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Design of BLDC Motor and Its Controlling

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Abstract*— A brushless DC electric motor (BLDC) is a motor that uses an electronic commutation method. This paper presents the design and control of a 1 kW, 3-phase, 48V BLDC motor. Stator with 12 slots and in-runner surface mounted rotor is designed and fabricated to produce the 1KW output power. A whole-coiled type winding with a length of 1094m and a copper winding weight of 0.78kg has been developed. The motor controller circuit consisting of a H-bridge inverter is designed which is used to control the speed of the motor. The simulation result obtained on Proteus software shows that the motor could operate successfully with the designed controller. For 1k ohm values of the potentiometer, the motor runs at the minimum speed of 94 RPM, and for the value of 1 ohm, the motor runs at its full rated speed that is 3100 RPM. BLDC motor and its controller could be used in a range of applications, including electric vehicles, industrial machinery, robotics and also home appliances.

***Index Terms*— BLDC Motor, Motor Controller, PIC Microcontroller, Stator Winding**

I. INTRODUCTION

Brushless DC motors are synchronous motors which use electronic commutation and have permanent magnet rotors with rotor position sensors. In contrast to DC motors with mechanical commutation techniques like brushes and commutator rings, brushless DC (BLDC) motors use electronic commutation, which is covered below. BLDC motors have many advantages over brushed DC motors, including greater efficiency, higher speed and torque control, less noise, and a longer lifespan. Because of their high power density, low maintenance requirements, and capacity for high speeds, they are frequently employed in a variety of applications, including electric cars and industrial machines. Due to their improved performance and dependability, BLDC motors are generally becoming more and more popular.

Fig.1: Fabricated BLDC Motor

II. MATHEMATICAL MODELING

Following assumptions are made to build the differential equation of the BLDC motor.

1) Output Power expected from motor is 1 kW
2) Maximum Speed of motor is 3100 RPM
3) The stator has Y-connected full-pitch winding, and the inner rotor has a non salient pole structure.
4) Three Hall sensors are connected on the stator symmetrically at 120 interval.
5) Core saturation, eddy current losses and the hysteresis losses are ignored.
6) Armature reaction is ignored, and the distribution of the air-gap magnetic field is thought to be a trapezoidal wave with a flat-top width of 120 electrical angle.
7) cogging effect is ignored and consider conductors are distributed continuously and evenly on the surface of the armature.

Considering the above conditions, design for stator and rotor were made.

III. BLOCK DIAGRAM

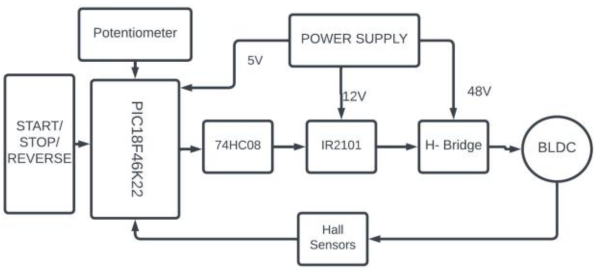

Fig. 2. Block diagram of system

Three hall sensors in a BLDC motor detect the position of the rotor and send signals to a microcontroller. This data is used by the microcontroller to control the power supplied to the stationary part (the stator) in order to generate a magnetic field that interacts with the rotor and causes it to spin. Despite the fact that the power source is direct current, this interaction produces an alternating current (AC) voltage waveform with a trapezoidal shape. The interaction between the magnetic fields of the rotor and stator keeps the rotor rotating.

IV. STATOR & ROTOR DESIGN

The design of the stator windings is critical to the overall performance and efficiency of a brushless DC motor. It is in charge of producing the magnetic field that drives the motor and has a direct impact on its torque and speed characteristics. As a result, optimizing the stator winding design is critical for achieving maximum performance and efficiency in BLDC motors.

Equations used for motor designing:-.

$$B = \mu H$$

B = Flux Density, H = Field Intensity

$$F = \Phi R$$

F = force,, R = Reluctance

$$R = \frac{1}{P} = \frac{1}{\mu A}$$

R = Reluctance, A = area

$$T = kD^2 L$$

T = torque, L = Length, D = diameter, K = Motor Constant

$$Pe = k_e h^2 f^2 B^2$$

P = Power, f = Frequency, k = Motor Constant

$$\Phi = \frac{N_i}{R}$$

Equation to find Flux

$$B_m = B_r + \mu_r \mu_o H_m$$

Bm = flux density of Magnet, Bm = flux density of Rotor

$$\phi = B_m A_m = B_r A_m = \mu_r \mu_o A_m H_m$$

Flux of the permanent magnets

$$\lambda = \frac{N^2}{R} i$$

Equation to find flux Linkage

$$e = \frac{dL_i}{dt} = L\frac{di}{dt} + i\frac{dL}{dt}$$

Equation for Induced voltage

$$T = \frac{1}{2} i^2 \frac{dL}{d\Theta} - \frac{1}{2}\Phi^2 \frac{dR}{d\Theta}$$

Equation to solve for torque from length

$$L_g = \frac{2\pi\mu_0 L_{st} R_{ro}}{g + \frac{l_m}{u_r C_\Phi}} N^2$$

Equation for Inductance for Air gap

$$k_m = \frac{2NB_g L_{st} R_{ro} I}{\sqrt{I^2(2R_{slot})}} = \frac{2NB_g L_{st} R_{ro}}{\sqrt{2pL_{st}N/A_{rob}}} = \frac{B_g R_o}{\sqrt{p}}\sqrt{v_{wb}}$$

Equations to find Motor constant k

$$T_{cog} = -\frac{1}{2}\Phi^2 \frac{dR}{d\emptyset}$$

Equation for Cogging torque

a. Rotor Design

A radially magnetized, tile-shaped rare-earth permanent magnet is put on the surface of the iron core for the surface-mounted PM rotor. In order to lower the cost of the motor, it is also possible to assemble the tile-shaped poles using rectangle strips. In order to provide a square air-gap flux density and lessen torque ripple, the designer of the motor always uses this construction with pole arc widths greater than 120 degree electric angles.

b. Stator Design:

The iron core contains single- or multiple-phase symmetric windings that can be coupled in "Y" or "D" type. The Y-type, in which the three phase windings are connected symmetrically without a neutral point, is typically utilized due to its performance and cost-effectiveness. Because stator winding design is critical, specialized software such as Ansys Electronic Software is used to design the stator winding for a 1KW 48V 20A BLDC motor. The software considers various motor specifications, such as slot length, slot depth, and other critical details, to generate an appropriate stator winding design that will allow the motor to operate at peak performance. This method ensures that the motor's stator winding design is tailored to its specific requirements, resulting in improved performance and efficiency.

Table1: Specifications for stator designing

Name	Value
Outer Diameter	119.52mm
Inner Diameter	80.1mm
Length	50.1mm
Stacking Factor	0.95
Steel Type	M36_24G
Number of Slots	12
Slot Type	4

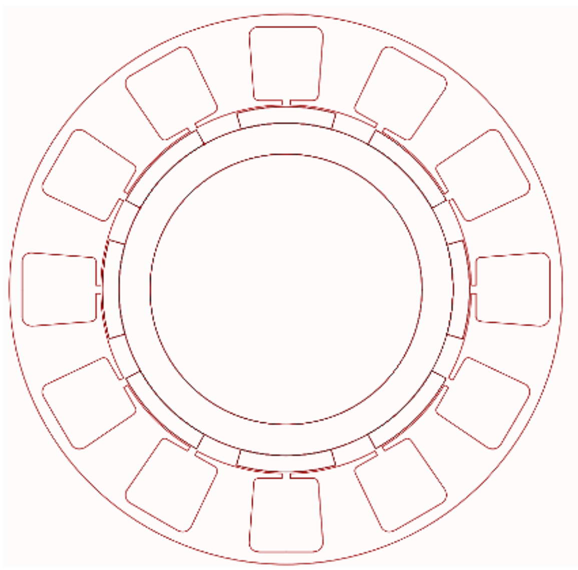

Fig.3 Stator with Slots and Rotor

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Fig. 4 Rotor of a BLDC Motor

When the necessary data is entered into the software, a visual representation of the stator, slots, and rotor is generated for analysis. The permanent magnet rotor in this brushless DC motor is made of the magnetic material Neodymium Iron Boron, which is a type of rare earth magnet.

Table 2:- Specifications for Winding Design

Name	Value
Winding Layers	2
Winding Type	Whole-Coiled
Parallel Branches	2
Conductors per slot	32
Coil Pitch	2
Number of Strands	23
Wire Wrap	0 mm
Wire Size	0.32 mm

The software was given the necessary inputs in the previous table to generate relevant data about the stator winding, such as copper weight and length.

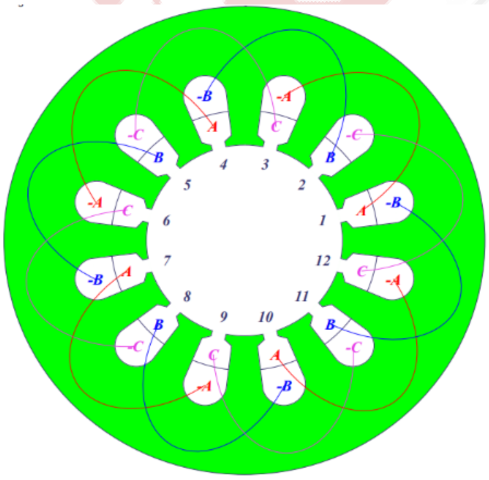

Fig. 5: Obtained Winding Design

Fig. 6:-Achieved Winding of Motor

To initiate rotation in a brushless DC (BLDC) motor, the three-phase coils are energized in a specific sequence. A BLDC motor's stator is typically wound with a full-coil configuration, which involves wrapping a continuous wire around the stator core and returning to its starting point. Each coil in this winding configuration has a different number of wire turns and is coiled in a specific way to create a magnetic field that interacts with the rotor magnets and causes rotation. The term "electronic commerce" refers to the sale of electronic goods.

c. Winding the Motor

The wires of the same phase are arranged in one cog for the focused full-pitch winding, which results in a constant air-gap flux density in the motor. It is possible to derive the waveform of the entire back-EMF, which resembles the air-gap flux density, by summing the back-EMF produced by wires in each phase. The platform width of the back-EMF waveform and the air-gap flux density waveform are identical. A superior trapezoidal back-EMF can therefore be produced by concentrated full-pitch winding.

1) To gain access to the stator, which houses the coils of a previously assembled brushless DC (BLDC) motor, the motor must be disassembled. The stator is the motor's stationary component that houses the coils and cannot be accessed without disassembly. When the motor is disassembled, access to the stator is gained, allowing inspection and maintenance of the stator winding or other components. The motor's disassembly and reassembly must be done correctly to ensure optimal performance and longevity.

2) A copper wire is wrapped around the stator pole of a brushless DC motor to wind the coils, leaving enough wire to connect to the motor's controller. To form the coils, the wire is wound in a specific pattern, creating a magnetic field that interacts with the rotor magnets to produce rotation. The number of coil turns required varies according to the desired motor speed and torque. The proper winding and connection of the coils is critical to the BLDC motor's performance and efficiency.

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3) After determining the appropriate number of turns, the copper wire is wound around the stator pole, with the number of windings varying depending on the motor specifications. Winding the wire in a specific configuration produces a magnetic field that interacts with the rotor magnets to produce rotation. Winding is a critical step in the assembly of a BLDC motor that necessitates precision and attention to detail to ensure optimal performance and efficiency.

4) After winding all three coils, they must be connected to the motor controller in the correct order. This is required for the motor to function properly. In order to produce torque and rotational movement, the motor controller successively feeds energy to the coils, which creates a rotating magnetic field that interacts with the permanent magnet rotor. The order in which the coils are energized is critical and can have an impact on the motor's performance, efficiency, and noise level. As a result, the controller must carefully follow the manufacturer's specifications.

5) The motor can be reassembled after the coils have been correctly connected to the motor controller. The permanent magnet rotor can be reinserted into the stator, which houses the coils. To avoid physical contact, ensure that the rotor is properly aligned with the stator and that there is adequate clearance between the rotor and stator. The motor should then be securely fastened or bolted together, and all electrical connections should be double-checked to ensure proper connection. Finally, the motor can be tested to ensure it runs smoothly and efficiently.

6) After reassembling the motor, it is critical to perform a thorough inspection to ensure that it is operating properly. Turn on the motor and test it to ensure that it is running smoothly and without any unusual sounds or vibrations. The performance of the motor should also be checked to ensure that it is producing the desired speed and torque levels. Before putting the motor into regular use, any necessary adjustments or corrections should be made.

Table 3: Specifications of BLDC Motor

Specifications	Value
Rated Output Power	1000W
Desired Rated Speed	3100 RPM
Rated Voltage	48V
Number of Slots	12
Number of Poles	8
Stator Inner Radius	8 cm
Stator Outer Radius	12 cm
Rotor Inner Radius	1.5 cm
Rotor Outer Radius	1.4 cm
Slot depth	1.3 cm
Magnet Material	Neodymium Iron Boron

V. CHARACTERISTICS OF MOTOR

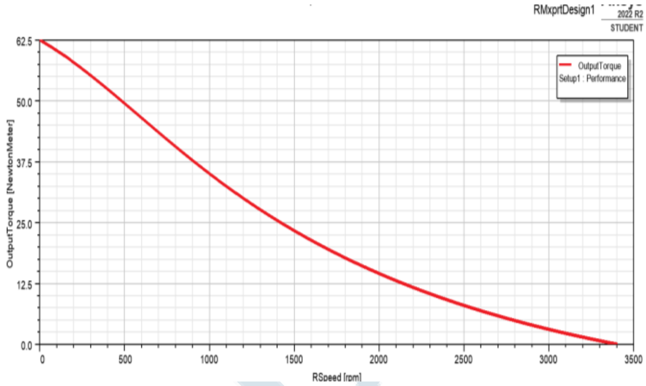

Fig. 7:- Torque vs Speed Characteristic

According to the graph, the BLDC (Brushless DC) motor has a high amount of beginning torque, measuring roughly 62.5 Nm. This means that the motor can generate a substantial amount of rotational torque immediately from the start, allowing it to accelerate quickly to its intended speed. In practice, this means that the motor is well-suited for applications requiring a lot of initial force to get things moving, such as heavy machinery, electric cars, or other sorts of industrial equipment. Overall, the BLDC motor's strong starting torque is a significant feature that might make it a desirable choice for a wide range of applications.

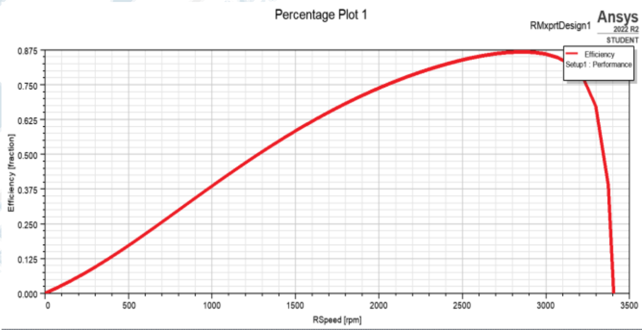

Fig. 8:-Efficiency vs Speed

The BLDC motor has an efficiency of roughly 87% at specific speed settings, according to the graph. This means that the motor can convert a large portion of the electrical power it consumes into mechanical output power, with only a tiny amount of energy wasted as heat or other types of waste. In other words, an efficiency of 87% indicates that the motor is quite effective at converting electrical energy into mechanical work, making it an excellent choice for applications requiring high energy efficiency, such as electric vehicles, renewable energy systems, or other power-intensive equipment.

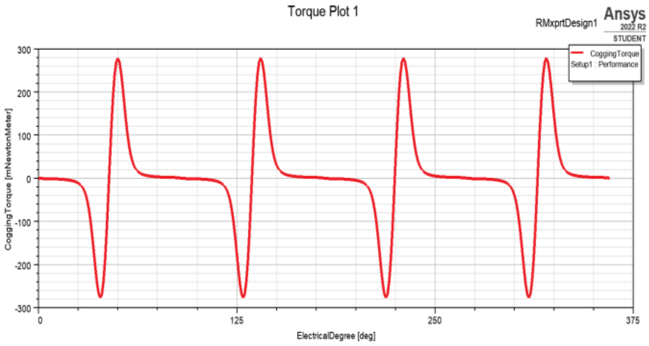

Fig.9: Cogging Torque plot

According to the graph, the SPM (Surface Mounted Permanent Magnet) architecture demonstrates a cogging torque of roughly 0.30 Nm. Cogging torque is the torque required to overcome the motor's rotor's static magnetic resistance as it rotates through the stator's magnetic field. This torque is undesirable since it might produce uneven motor rotation and noise. As a result, a low cogging torque, such as the 0.30 Nm value seen in this graph, is generally regarded as a favorable motor attribute which is desired.

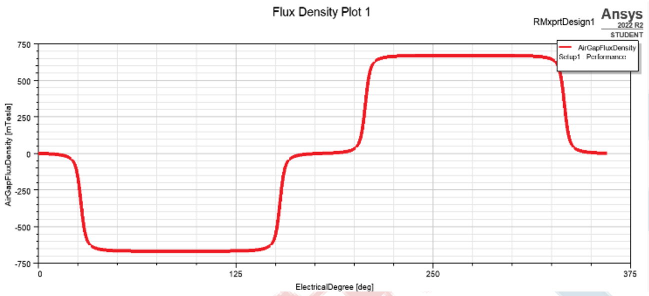

Fig. 10: Flux Density Plot

According to the graph, the flux density of the SPM (Surface Mounted Permanent Magnet) topology is around 650 mT. Flux density is the strength of the magnetic field in the air gap of the motor, and it is a significant metric in determining the motor's overall performance.A high flux density, such as the 650 mT value shown in this graph, generally implies that the motor can generate a strong and consistent magnetic field, which is necessary for efficient and reliable motor performance. In practice, this means that the SPM motor with this high flux density may produce a high amount of power and torque, making it suited for demanding applications such as electric vehicles, industrial machines, and other high-performance equipment.

VI. MICROCONTROLLER SELECTION

To ensure that the correct electrical voltage is given to the motor, we must always know where the rotor is. There are several approaches to this, including the use of sensors such as Hall sensors or optical sensors. Another method is to detect the motor's back electromotive force (emf) to determine the position of the rotor without using a separate sensor.

The most common method for determining the position of the rotor in a motor is to utilize Hall effect sensors, which detect when the rotor's magnets pass past them. We're employing the same strategy because it's simple and inexpensive.

Controlling BLDC motors is a difficult operation that necessitates precise and effective control strategies. Microcontrollers have become a popular choice for implementing BLDC motor control algorithms in recent years. The PIC18F is a popular microcontroller because it has powerful processing capabilities, is inexpensive, and is simple to use.

The microcontroller should receive signals from the three hall sensors and utilize this information to change the pulse width modulation (PWM) signals that go to the gate driver integrated circuit (IC) to accomplish the needed motor control. It should also be able to receive analogue input from a potentiometer to control the motor's speed.

The microcontroller should have the following qualities to perform these functions:

1) Ability to interpret information from three hall sensors
2) PWM signal generation capability for the gate driver IC
3) Analog-to-digital converter (ADC) to receive potentiometer input

VII. SIMULATION OF CONTROLLER

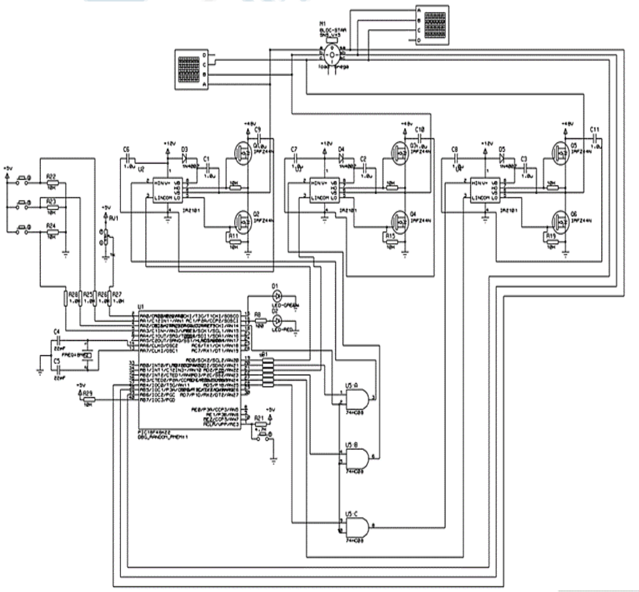

Fig.11 Schematic of Bldc Motor controller

Main Components of BLDC Motor Controller:-

1) Microcontroller: PIC18f46k22 microcontroller is used. It has PWM generation capability.
2) MOSFET Driver: IR2101. it converts 5V PWM to 12V
3) MOSFET Bridge/ H-Bridge: Used to selectively energize winding
4) Hall Sensors in Motor: Detect position of rotor

Proteus Pro Simulator software is used to simulate the BLDC motor controller. Using a PIC18F46K22

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microcontroller, a total of six PWM signals at 8 kHz are produced (PWM0 to PWM5, Pin C7). The microcontroller's duty cycle is managed by a reference input ADC signal sent via a potentiometer slider. The microcontroller's reference is then obtained via a voltage divider circuit, which is then utilized to generate PWM signals to control the rotor speed, duty cycle, and output current. The MOSFETs are then driven with PWM signals by a 3-channel dual-channel MOSFET driver (IR2101). Additionally, these drivers start the switch dead time.

Table 4: Six step hall effect Commutation

H1	H2	H3	A High	A low	B High	B low	C high	C low
1	0	1	0	1	0	0	1	0
0	0	1	1	0	0	0	0	1
0	1	1	0	0	1	0	0	1
0	1	0	0	0	0	1	1	0
1	1	0	1	0	0	1	0	0
1	0	0	0	1	1	0	0	0

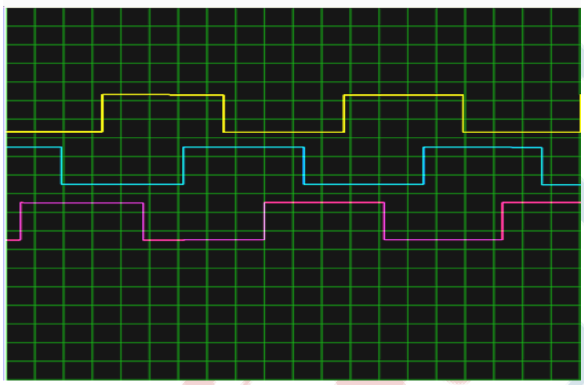

Fig 12: Hall effect Sensor Output

Figure 12 shows hall effect sensor output waveform as shown in graph total possible combinations of hall effect states are six for each of the states different switches will be turned on and off to energize a particular winding.

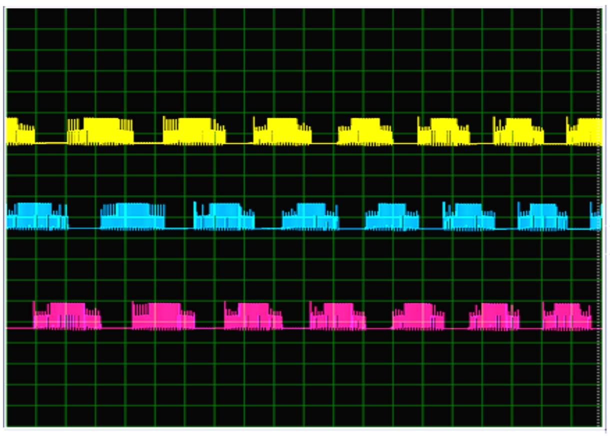

Fig 13: Motor Phase Voltage

Figure 13 shows the motor controller's output waveform.Time division is set to 10ms, and voltage division is set to 20V. The circuit includes 48V DC power. As a result, we can see that these three phases have a peak to peak voltage of 48V. The output waveform obtained have some overshoot and harmonics. This issue can be resolved by using low Pass Filter

VIII. POWER SUPPLY DESIGN

To power the motor, we need a 48-volt, 20-amp DC supply. We used PSIM software to simulate the circuit. A simple diode bridge rectifier is used to convert ac to dc, and a filter and regulator IC are used to get a stable power supply.

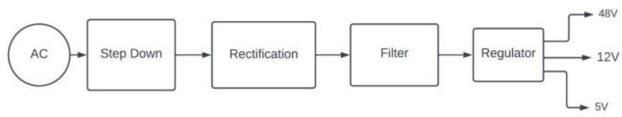

Fig. 14 : block diagram of the power supply.

The AC mains supply is given to a stepdown transformer, which brings the AC voltage down. Next, this AC is rectified using a bridge circuit. Output from the rectifier is passed through a filter and regulator circuit to get a constant 48 V DC. IC7805 and IC7812 are used to convert 48V DC to 5V and 12V to power other ICs.

A. Controlling of Speed

$$fe = (Nm/120)s$$

Where, fe is Fundamental electrical frequency

Nm is Number of Magnets

S is motor mechanical speed

The above equation gives the frequency at which the commutation must be done to achieve the desired speed.

For maximum rated value of motor speed (i.e. 3100 RPM). A 1K potentiometer for speed control. The variable terminal of POT is connected to the microcontroller's ADC terminal. The other two terminals of POT are connected between 5 volts and ground. Depending on the setting of POT, the voltage at the variable terminal of POT changes. The PIC18f46k22 has a 10-bit ADC. It converts the analog voltage at the POT variable terminal to a digital value.

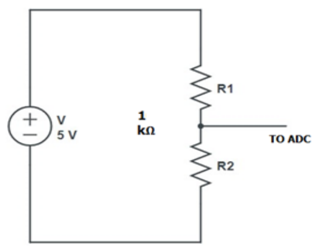

Fig. 15 Equivalent Circuit

The above diagram is the equivalent circuit of the POT connection. The maximum value that R2 POT can give is 1 kΩ,. so when pot is at 80%, R1 is 200 Ω and R2 is 800 Ω.

so, Voltage at Vo terminal is

$$Vo = (R2/R1 + R2) * Vin$$

When 5 volts is supplied to ADC, it gives full 1024

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resolution, and Duty cycle set is 100% and speed is Maximum(3100 RPM)

Table 6: Set resistance and Duty Cycle

Sr. No	Resistance value	Duty Cycle
1	1.952	10
2	3.904	20
3	7.808	30
4	15.616	40
5	31.2	50
6	62.48	60
7	124.92	70
8	249.8	80
9	500	90
10	1000	100

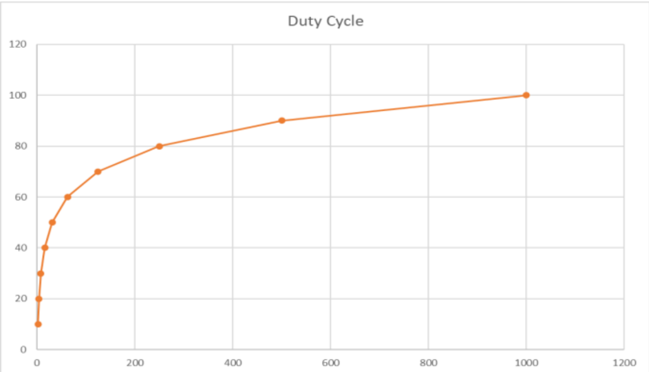

Fig.16. Resistance vs Duty Cycle

IX. VIII. CONCLUSION

Finally, a 1 kW in-runner BLDC motor with a 12-slot stator and a surface-mounted rotor was designed and built, together with an H-bridge inverter motor controller. The simulation results showed that functioning at speeds ranging from 94 to 3100 RPM was successful. This motor and controller could be used in electric cars, industry, robotics, and household goods. Future development could concentrate on optimizing the architecture for specific applications as well as refining control algorithms for better performance.

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