMI) compared to brushed motors, making them suitable for applications where EMI is a concern, such as in medical devices and communication equipment.

2.1.4 Stator

The structure of the stator of a BLDC Motor is similar to that of an induction motor. It is made up of stacked steel laminations with axially cut slots for winding. The winding in BLDC are slightly different than that of the traditional induction motor.

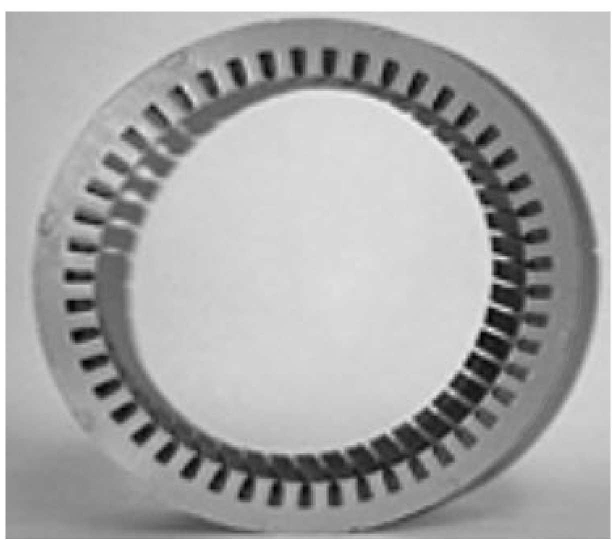

Figure 2.3 – structure of the stator of a BLDC Motor

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

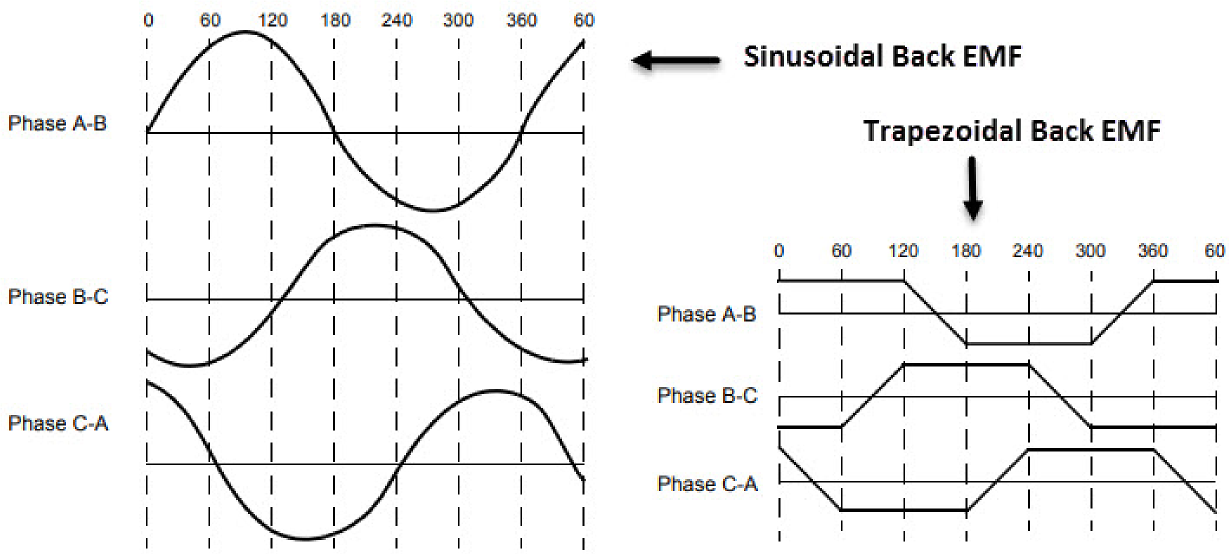

FIGURE 2.4 – Sinusoidal Back EMF and Trapezoidal Back EMF

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

2.1.5 Rotor

The rotor part of a Brushless DC Motor (BLDC) Motor is made up of permanent magnets, usually rare earth alloy magnets like Neodymium (Nd), Samarium Cobalt (SmCo), and alloys of Neodymium, Ferrite, and Boron (NdFeB). The number of poles in a BLDC motor can vary between two and eight, with North (N) and South (S) poles placed alternately. The following image shows three different arrangements of the poles :

1. In the first case, the magnets are placed on the outer periphery of the rotor. 2. In the second case, the magnets are distributed on the inner and outer peripheries of the rotor. 3. In the third case, the magnets are placed on the inner and outer surfaces of the rotor, with a hollow center.

The rotor's pole arrangement depends on the specific application and the desired magnetic field strength. Brushless motors are available in three configurations : single phase, two phase, and three phase, with the three-phase BLDC being the most common[5].

The second configuration is called magnetic-embedded rotor, where rectangular permanent magnets are embedded into the core of the rotor. In the third case, the magnets are inserted into

FIGURE 2.5 – different arrangements of the poles

the iron core of the rotor.

2.1.6 Position Sensors (Hall Sensors)

A Brushless DC Motor (BLDC) operates without brushes for commutation, relying instead on electronic control. To determine the rotor's position and energize the stator windings in the correct sequence, a position sensor, typically a Hall Sensor, is used. Most BLDC Motors employ three Hall Sensors embedded in the stator to detect the rotor's position, with the output of each sensor being either HIGH or LOW, depending on the proximity of the North or South pole of the rotor. By combining the results from the three sensors, the exact sequence for energizing the stator windings can be determined. The A1104 Hall Effect IC, for example, includes a Voltage Regulator, Hall Device, Small Signal Amplifier, Schmitt Trigger, and an Output NMOS Transistor.

The rotor of a BLDC Motor is typically composed of permanent magnets, such as Neodymium (Nd), Samarium Cobalt (SmCo), or an alloy of Neodymium, Ferrite, and Boron (NdFeB). The number of poles in the rotor can vary between two and eight, with North and South poles placed alternately based on the application. The pole arrangement is crucial for the motor's performance, and the most common configuration is the three-phase BLDC Motor.

The absence of brushes in BLDC Motors leads to several advantages, including higher efficiency, lower wear, and reduced noise. These motors are widely used in various applications, such as electric vehicles, industrial robots, and consumer electronics.

2.2 Working Principle

Consider the following setup of three windings in the stator designated A, B and C. For the sake of understanding, let us replace the rotor with a single magnet.

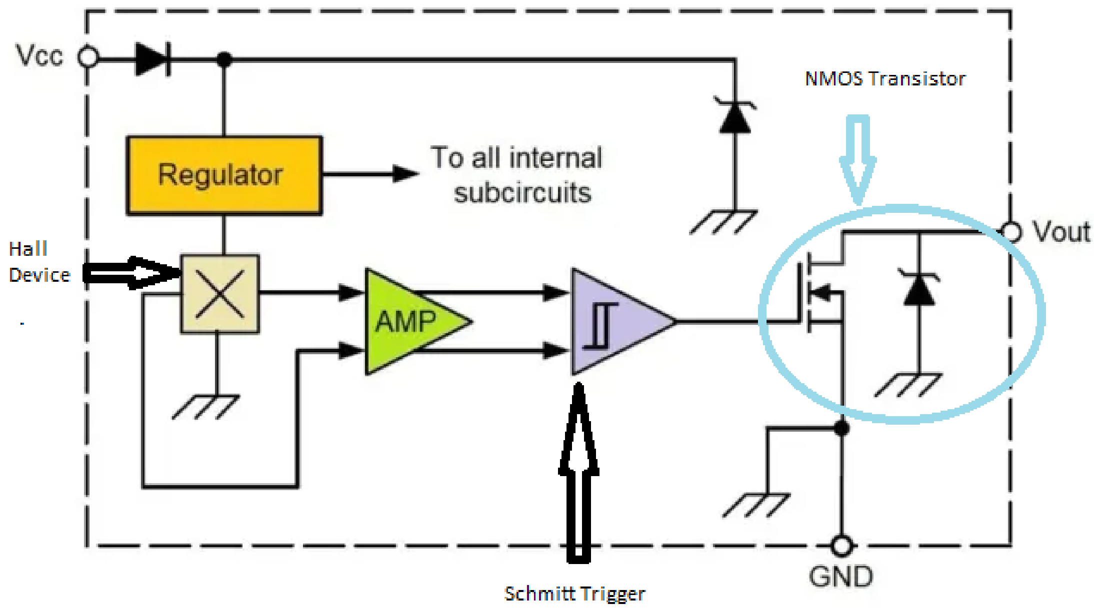

Figure 2.6 – Block Diagram of the Hall Effect Sensor

We know that when a current is applied through a coil, a magnetic field is generated and the orientation of the field lines i.e. the poles of the generated magnet will depend on the direction of the current flowing through the coil.

Using this principle, if we supply current to the coil A so that it will generate a magnetic field and attract the rotor magnet. The position of the rotor magnet will shift slightly clockwise and will align with A.

If we now pass current through coils B and C one after the other (in that order), the rotor magnet will rotate in clock wise direction.

To increase efficiency, we can wind the opposite coils using a single coil so that we get double attraction. Further increasing the efficiency, we can energize two coils at the same time so that one coil will attract the magnet and the other coil will repel it. During this time, the third will be idle.

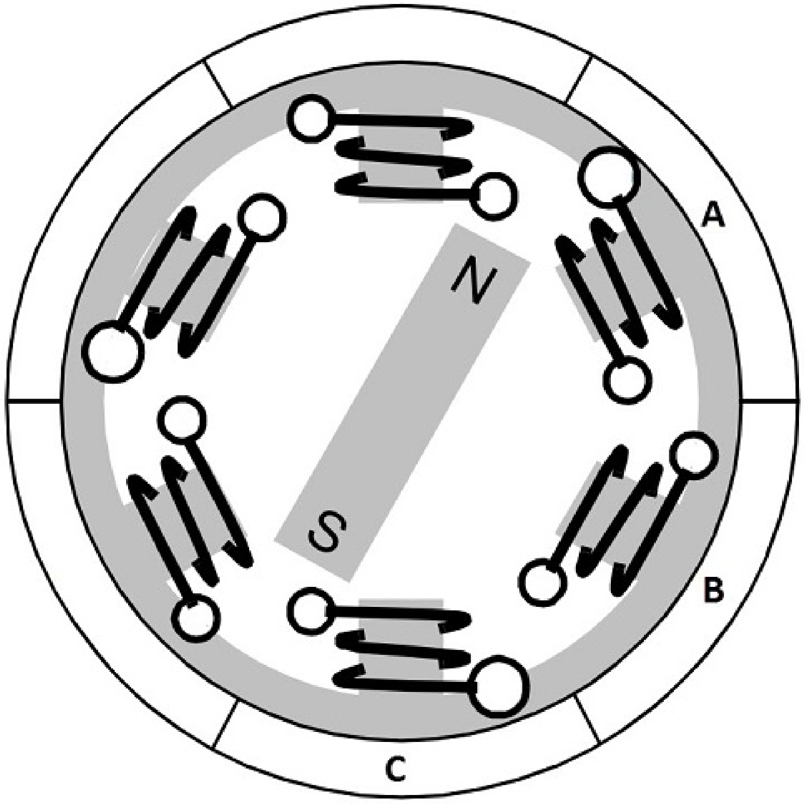

FIGURE 2.7 – Stator windings

For a complete 3600 rotation of the rotor magnet, six possible combinations of the coils A, B and C are applicable and are shown in the following timing diagram.

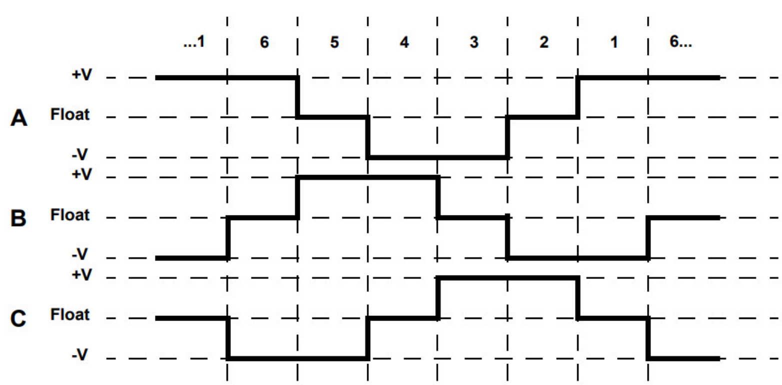

FIGURE 2.8 – 3600 rotation of the rotor magnet

Base on the above diagram, we can confirm that at any time, one phase is positive, one phase is negative and the third phase is idle (or floating). So, based on the inputs from the Hall Sensors, we have two switch the phases as per the above diagram.

2.3 Driving Brushless DC Motors

Driving a Brushless DC Motor (BLDC) requires a more sophisticated approach compared to driving a brushed DC motor, as BLDC motors use electronic switches for commutation instead of mechanical brushes. The main components of a BLDC motor driving system include a power supply, an electronic speed controller (ESC), and a position sensor, usually a Hall Sensor.

The driving process for a BLDC motor involves the following steps :

1. The ESC receives a reference signal, which may be a desired speed or position, from the control system.
2. The ESC calculates the required current for each stator coil based on the reference signal and the motor's current position.
3. The ESC controls the power supply to energize the appropriate stator coils in the correct sequence, ensuring smooth and controlled rotation.
4. The position sensor detects the motor's position and provides feedback to the ESC, allowing it to adjust the power supply accordingly.

Some popular algorithms used for controlling BLDC motors include PID (Proportional, Integral, Derivative) control, which is a simple and widely used method for regulating motor speed and position. The efficiency of a BLDC motor is the value at rated torque at rated speed, and it can be higher than that of a brushed DC motor with the same power output. BLDC motors are gaining popularity in various applications due to their higher efficiency, lower wear, and reduced noise, making them more attractive in industries such as consumer electronics, industrial automation, and automotive.

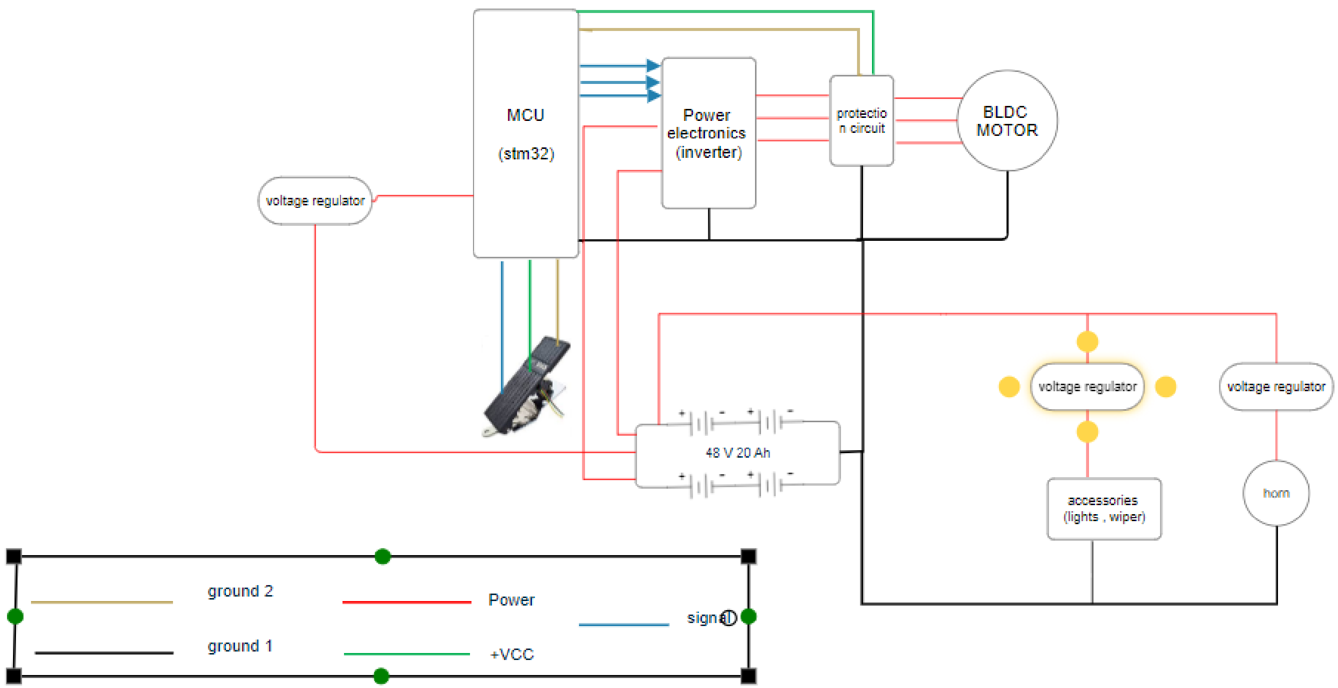

FIGURE 2.9 – Block Diagram

2.4 Compoment of the electrical control system

This drive circuitry is often known as Electronic Speed Controller System or simply an ESC. One common setup is called the Full Bridge Drive Circuit. It consists of an MCU with PWM outputs, six MOSFETS for the three phases of the stator windings, feedback from the Hall sensors and some power supply related components.

The variable speed drive control system employing an STM32 microcontroller is a complex assembly of interconnected components. Here is a detailed explanation of the components mentioned in your description :

1. **STM32 Microcontroller :**
- Role : Central control unit responsible for generating control signals for the MOSFETs, managing Hall sensors, and executing control algorithms.

FIGURE 2.10 – STM32 Card

Functions :
- Generation of PWM signals to control the MOSFETs.
- Processing information from Hall sensors to synchronize motor phase commutation.
- Implementation of control algorithms, such as PID control, for regulating motor speed, torque, or position.

2. **MOSFETs (Six in Total) :**

- Role : Power control devices regulating the current flowing through the stator coils.
- Arrangement : Typically organized in three pairs to control motor phases.

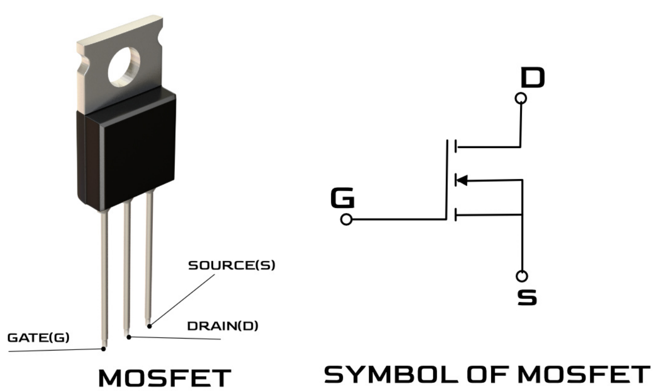

FIGURE 2.11 – Mosfets

The selection of MOSFETs for our motor control system, operating within a power range from 100 W to 1900 kW, is well-founded. Specifically, for our 1200 W motor, MOSFETs prove to be the ideal choice. Their versatility across a wide power spectrum, combined with attributes such as lower on-state voltage drops, faster switching speeds, and ease of drive, align perfectly with the moderate power requirements of our application. Additionally, MOSFETs offer advantages in terms of size, weight, and thermal considerations, contributing to a compact and efficient system design. This choice not only ensures optimal performance for our 1200 W motor but also provides a cost-effective solution, emphasizing the adaptability of MOSFETs across various power levels.

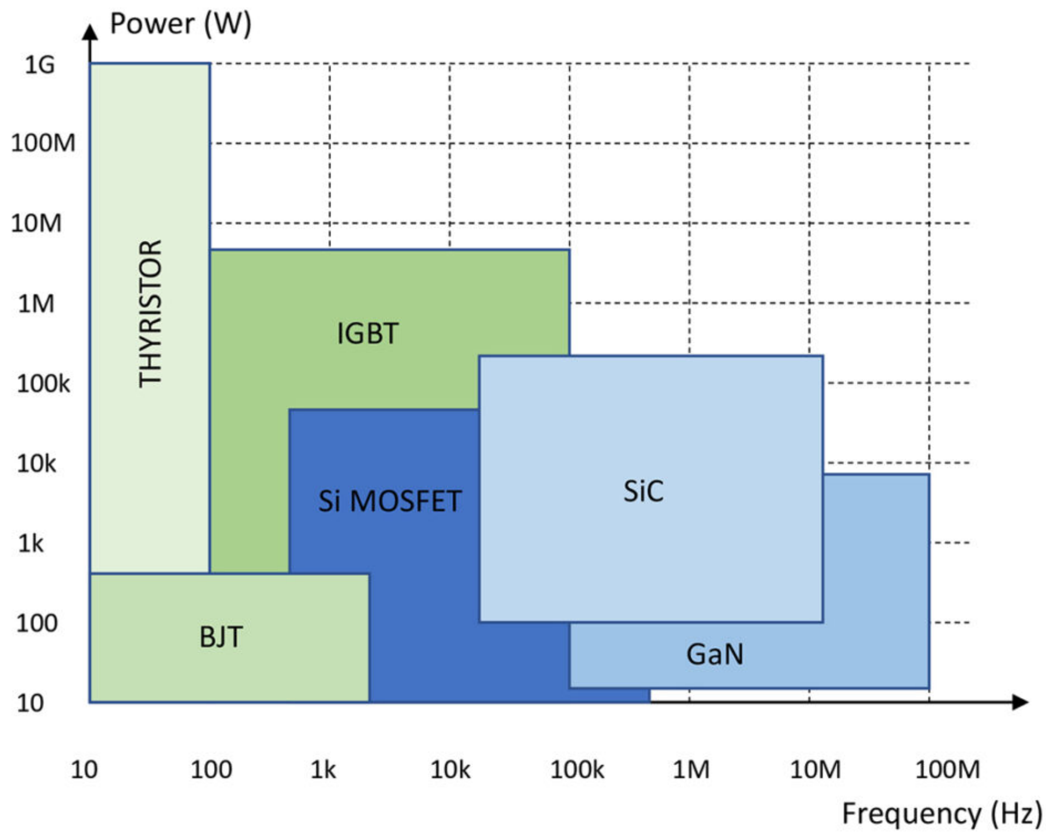

FIGURE 2.12 – How To Select The Right Gate Driver

3. **Hall Sensors :**
- Role : Detect the rotor position and provide information to the microcontroller for synchronized phase commutation.
- Utility : Enables electronic switching of motor phases, contributing to precise rotation control.

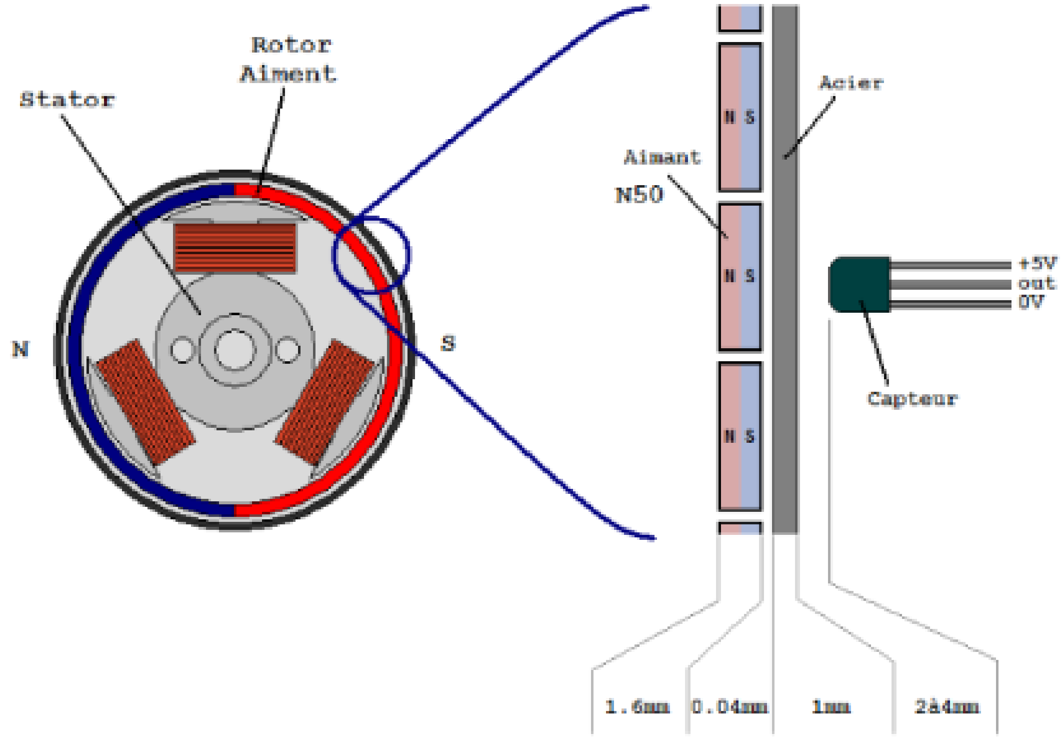

FIGURE 2.13 – Hall sensors

4. **Freewheeling Diodes :**

- Role : Provide a return path for inductive currents when the MOSFETs are off, minimizing disturbances and ensuring more stable operation.

5. **Capacitors :**

- Role : Stabilize the power supply by offering an additional energy source during load or discharge peaks.
- Utility : Reduce voltage fluctuations and minimize electromagnetic disturbances.

6. **Filter Resistors and Capacitors :**

- Role : Filter and smooth electrical signals, ensuring stable operation and reducing electromagnetic noise.

7. **Connectors and Terminals :**

- Use : Facilitate power, motor, and control connections, simplifying system installation and maintenance.

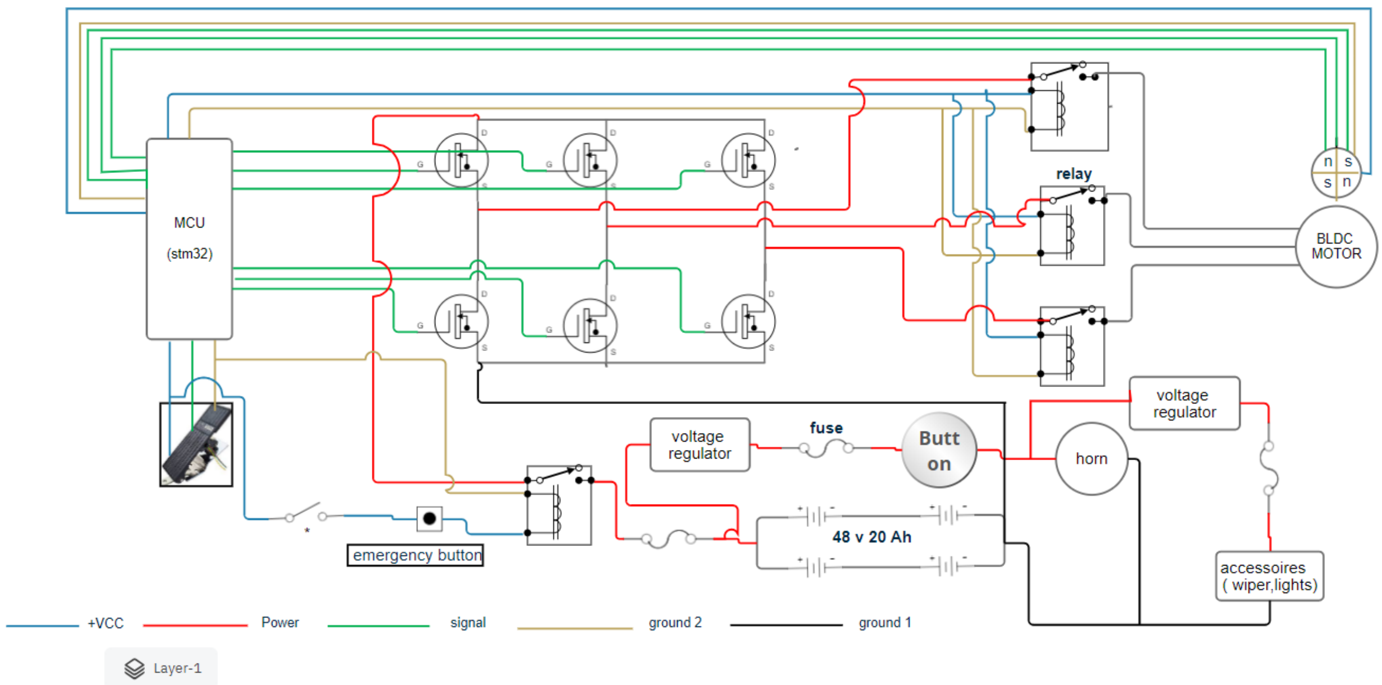

FIGURE 2.14 – Electrical wiring Diagram

By combining these components, the variable speed drive control system provides a robust and flexible platform to meet the specific requirements of the application. The careful design of these components ensures reliable performance, precise regulation, and efficient management of energy resources.

Conclusion

In conclusion, the chapter on the control law of a brushless motor has provided a comprehensive exploration of the principles and methodologies governing the operation of brushless motors. The discussion encompassed key topics such as motor control strategies, pulse-width modulation techniques, and feedback systems.

The understanding of these control laws is foundational to achieving precise and efficient control over brushless motors in various applications. The chapter has emphasized the significance of closed-loop control mechanisms, illustrating their role in enhancing motor performance, responsiveness, and overall system reliability.

By delving into the intricacies of control laws, this chapter aims to equip readers with the knowledge necessary for implementing effective control strategies in brushless motor systems. The integration of theoretical concepts with practical applications enhances the reader's capability to design and optimize systems employing brushless motors.

In essence, this chapter serves as a valuable resource for engineers, researchers, and enthusiasts seeking a deeper insight into the control aspects of brushless motors, ultimately contributing to advancements in motor technology and its diverse applications.

General Conclusione

In conclusion, the comprehensive exploration of forces and power calculations in a vehicle system, coupled with the in-depth analysis of the control law of a brushless motor, provides a well-rounded understanding of crucial aspects in engineering design and control systems.

The forces and power calculations chapter illuminated the intricacies of forces influencing a vehicle, including mass, rolling resistance, aerodynamic forces, and gravity. Through systematic calculations, the chapter facilitated the estimation of power requirements, guiding the selection of an appropriate motor for optimal performance.

Concurrently, the control law of a brushless motor chapter delved into advanced control strategies, emphasizing closed-loop systems and pulse-width modulation techniques. The theoretical insights coupled with practical applications equipped readers with knowledge essential for implementing effective control strategies in brushless motor systems.

Together, these chapters offer a synergistic perspective, underscoring the symbiotic relationship between mechanical and control aspects in engineering systems. The forces and power calculations lay the groundwork for designing efficient vehicle propulsion systems, while the discussions on control laws deepen our understanding of sophisticated control strategies crucial for precise and responsive system operation.

This dual-focus approach enhances the reader's capability to approach engineering challenges holistically, considering both the physical forces governing motion and the nuanced control mechanisms steering the operation. Overall, these chapters contribute to a comprehensive understanding of the multifaceted nature of engineering design and control, fostering advancements in the field.

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