EGB241

DC MOTOR PROJECT

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GROUP 1

Table Of Contents

1. Introduction

DC motors have been implemented for various uses that help enhance our living. These uses included - but not limited to – electric vehicles, cranes, conveyor systems, elevators and ceiling fans etc. (Industrial Quick Search(IQS)). As for our design, we have intended to use our motor as a scaled version of a ceiling fan. A standard rpm required for a ceiling fan is between 200-300rpm, but can change according to height, size and area (Crompton, 2023).

This report details the design and construction of a lap wound brushed commutated DC motor. Our group has been tasked with making specific design decisions to optimise the motor for its operation as a ceiling fan within the following constraints listed by the client. The motor must;

- Be supplied by a DC source
- Have a minimum of 3 and a maximum of 8 coils
- Use less than 45 metres of wire
- Draw less than 5 Amps
- Operate at less than 30 volts
- Have a maximum no-load speed of less than 2000 rpm
- Have a field supplied by two permanent magnets

Design decisions will be made within these parameters including our own selection of wire and magnets as a result of motor construction calculations. This motor will also be tested, first theoretically, mapping the torque, speed and current response of the system. Once this experimentation has obtained acceptable results the motor will then be constructed using equipment provided by the client to determine whether it is suitable for application in the field.

2. Part A: Design Phase

The design phase objective was to calculate all necessary variables to theoretically simulate characteristics of the motor prior to construction. The calculation of the motor constants, resistance, speed, torque and mechanical power output were vital in forming the construction of the motor and the materials that would be used. Excel and Matlab were utilised to present the theoretical values and expected response of the motor.

2.1 Calculations

The main calculations for the construction motor characteristics were dependent on the values we chose/calculated in the table below. Although all calculations were computed through excel (see section 2.3), the formulas for the main calculations are as follows :

N_c	**41**
C	8
a	2
P	2
l_{chord}	45mm
l_{rotor}	19.2 mm

$$Z = 2CN_c = 2 * 8 * 41 = 656$$

$$k_1 = \frac{ZP}{60a} = \frac{656*2}{60*2} = 10.933$$

$$k_2 = \frac{ZP}{2\pi a} = \frac{656*2}{2*\pi*2} = 104.41 rad^{-1}$$

$$l_1 = 2 * l_{chord} + 2 * l_{rotor} = 2 * 45 + 2 * 19.2 = 128.4mm$$

$$l_2 = l_1 * N_c = 128.4 * 41 = 5264.4mm$$

$$l_3 = l_2 * C = 5264.4 * 8 = 42.11m$$

The next calculations made were in regards to the motors performance characteristics. These calculations help us reach our operational requirements given by the client. The main restraints given were that the motor draws less than 5amps, operates with less than 30 Volts and has a maximum no load speed of 2000rpm. These were computed with the formulas below:

$$n_{no\ load} = \frac{V_{supply}}{k_1 * \phi} = \frac{2}{10.933 * \left(\frac{0.0937}{1000}\right)} = 1952.239 \text{ rpm}$$

$$I_{max} = {}^{V_{supply}}\!/_{R_{rotor}} = {}^{2}\!/_{1.278} = 1.56$$

$$R_{rotor} = \rho \frac{\frac{l_3}{a}}{\pi\left(\frac{d}{2}\right)}$$

The resistance of the rotor was calculated using the wire characteristics below and inbuilt coding functions in excel such as 'VLOOKUP' to get the desired result. See below for the excel formula.

```
=1+(C32*VLOOKUP(C20,'WIRES (OPT)'!A24:I35,8)/4000)
```

AWG	Diameter		Turns of wire, without insulation		Area		Resistance/Length	
	(in)	(mm)	(per in)	(per cm)	(kcmil)	(mm^2)	mΩ/m	mΩ/ft
19	0.0359	0.912	27.9	11	1.29	0.653	26.42	8.051

The output characteristics of our motor can determine how efficient our design is, this is proven by the torque generated, ideal mechanical power out and expected electrical power out.

$$\tau(t) = k\phi I_a(t) = 0.0153 \text{ Nm}$$

$$P_{elect}(t) = V_{supply} * I_{max}(t) = 2 * 0.78 = 1.56W$$

$$P_{max} = \left(\frac{\tau(t)}{2}\right) * \frac{n_m(t)}{2} * \left(\frac{2\pi}{60}\right) = \left(\frac{0.0153}{2}\right) * \left(\frac{1952}{2}\right) * \frac{2\pi}{60} = 0.78\ W$$

$$n(t)\% = \left(\frac{P_{act}}{P_{in}}\right) * 100 = \frac{0.626}{1.56} * 100 = 40\%$$

2.2 Material Selection

To achieve an optimal design each variable material had to be chosen appropriately. The type of magnet to generate flux and the type of wire used in the lap wound system were two key design factors for this motor.

An option of five magnets were proposed and magnet #3495 was chosen. This was because it had the highest amount of flux available, creating an ideal condition for the motor to output high torque. The larger area of the magnet also means the flux will be spread more evenly across the rotor, assisting in a smooth revolution when operating.

AVAILABLE MAGNETS						
CODE	**B (G)**	**LENGTH (L) (mm)**	**WIDTH (W) (mm)**	**HEIGHT (mm)**	**A (LxW) (cm^2)**	**PHI (mWb)**
#2522	1400	50	20	12.7	10	0.14
#3495	3709	40	15	8	6	0.22254
#3460	2408	25	12.5	3.5	3.125	0.07525
#3470	3625	25	12.5	6	3.125	0.11328125
LM1614	580	20	15	5	3	0.0174

By: Farzad Farajizadeh (20.04.2019)

The wire chosen to generate the electric fields in the rotor was AWG (American Wire Gauge) 19. This was the smallest gauge option available (largest diameter) indicating that it would have the least resistance. It does mean that this wire is more expensive, however the resistance in wires go up significantly with each increase in AWG so it was determined that this value was suitable.

AWG	Diameter		Turns of wire, without insulation		Area		Resistance/Length	
	(in)	(mm)	(per in)	(per cm)	(kcmil)	(mm^2)	mΩ/m	mΩ/ft
19	0.0359	0.912	27.9	11	1.29	0.653	26.42	8.051

2.3 Excel Spreadsheet

Our motor specifcs such as construction and performance calculations are all included in our excel spreadsheet below.

EGB241 EXCEL ASSIGNMENT INTERFACE FILE

Group Details		Status (Should be filled by Tutors):			
Group No.:		Semester:		Submission Date:	DD/MM/YYYY

Members

Student Number	First Name	Last Name	Contribution (Percent)
n11042338	Nicklin	Creese	33%
n10749845	Quinn	Sweeney	33%
n11048409	Emma	Johnston	33%

Input and Output Properties

INPUTS (Geometric Properties)		
Parameter	Value	Unit
Length of rotor (L_R):	19.2	mm
Radius of Windings (r_{ave}):	22.5	mm
No. of Poles (p):	2	

INPUTS (Winding Properties)		
Parameter	Value	Unit
Winding Type:	Lap Wound	
Multiplex:	1	
Maximum Current Density (J):	4	A/mm^2
Gauge of Wire (AWG):	19	
No. of coils of rotor (C):	8	ERROR CHECK
No. of turns of wire per coil (N_c):	41	

OUTPUT (Intermediate Winding Properties)		
Parameter	Value	Unit
No. of conductors (Z):	656	
No. of Parallel Paths (a):	2	
Winding Angle Lap ($\theta_{w,L}$):	3.141592654	Rad
Winding Angle Wave ($\theta_{w,W}$):	3.141592654	Rad
Chord Length (L_c):	45	mm
Length of 1 turn (L_{W1}):	128.4	mm
Length of 1 coil:	5264.4	mm
Length of all coils (L_W):	42.1152	m (< 45 m)
Cross section of coils inside slot:	107.092	mm^2

Available Components	
Permanent Magnets:	**#2522, #3495, #3460, #3470, LM1614**
Wiress (AWG):	**18 - 29**
Permissible Length of Wire:	**45 m**
Rotor Laminations (slots / thickness):	**(5 / 1 mm), (6 / 1 mm), (8 / 1.2 mm)**
Rotor Laminations (r_{min},r_{max}):	**(15 mm, 30 mm)**
Number of Laminations per kit:	**16**

ASSESSMENT FLAGS:	CORRECT	WRONG

INPUT (Magnetic Properties)		
Parameter	Value	Unit
Magent type:	#3495	
Percent of flux leakage (FL):	50%	

INPUT (Electrical Properties)		
Parameter	Value	Unit
Terminal Voltage (V_T):	2	V
Degradation Factor (DF):	20%	

OUTPUT (Intermediate Magnetic Properties)		
Parameter	Value	Unit
Flux density at surface (B):	3709	G
Area of magnet surface (A):	6	cm^2
Total flux of magnet (Φ_{Total}):	0.187402105	mWb
Flux passing through rotor ($\Phi_{linkage}$):	0.093701053	mWb

OUTPUT (Intermediate Electromagnetic Properties)		
Parameter	Value	Unit
Motor Constant (K_1):	10.93333333	
Motor Constant (K_2):	104.4056427	1/Rad
Resistance of Armature (R_a):	1.278170896	Ω
Maximum Armature Current ($I_{a,max}$):	1.564735988	A

OUTPUT (Final Electromagnetic Properties)		
Parameter	Value	Unit
Maximum Rotational Speed ($n_{r,max}$):	1952.238786	rpm
Rotational Speed at Max Torque ($n_{r,fl}$):	0	rpm
Rotational Speed at Max Torque ($w_{r,fl}$):	0	Rad/sec
Maximum Generated Torque (T_{max}):	0.015307685	Nm
Maximum Produced Power (P_{max}):	0.782367994	W
Motor may actually produce (P_{act}):	0.625894395	W
Input Power (P_{in}):	1.564735988	W
Efficiency:	40	

MARKED BY:	

2.4 Expected Response

The expected response of the motor is described mathematically by equation 1 [1]:

$$\frac{dn_m}{dt} = \frac{60 * k_2 \ * \phi * V_{supply}}{2\pi * R_A * J} - \frac{60 * \tau_{load}}{2\pi * J} - \frac{60 * k_2 * k_1 \phi^2 n_m}{2\pi * R_A * J} \tag{1}$$

The variables within the equation are determined within the excel interface. As seen k_1 is a 'motor voltage constant'. k_2 is a 'motor torque constant'. V_supply is the voltage applied to the motor from a power source. τ_load is the torque opposing movement, in this case the force of internal friction which is typically 0.04Nm. R_A is the resistance in the armature. ϕ is the magnetic flux passing through the motor. n_m is the rotational speed in rpm. J is the moment of inertia for the rotor which was estimated to be equal to 2.3939*10^(-4).

Due to the complexity of determining an exact solution of n_m for this differential equation, an approximation will be determined. To approximate the solution to this ordinary differential equation, the Runge-Kutta 4th order method will be implemented. This is to ensure a high accuracy within the approximation. All critical motor characteristics at a given time include, current, torque, rotational speed, and efficiency. The motor characteristics were calculated by applying a series of formulas to the rotational velocities (rpm) obtained from the Runge-Kutta method.

$$Emf(t) = k1 * \ \phi n_m(t)$$

$$I(t) = \frac{\left(V_{supply} - \ Emf(t)\right)}{R_A}$$

$$\tau_{ind}(t) = k_2 * \phi * I(t)$$

$$P_{mech}(t) = \tau_{ind}(t) * 2\pi * \frac{n_m(t)}{60}$$

$$P_{elec}(t) = V_{supply} * I(t)$$

$$P_{load}(t) = t_{load} * \frac{2\pi * n_m(t)}{60}$$

$$\eta_{\%}(t) = \frac{P_{mech}(t) - P_{load}(t)}{P_{elec}(t)} * 100$$

The results of the MATLAB analysis were used to construct multiple plots describing the critical motor characteristics of the design. These include: The rotational speed, current, torque and mechanical power at any given time as well as efficiency and torque vs speed curves.

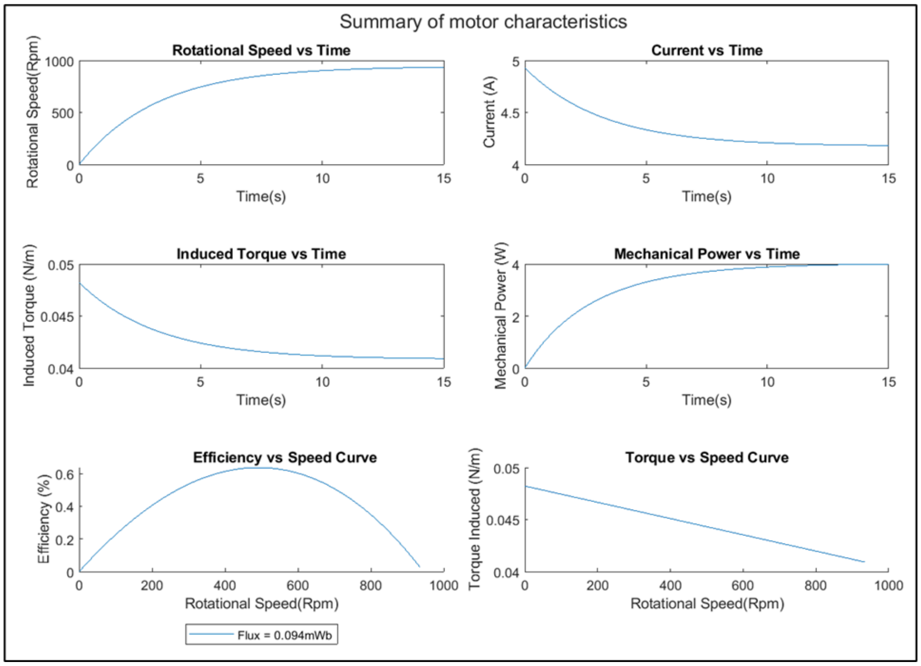

Figure 1: The summation of the expected motor characteristics

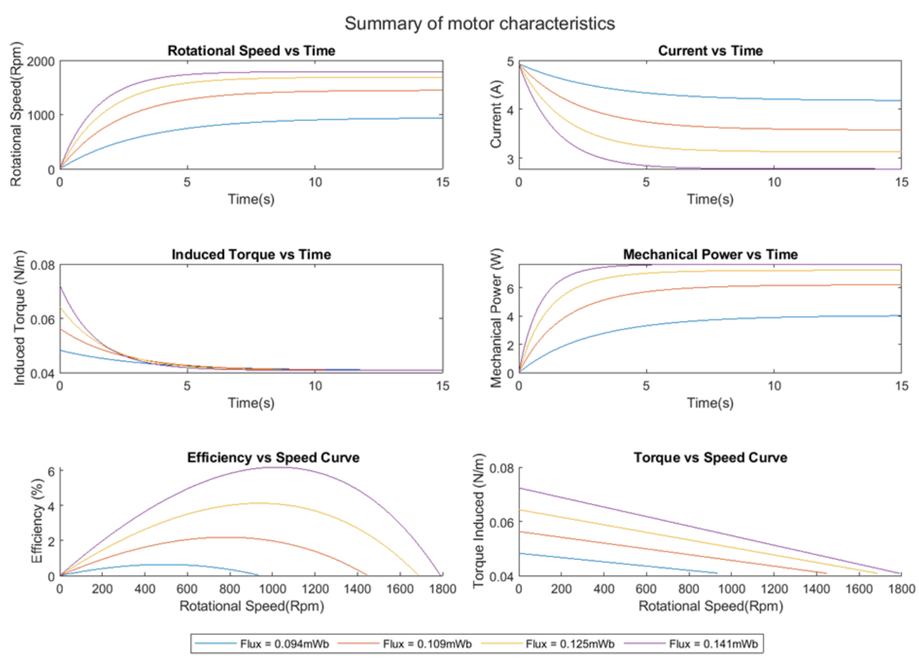

Figure 2: Expected motor characteristics for a range of magnetic flux of to +50%.

The anticipated results of the DC motor design can be summarised based on the information provided in Figure 1. The figure provides a comprehensive overview of the motor characteristics, showcasing six distinct plots that highlight various performance parameters.

One of the key expected outcomes is the motor's maximum rotational speed, which is projected to reach 935.2 revolutions per minute (rpm). This speed falls within the upper specified speed limit requirements, demonstrating that the motor design rotational velocities are safe.

Additionally, the maximum current attained by the motor is expected to be 4.93 amperes (A), with a plateau at around 4.18 A. These current values are well within the specified limit of less than 5 amps, indicating that the motor design successfully meets the current requirements.

However, the motor's expected efficiency is 0.6%, which is not considered ideal. Despite this suboptimal efficiency, it still satisfies the design requirements established for the project. Although there is room for improvement in terms of efficiency, the motor design fulfils the necessary criteria outlined in the project's specifications.

Further analysis was conducted to understand the impact of deviation from the calculated magnetic flux magnitude through the rotor, as shown in Figure 2. Increasing the magnetic flux improves torque-to-speed correction while reducing current draw, resulting in a non-linear increase in maximum efficiency. Additionally, even with a flux variation of +50%, the maximum achieved rpm was 1790, below the required speed limit. It can also be stated that maximum current is calculated by the input variables V_{supply}/R_A thus is unaffected by the increased magnetic flux.

3. Part B: Construction & Testing

With all the motor variables obtained the design can now enter the construction phase. This section covers the testing methods used to ensure each function of the motor was behaving as expected and what was done when encountering unexpected issues. Construction iterations and quality assurance also played a significant role in this phase to avoid any pitfalls were necessary. Once the motor was constructed the test results were acquired.

3.1 Construction Procedure

The construction process was done in 5 stages.

Stage 1. Collect all equipment including the 45m of copper wire, stator core and a motor housing.

Stage 2. Constructing stator assembly

The stator core was wound in a lap configuration using the provided amount of copper wire. However, it was discovered that the actual length of each winding was longer than expected. A reduction in the amount of windings per coil was taken to ensure that the total amount of copper wire used remained below 45 metres. As a result, each coil was wound with a total of 36 windings with 2 metres left (43 metres used) of excess wire.

To maintain balance and optimise motor efficiency, it was important to keep the radius of the windings consistent. This was achieved by winding the required coils exclusively on either the left or right side of the commutator slot. This arrangement was necessary because each slot accommodated two coils. By keeping the radius of windings consistent, a balanced force was achieved within the motor, which assists in achieving a high overall efficiency.

Stage 3. Commutator assembly

This stator assembly then had to be linked to a commutator and subsequently a power source. The commutator was constructed from scratch using copper pipe. The copper pipe was cut into eight individual equal sections and attached to an increased diameter pvc pipe. This resulted in eight individual commutator slots. This pvc pipe was connected to the main rotate shaft to construct the final motor stack.

Stage 4. Full motor assembly

To finalise the design, the motor stack was integrated to the provided motor housing. This was achieved by placing the rotor within the provided slots. The supplied brace plates were installed on one end of the rotor, connecting it to a bearing, while a bushing was used on the other end.

This arrangement was implemented to minimise any translational movement along each axis in the motor's design.

Stage 5. Addition of final components

The complete motor assembly included pre-installed magnet housings, enabling the addition of magnets to the design.

The final required element of the motor was to supply power to the opposite slots on the commutator. This was achieved through the use of two small rectangular copper plates.

The copper plates are mounted in parallel to the motor housing to establish proper connectivity with the opposite slots on the commutator. A rubber band was utilised to ensure a consistent, low-resistance is observed between the brushes and the commutator.

The five construction stages result in an operation dc motor.

3.2 Construction Iterations

The first iteration was placing a steel plate above the rotor, magnets and windings. This was done to create a more efficient flux flow between the north and south poles of the magnets on either side of the rotor, leading to higher torque capabilities in the design. This is believed to suit the motor application due to the fan not needing a high rpm to operate but a reasonable level of torque is required. This was also enhanced by positioning the magnets closer to the motor and in a vertical position. It directed the coverage of flux across the majority of the motor and also increased the flux density through the rotor. This was applied to the prototype by constructing wood moulds to hold the magnets in position. To decrease the electrical losses of the motor the wires were soldering to the connection. This also enabled a more stable bond. These iterations resulted in a higher reliability and enhanced performance during the testing stage

3.3 Quality Assurance

Several measures were taken to make the motor more robust and safe to operate during the construction phase. This included adding electrical tape around the rotor to avoid breaking the wire and shorting the motor. Applying a back board to the motor housing provided in conjunction with more bolt holes allowed the design to operate smoothly without causing damage to surrounding components or itself.

3.4 Motor Results

No Load Results					
	1	**2**	**3**	**4**	**5 (Motor Fail)**
Current In	5	4.5	3.1	2	1.5
Current Out	0.9	0.87	0.56	0.02	0
Voltage In	3	2.8	1.5	1.2	0.5
Voltage Out	0.28	0.12	0.16	0.97	0
RPM	427	520	292	210	0

3.5 Review Phase

After testing the lower and high thresholds of our motors rpm, our motor system would work well as a ceiling fan as it comfortably sits between 200-400 rpm (approximate range of speed for ceiling fans) while staying within a safe voltage and current level. Concurrent engineering methods were used throughout the entire product development cycle, optimising the motor's design, manufacturing processes, and performance simultaneously. Our approach ensured that potential issues related to motor efficiency, reliability, and cost are addressed early on, reducing the need for revisions later. This process also enabled faster development for the motor by undertaking calculations simultaneously and leveraging shared knowledge. Ultimately, this resulted in a high-quality, efficient, and reliable motor that met client expectations and requirements.

Some improvements are recommended before the product reaches the final design stage. The first improvement would be to add pole pieces to the magnet to increase the amount of magnetic flux passing through the entire stator core. This helps increase the efficiency and performance of the electromechanical system by improving the magnetic coupling between the rotor and stator. By increasing the magnetic flux, the overall power output and torque capability of the system can be improved. The second improvement is to smooth the commutator across the whole diameter, doing so would exponentially decrease the friction resulting in a longer lasting brush.

3.6 Group Contribution Table

Name and Student Number	Parts contributed
Nicklin Creese (11042338)	Calculations, Expected Response (All Matlab script), Construction Procedure
Emma Johnston (11048409)	Introduction, Calculations, Material Selection
Quinn Sweeney (10749845)	Introduction, Material Selection, Quality Assurance, Construction Iterations, Review Phase

4. References

Crompton. (2023, May 10). *What is RPM related to a Ceiling Fan's Speed?* Crompton. Retrieved May 26, 2023, from https://www.crompton.co.in/blogs/fans/ceiling-fan-rpm/

Industrial Quick Search(IQS). (n.d.). *DC Motor: What Is It? How Does It Work? Types, Uses*. IQS Directory. Retrieved May 26, 2023, from https://www.iqsdirectory.com/articles/electric-motor/dc-motors.html

[1] S. Nielsen, *Motor design and construction,* Queensland University of Technology .

5. Appendix

J is the moment of inertia for the rotor. This can be calculated knowing that 42.11m of copper wire was used and the rotor laminations chosen. The cylinder extends from a radius 5mm to 30mm. The volume of a solid steel laminations is calculated to be 271.3g. The total weight of

$$(30mm)^2\pi * (16mm * 1.2) = 54286mm^3$$

Minus 5mm radius centre hole for metal rod:

$$54286mm^3 - (5mm)^2\pi * (16 * 1.2mm) = 52778.0355mm^3$$

Minus 8 slots estimated to be rectangles of 8mm by 15mm.

$$52778.0355mm^3 - 8 * \left(15mm * 8mm * (16 * 1.2mm)\right) = 34346mm^3$$

Steel has a density of 7.9gm/cm3, therefore the steel within the design has a weight of

$$34346mm^3 * \frac{1cm^3}{1000mm^3} * \frac{7.9\text{g}}{\text{cm}^3} = 271.3\text{g}$$

The amount of copper used is 42.1m of wire with a cross sectional area of $0.653mm^2$ and a density of 8.96g/cm^3

$$\left(42.1m * \frac{100cm}{1m}\right) * \left(0.653mm^2 * \frac{1cm^2}{100mm^2}\right) * \frac{8.96g}{cm^3} = 246.32g$$

A total weight of 517.6g (0.5176kg) is seen. The moment of inertia becomes.

$$J = \frac{1}{2} * 0.5176\,(0.005^2 + 0.03^2)$$

$$J = 2.3939 * 10^{-4}$$

Appendix 1: The derivation of the value of J