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Software based design and development of BLDC motor and its parameter Control

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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.

1. INTRODUCTION

The Brushless DC motors are synchronous motors thatuse electronic commutation and have a permanent magnet rotor with a rotor position sensor. Unlike DC motors with mechanical commutation techniques such as brushes and commutator rings, brushless DC (BLDC) motors use electronic commutation, which is covered below. Brushless DC motors are superior to the brushed DC motors, including greater efficiency, greater speed and torque control, lower noise, and longer life. Because of their high power density, low maintenance requirements, and capability for high speeds, they are frequently employed in a variety of applications, including electric cars and industrial machines. Due to their improved performance and reliability, BLDC motors are becoming more and more popular in general.

Figure 1. Fabricated BLDC Motor

Table 1:Comparison of brushed and brushless D.C. Motor

Parameter	**Conventional Motor**	**BLDC**
Cost	Low	High
Efficiency	75 to 80%	90% and more
Size	Large and significantly Heavy	Small and LightWeight
Performance	Loses torque over time	Provides High torque for long time
Maintenance	Brushed must be changed frequently	Minimal Maintenance
Drive Mechanism	Commutator, Brush-based friction drive	Electronic frictionless drive

2. MATHEMATICAL MODELING

The following assumptions are made to formulate the differential equation of the BLDC motor.

- The expected output power from the motor is 1 kW.
- The maximum speed of the motor is 3100 RPM

- The stator has a Y-connected full-pitch winding and the inner rotor has a non-core pole structure.
- Three hall sensors are symmetrically connected on the stator at 120 intervals.
- Core saturation, eddy current losses and hysteresis losses are neglected.
- Armature reactance is neglected, and the air-gap magnetic field distribution is assumed to be a trapezoidal wave with a flat-top width of 120 electric angle.
- The cogging effect is neglected and consider that the conductors are continuously and uniformly distributed over the surface of the armature.

Considering the above conditions, the design for stator and rotor is done.

2.1 Block diagram

Three Hall sensors in the BLDC motor detect the rotor position and send a signal to the microcontroller. This data is used by the microcontroller to control the power supplied to the stationary part (stator) for creation of the magnetic field for the rotor and makes it spin. Although the power source is direct current, this interaction creates an alternating current (AC) voltage waveform a trapezoidal shape. The interaction between the magnetic fields of the rotor and stator keeps the rotor rotating.

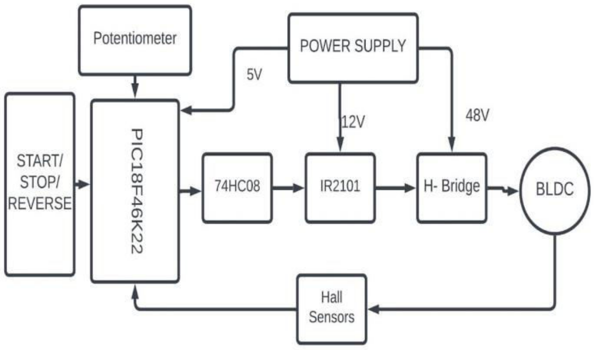


Figure 2. Block diagram of system

2.2 Designofstator and rotor

The design of the stator windings is important for the overall performance and efficiency of brushless DC motors. It is responsible for generating the magnetic field that drives the motor and directly affects the torque and speed characteristics. Consequently, it is important to optimize the stator winding design to achieve maximum performance and efficiency in BLDC motors.Equations used for motor designing as as follows

$$B = \mu H$$

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

$$T = kD^2L$$

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

Equation to find flux

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

Bm = Flux density of magnet, Bm = Flux density of rotor

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

Flux of the permanent magnets

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

Equation to find flux linkage

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

Equation for Induced voltage

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

Equation to solve for torque from length

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

Equation for Inductance for Air gap

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

Equation to find motor constant k

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

Equation for Cogging torque

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

2.2.1 Rotor design:

On top of the iron core is placed a strongly magnetized, box-shaped rare earth permanent magnet for the rotor of PM. It is also possible to assemble the box-shaped pole using rectangular strips to reduce the cost of the motor. In order to ensure the flow density of the square air gap and reduce torque drag, motor designers always use this structure with a pole arc width greater than 120 degrees electrical angle.

2.2.2 Stator design:

An iron core contains one or more phase-symmetrical windings that can be connected in a "Y" or "D" pattern. A symmetrically connected Y-type of three-phase winding without a neutral point is commonly used due to its efficiency and cost-effectiveness. Since the stator winding design is very important, special software like Ansys Electronic Software is used to design the stator winding for 1KW 48V 20A BLDC motor. The software considers various motor characteristics, such as slot length, slot depth, and other important details, to create the right stator winding design that allows the motor to operate at peak performance. This method ensures that the motor meets the special requirements of the stator winding design, resulting in increased performance and efficiency.

Table2:- 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

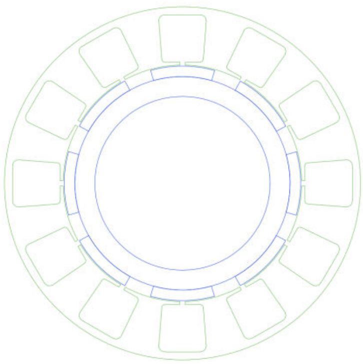


Figure 3: Stator with Slots and Rotor

Figure 4: Rotor of BLDC Motor

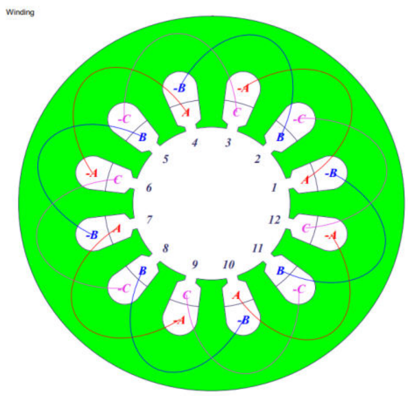


Figure 5: Winding Design

Figure 6:-Achieved Winding of 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 3:- 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 wire of the same phase is placed in a single hole for the full volume of the winding, which causes a constant air gap flow density in the motor. By summing the back-EMF generated by the wire in each phase, the total back-EMF wave can be obtained, which is similar to the air gap current density. The platform width of the EMF wave again and the air gap current density wave are identical. Therefore, a trapezoidal high back-EMF can be produced by a fully concentrated curve.

1) the motor must be disassembled to access the stator housing the coils of the pre-installed brushless DC (BLDC) motor. The stator is the stationary part of the motor that holds the coils and cannot be accessed without disassembly. When the motor is disassembled, access to the stator is possible, allowing inspection and maintenance of the stator windings or other components. Engine disassembly and reassembly must be done correctly to ensure optimal performance and longevity.

2) copper wire wrapped around the brushless DC motor stator pole to wind the coils, leaving enough wire to connect to the motor controller. To form coils, the wire is wound in a special pattern and creates a magnetic field that interacts with the rotor magnet to cause rotation. The number of coil turns required varies with the desired engine speed and torque. Winding and proper connection of coils are important for BLDC motor performance and efficiency.

3) After determining the appropriate number, the copper wire is wound around the stator poles, the number of windings varies depending on the characteristics of the motor. Twisting the wire in a specific configuration creates a magnetic field that interacts with the rotor magnet. Winding is a critical step in BLDC motor assembly that requires precision and detail to ensure optimal performance and efficiency.

4) After rotating all three coils, connect the motor in the correct order. This is necessary for the machine to function properly. To produce torque and rotational motion, the motor controller continuously feeds the coils, which produce a rotating magnetic field that interacts with the permanent magnet rotor. The energy from the coils is important and can affect the performance, efficiency and noise level of the motor. Finally, the controller must carefully follow the manufacturer's specifications.

5) After the motor is properly attached to the motor, the motor can be reassembled. The permanent magnet rotor can be fed back into the stator holding coils. To avoid physical contact, make sure that the rotor fits the stator properly and there is enough clearance between the rotor and the stator. The motor must then be installed or assembled and all electrical connections must be double-checked to ensure proper connection. Finally, the machine can be tested for smooth and efficient operation.

6) After rebuilding the engine, it is important to check it carefully to make sure it is working properly. Start the engine and check that it runs smoothly and without unusual noises or vibrations. It must ensure that the engine operates at the desired speed and torque

level. Any adjustments or necessary adjustments must be made before the machine is used regularly.

4. CHARACTERISTICS OF MOTOR

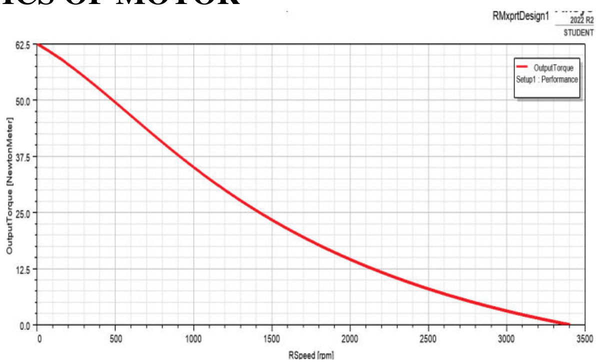


Figure 7:- Torque vs Speed Characteristic

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.

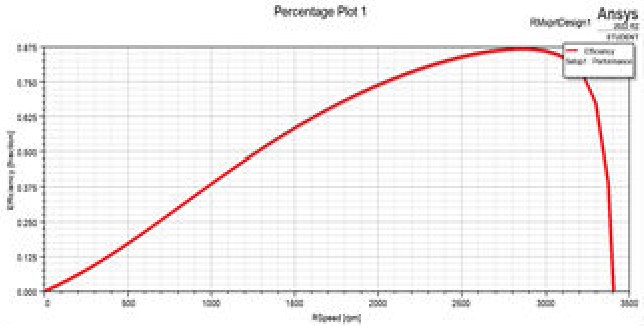


Figure 8:-Efficiency vs speed

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

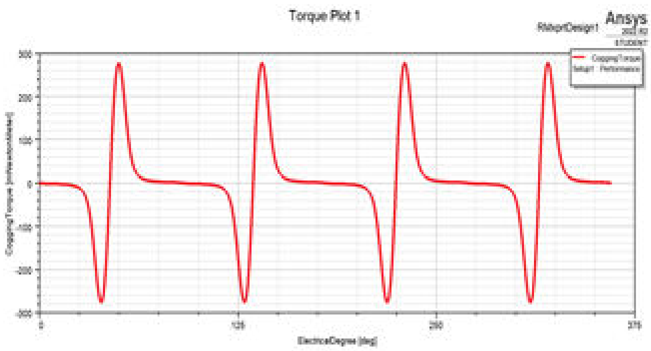


Figure 9:-Cogging Torque plot

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

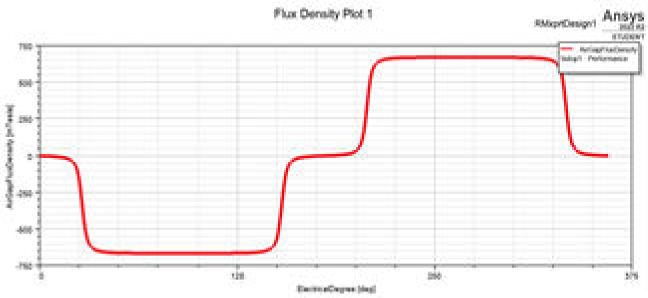


Figure 10:- Flux Density Plot

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.

5. 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.

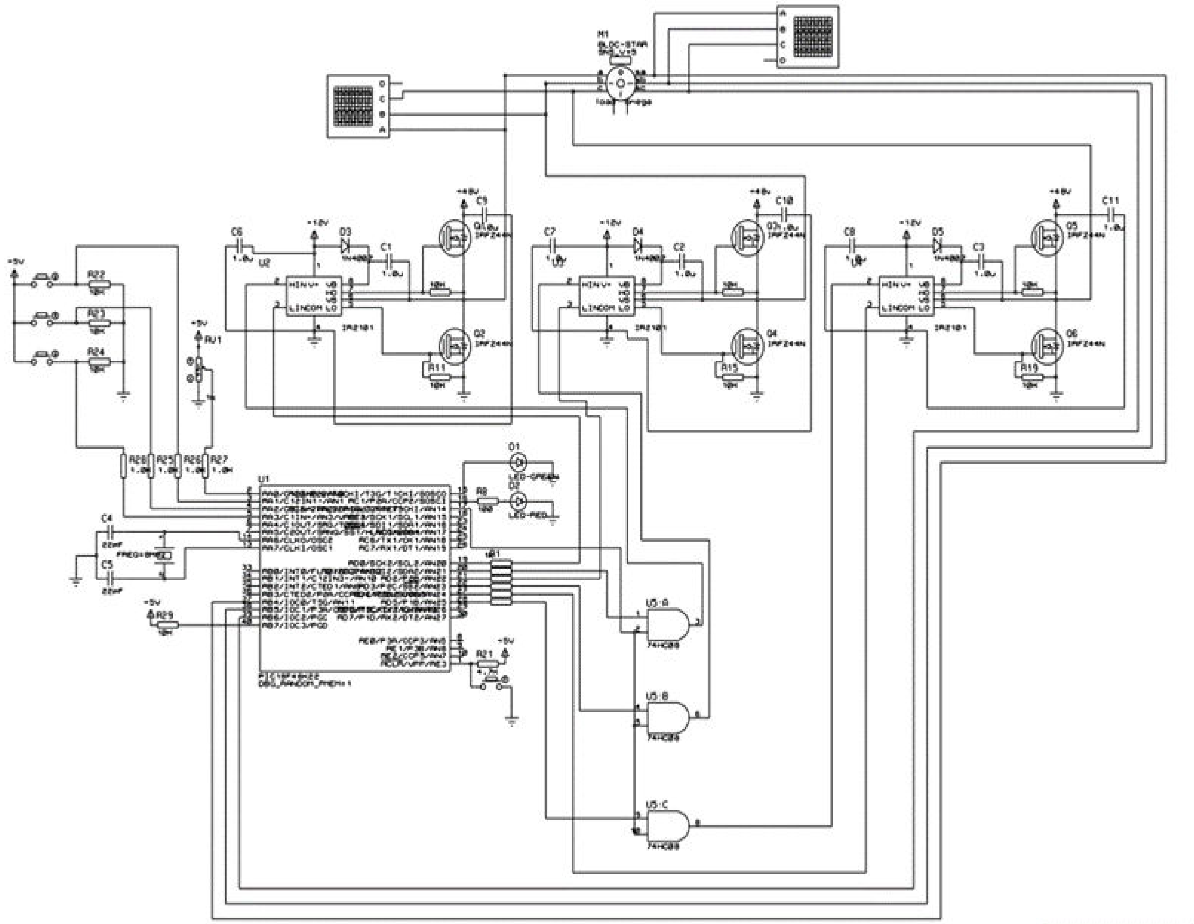
The microcontroller should receive signals from the three hall sensors and utilize this information to change the pulse width modulation (PWM) signals that go to the gate driver integrated circuit (IC) to accomplish the needed motor control. It should also be able to receive analogue input from a potentiometer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

Figure11 Schematic of Bldc Motor controller



6. SIMULATION RESULTS

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 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 at dead time.

Table 4:- Six step hall effect Commutation

H 1	H 2	H 3	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

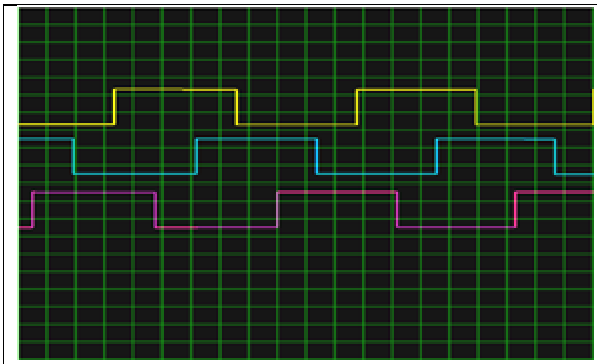


Figure 12: Hall effect Sensor Output

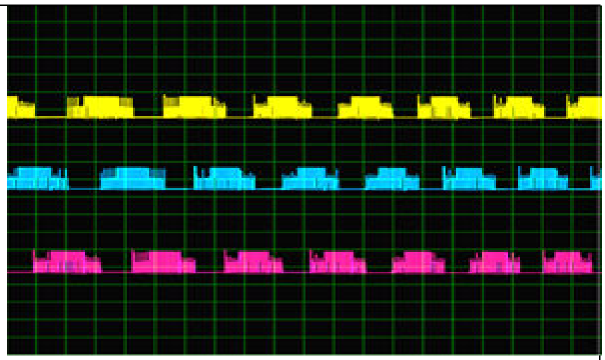


Figure 13: Motor Phase Voltage

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. 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

6.1 Controlling of Speed

$fe = (Nm/120)s$

Where, feis 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.

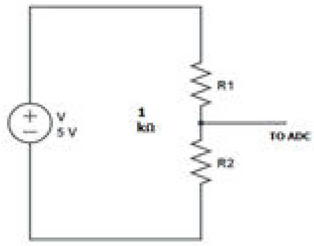


Figure 15 Equivalent Circuit

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

Table 5 : 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

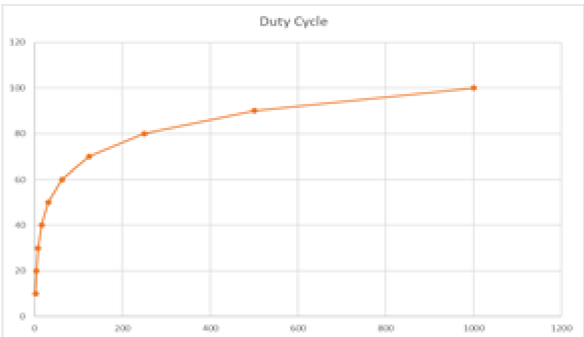


Figure16 Resistancevs Duty Cycle

8. CONCLUSION

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. The simulation results of performance parameters are found satisfactory. 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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