Lab-3: Permanent Magnet Brushed DC Motor

ELEC 342

Lab Experiment: 3

Section: D

Bench #: 7

Partners	Student ID #:	% participation	Signatures
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Date Performed: 10th March' 23

Date Submitted: 17th March' 23

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Pre-Lab:

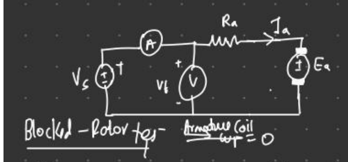
1)Deepak Roshan Thiagarajan

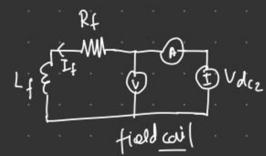
Prelab 3

Deepak Roshan Thiagarajan
LAB 3
62802418

1)
- Prepare a list of equations for calculating the equivalent circuit parameters using the Blocked-Rotor and No-Load Tests.

Blocked-Rotor Test

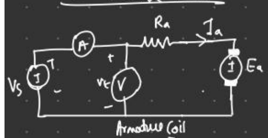




To achieve $\omega_r = 0 \rightarrow E_a = 0$ (Short-circuit)

$$R_a = \frac{V_t}{I_a} \quad ; \quad R_f = \frac{V_f}{I_f}$$

No-Load Test



Open Circuit coil

$$E_a = k_a \phi \omega_r \quad ; \quad T_e = k_a \phi I_a$$

$$V_t = E_a + I_a R_a$$

$$\text{Power} = \omega_r T_e = E_a I_a$$

$$T_e = T_{frict}$$

2) Assume the motor is operating in the first quadrant using DC-DC converter, and at a given speed, $E_a = k_t \omega_r$. Rewrite the equation $v_a = R_a i_a + L_a \frac{di_a}{dt} + E_a$ to find the expression for the armature inductance when the upper switch of the converter is ON (Hint: replace di_a with ΔI_a and dt with Δt, assuming you have two data points). Alternatively, you can also find the armature inductance using the OFF time interval. Also assume the value of the current ripple is $\Delta I_a = I_2 - I_1$.

$$\left.\begin{array}{l} E_a = K_t \omega_r \; ; \quad \Delta I_a = di_a = I_2 - I_1 \\ \Delta t = t_2 - t_1 \end{array}\right\} \text{Given assumptions}$$

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + E_a$$

$$V_a = R I_a + L_a \frac{\Delta i_a}{\Delta t} + E_a$$

$$\therefore L = \frac{(v_a - R_a i_a - K_t \omega_r) \times \Delta t}{\Delta i_a}$$

$$\boxed{\Rightarrow L = \frac{(v_a - R_a i_a - K_t \omega_r) \times (t_2 - t_1)}{(I_2 - I_1)}}$$

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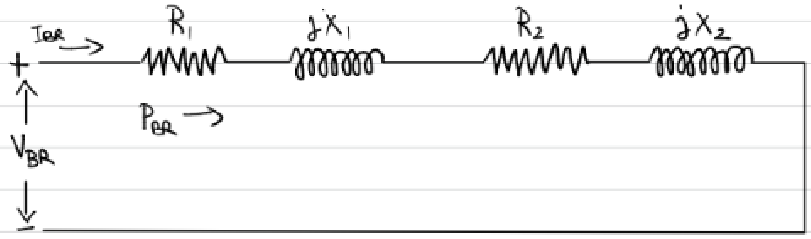
2) Anshul Israni

PRELAB-3

- Prepare a list of equations for calculating the equivalent circuit parameters using the Blocked-Rotor and No-Load Tests.

* BLOCKED ROTOR TEST →

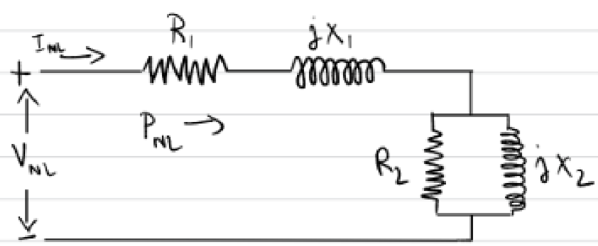


Total resistance seen by the circuit: $Z_{BR} = \frac{(V_{BR}/\sqrt{3})}{I_{BR}}$

$\therefore R_{BR} = R_1 + R_2 = \frac{P_{BR}}{I_{BR}^2}$

$\therefore X_{BR} = X_1 + X_2 = \sqrt{Z_{BR}^2 - R_{BR}^2}$

* NO LOAD TEST →



Total resistance seen by the circuit: $Z_{NL} = \frac{(V_{NL}/\sqrt{3})}{I_{NL}}$

$\therefore R_{NL} = R_1 + R_2 = \frac{V_{NL}^2}{P_{NL}}$

$\therefore X_{NL} = X_1 + X_2 = \sqrt{Z_{NL}^2 - R_{NL}^2}$

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- Assume the motor is operating in the first quadrant using DC-DC converter, and at a given speed, $E_a = k_t \omega_r$. Rewrite the equation $v_a = R_a i_a + L_a \frac{di_a}{dt} + E_a$ to find the expression for the armature inductance when the upper switch of the converter is ON (Hint: replace di_a with ΔI_a and dt with Δt, assuming you have two data points). Alternatively, you can also find the armature inductance using the OFF time interval. Also assume the value of the current ripple is $\Delta I_a = I_2 - I_1$.

$$E_a = K_t \cdot \omega_r$$

$$V_A = R_A \cdot i_a + L_a \cdot \left(\frac{di_a}{dt}\right) + E_a$$

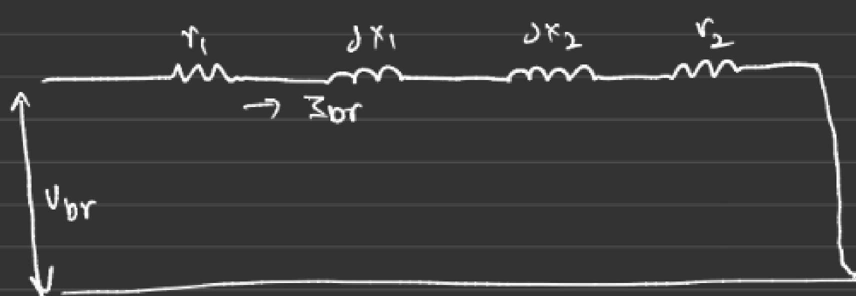
$$\therefore V_A = R_A \cdot i_a + L_a \cdot \left(\frac{\Delta I_a}{\Delta t}\right) + K_t \cdot \omega_r$$

$$V_A = R_A \cdot i_a + L_a \left(\frac{I_2 - I_1}{t_2 - t_1}\right) + K_t \cdot \omega_r$$

$$\therefore \boxed{L_a = \frac{(V_A - R_A \cdot i_a - K_t \cdot \omega_r) \cdot (t_2 - t_1)}{(I_2 - I_1)}}$$

3)Pratham Goel

Blocked Rotor test



$$Z_{br} = \frac{V_{br}/\sqrt{3}}{I_{nL}}$$

$$r_{br} = \frac{P_{br}}{I_{br}^2} = r_1 + r_2$$

$$X_{br} = \sqrt{Z_{br}^2 - R_{br}^2}$$

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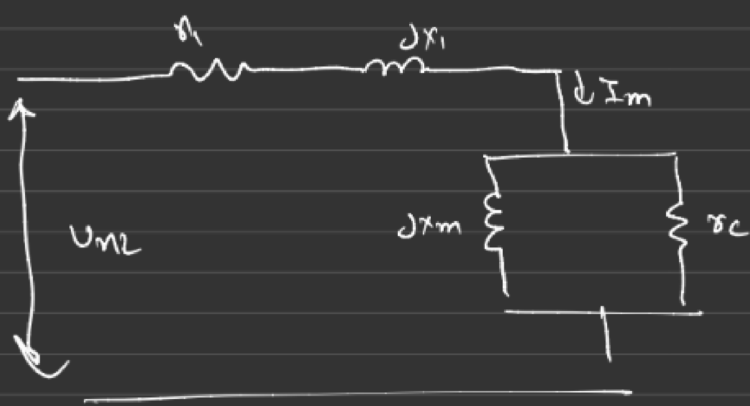
No load test

$$Z_{nL} = \frac{U_{nL}/\sqrt{3}}{I_{nL}}$$

$$r_{nL} = \frac{P_{nL}}{I^2_{nL}} = r_1 + r_c$$

$$x_{nL} = \sqrt{Z_{nL}^2 - R_{nL}^2} = x_1 + x_m$$



#2 $E_a = K_t \omega_r$

$$V_a = R_a i_a + L_a \frac{\Delta I_a}{\Delta t} + K_t \omega_r$$

$$V_a = R_a i_a + L_a \underbrace{\cancel{\frac{(I_{a2} - I_{a1})}{t_2 - t_1}}}_{\text{zero}} + K_t \omega_r$$

since inductor

$$V_a = E_A + R_a I_a$$

$$\boxed{\frac{V_a - E_A}{I_a} = R_a}$$

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Task 1A, Table 1: Armature + Brush Resistance Measurement

V_1, V			I_1, A			Calculate R_a, Ω		
0.91	2.39	3.65	1.15	3.19	4.72	0.791	0.749	0.773
						Average: 0.7713		

Task 1B, Table 2: No-Load Measurement

Measurement	**1**	**2**	**3**	**4**	**5**	**6**
$V_1(ave), V$	5.68	11.38	18.15	24.26	31.08	38.94
$I_1(ave), A$	0.75	0.89	0.98	1.03	1.06	1.07
$n_1(ave), rpm$	209	443	725	979	1266	1602
Calculation						
k_t, $[V \cdot \sec/rad]$	0.233091	0.23051	0.229106	0.228886	0.228266	0.227196
Average k_t	0.2295091					
T_{fric}, Nm	0.172132	0.204263	0.224919	0.236394	0.24328	0.245575

Task 2A, Table 3: Load Test Measurement: (up to 6 measurement points)

Measurement #	1	2	3	4	5	6
$V_1(ave), V$	42.39	42.32	42.33	42.40	42.31	42.38
$I_1(ave), A$	2.08	2.44	3.18	3.88	4.54	5.83
$P_1(ave), W$	88.1	103.1	134.5	164.7	192.1	246.9
$V_2(ave), V$	40.72	39.84	38.74	37.81	36.76	34.88
$I_2(ave), A$	0.05	0.46	1.23	1.97	2.66	3.93
$P_2(ave), W$	2.1	18.1	47.6	74.4	97.7	137.1
n, rpm	1728	1717	1691	1676	1649	1628
T_m, Nm	0.25	0.34	0.5	0.66	0.80	1.08

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P_2 / P_1	0.0238	0.1755	0.3539	0.4517	0.5085	0.5552
$SR = (n_1 - n_{6,load}) / n_{6,load}$			0.06142506142			
DC Machine (Generator) Voltage Constant $k_v = V_{2,oc} / \omega_r$			0.225027309208			

Task 2B, Table 4: Motor Speed Control by Adjusting Voltage

Measurement #	1	2	3	4	5	6
$V_1(ave), V$	5.32	11.46	19.49	25.38	31.92	45.43
$I_1(ave), A$	1.64	2.43	3.46	4.09	4.76	6.13
$P_1(ave), W$	8.7	27.8	67.4	103.7	152.0	278.7
$V_2(ave), V$	3.6	8.63	15.32	20.34	26.02	37.54
$I_2(ave), A$	0.40	0.96	1.82	2.36	2.97	4.23
$P_2(ave), W$	1.5	8.3	27.9	48.0	77.2	158.7
n, rpm	172	436	717	950	1207	1749
T_m, Nm	0.25	0.39	0.59	0.72	0.85	1.12
P_2 / P_1	0.1724	0.2985	0.4139	0.4628	0.5079	0.5694

Task 3A, Table 5: Motor Speed Control by Duty-Cycle (2 kHz): Vdc = 45.1

Measurement #	1	2	3	4	5
Duty-Cycle, d	0.1	0.3	0.5	0.7	0.9
$V_1(ave), V$	4.39	13.73	21.43	30.15	39.37
$I_1(ave), A$	1.44	2.67	3.78	4.59	5.49
Current Ripple $\Delta I_1, A$	1.909	1.909	1.909	1.909	1.909
$P_1(ave), W$	6.7	38.9	83.1	140.1	216.6

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$V_2(ave), V$	2.68	9.99	17.43	24.98	32.49
$I_2(ave), A$	0.30	1.20	2.06	2.85	3.67
$P_2(ave), W$	0.8	12.0	36	71.3	119.2
n, rpm	109	480	816	1171	1506
T_m, Nm	0.22	0.45	0.63	0.82	0.98
P_2 / P_1	0.1194	0.3084	0.4332	0.5089	0.5503

Task 3B, Table 6: Motor Speed Control by Duty-Cycle (10 kHz): Vdc = **45.1**

Measurement #	1	2	3	4	5
Duty-Cycle, d	0.1	0.3	0.5	0.7	0.9
$V_1(ave), V$	4.32	13.27	21.72	30.94	39.67
$I_1(ave), A$	1.56	2.67	3.69	4.62	5.54
Current Ripple $\Delta I_1, A$	0.596	0.596	0.596	0.596	0.596
$P_1(ave), W$	6.9	36.0	80.9	143.5	219.8
$V_2(ave), V$	2.64	9.79	17.51	25.26	32.59
$I_2(ave), A$	0.30	1.18	2.07	2.88	3.68
$P_2(ave), W$	0.8	11.5	36.3	72.9	119.9
n, rpm	144	456	816	1176	1512
T_m, Nm	0.23	0.44	0.64	0.82	0.99
P_2 / P_1	0.1159	0.3194	0.4487	0.5080	0.5455

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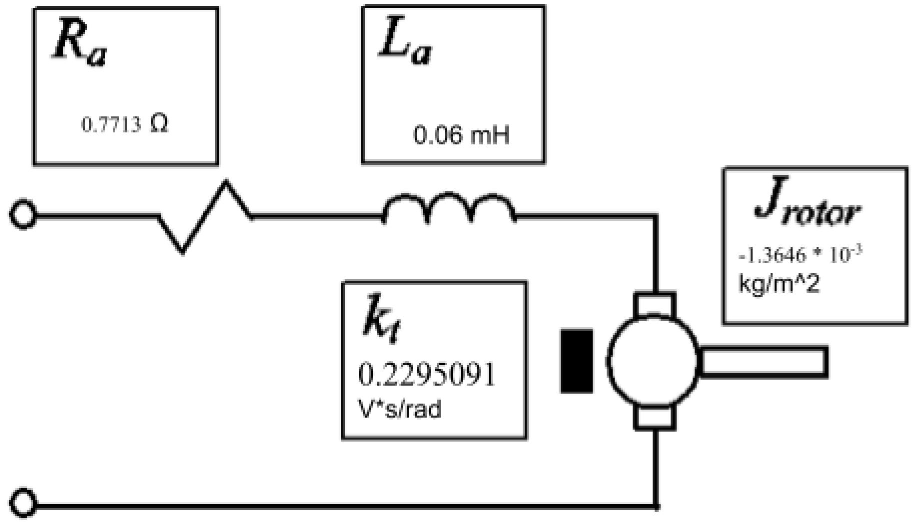

Fig. A. DC Machine Equivalent Circuit. Fill in the corresponding boxes with machine parameters. Make sure to include the units.

Task 4, Table 7: Motor Speed Control using Universal Inverter Box (at 2.5 kHz)

Measurement #	1
Duty-Cycle, d	0.50
$V_1(ave), V$	22.74
$I_1(ave), A$	3.81
$P_1(ave), W$	90.2
$V_2(ave), V$	19.34
$I_2(ave), A$	2.26
$P_2(ave), W$	43.7
n, rpm	912
T_m, Nm	0.68
Use the set of measurements complete the following section of the Table	

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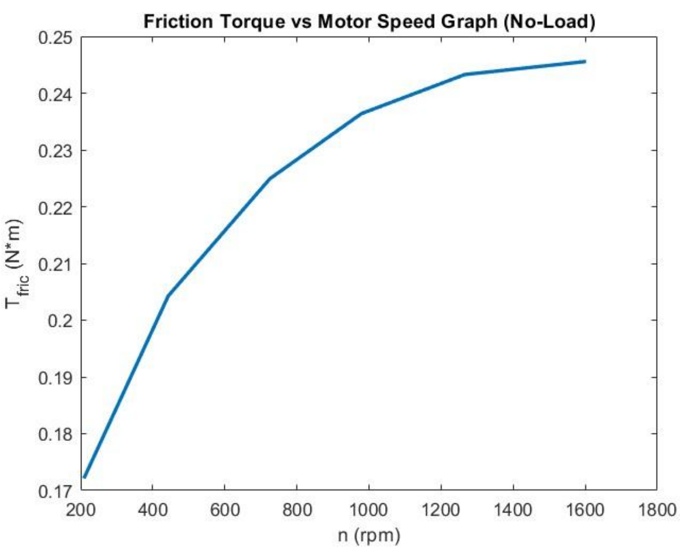
Input to Inverter Box		Input power at the DC Motor terminals P_{dc-mot}, W	Output mechanical power P_m, W	Efficiency of the Inverter, % P_{dc-mot}/P_{inv}	Efficiency of the Motor, % P_m/P_{dc-mot}	Efficiency of Inverter-Moto r combined, % P_m/P_{invt}
Voltage, Vdc	Current, A					
45.1	1.9					
Total input power to the Inverter Box P_{inv}, W						
85.69		90.2	64.94	105.26%	71.99%	75.788%

Consider the chain of the components that you had in this lab including the following:

DC Source, **DC-DC Converter**, **DC Machine 1**, **DC Machine 2**, and **Load Resistors Box**.

Using the data you recorded in Table 7, calculate and fill in the energy conversion efficiency at each energy conversion stage in the above chain. Comment on the efficiency of these stages to deliver the energy to the final resistor load.

Task 5A: Determining Motor Parameters

1) The value of R_a is recorded in Table 1.
2) The value of K_t is recorded in Table 2. The values of K_t and K_v are very close to each other, differing by only about 0.0044812. This shows that these two constants should be equal.
3) The value of T_{fric} is recorded in Table 2.
4) 

As the speed of the DC motor increases, the amount of friction torque it experiences reaches a maximum value, as shown in the graph above. This friction is caused by the sliding motion between the motor's brushes, shaft, and bearings, and is the main reason for energy losses in the system.

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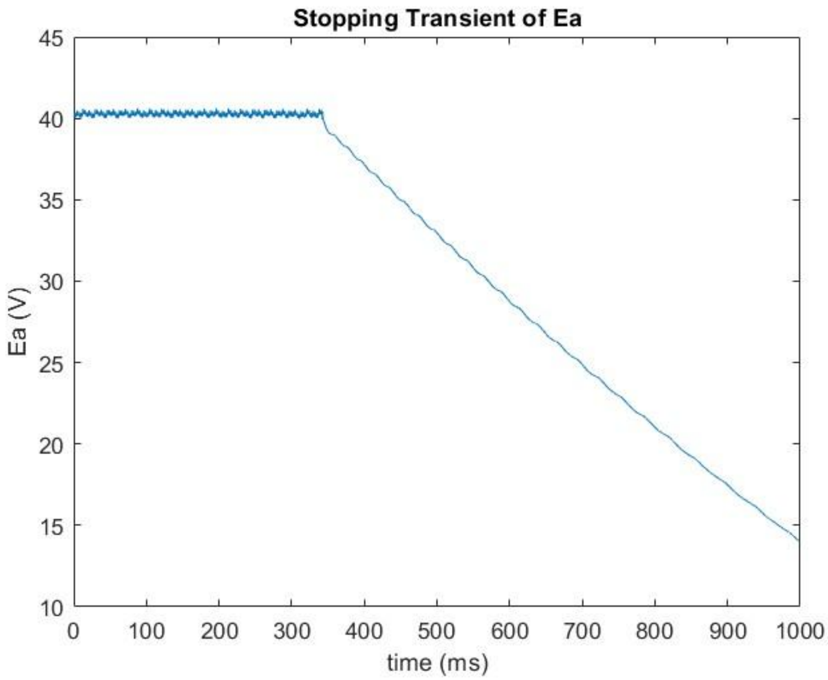
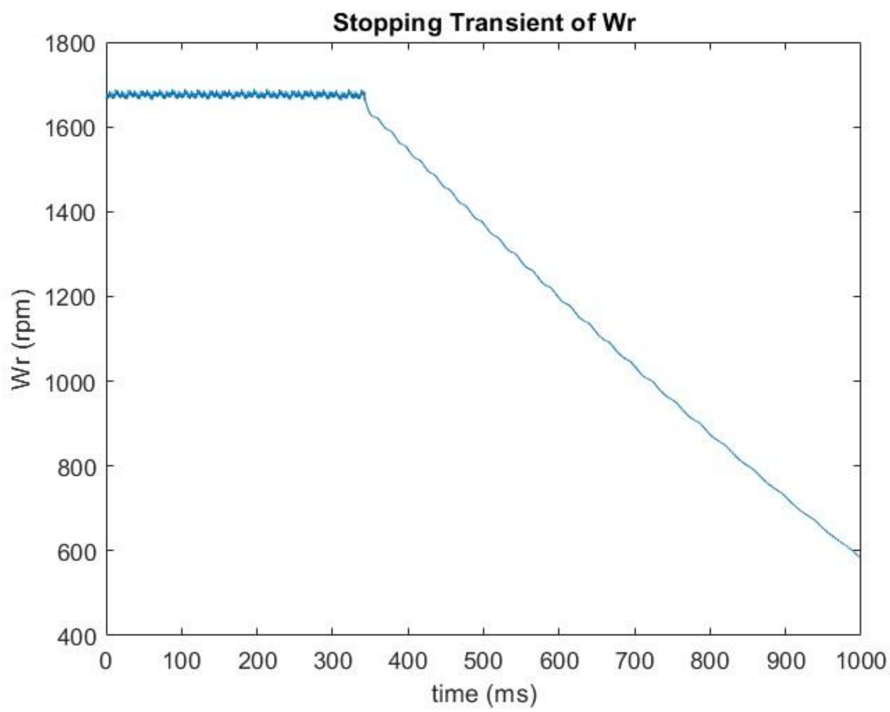
5) Below are the graph for ‘Stopping Transient of E_a and ω_r’:





Using the two data points shown in the above graph of ‘Stopping Transient of E_a’, we can approximate the slope as shown below:

$dE_a / dt = (39.154 - 15.702) / \{(350.368 - 949.28) * 10^{-3}\} = -39.158$ V/s

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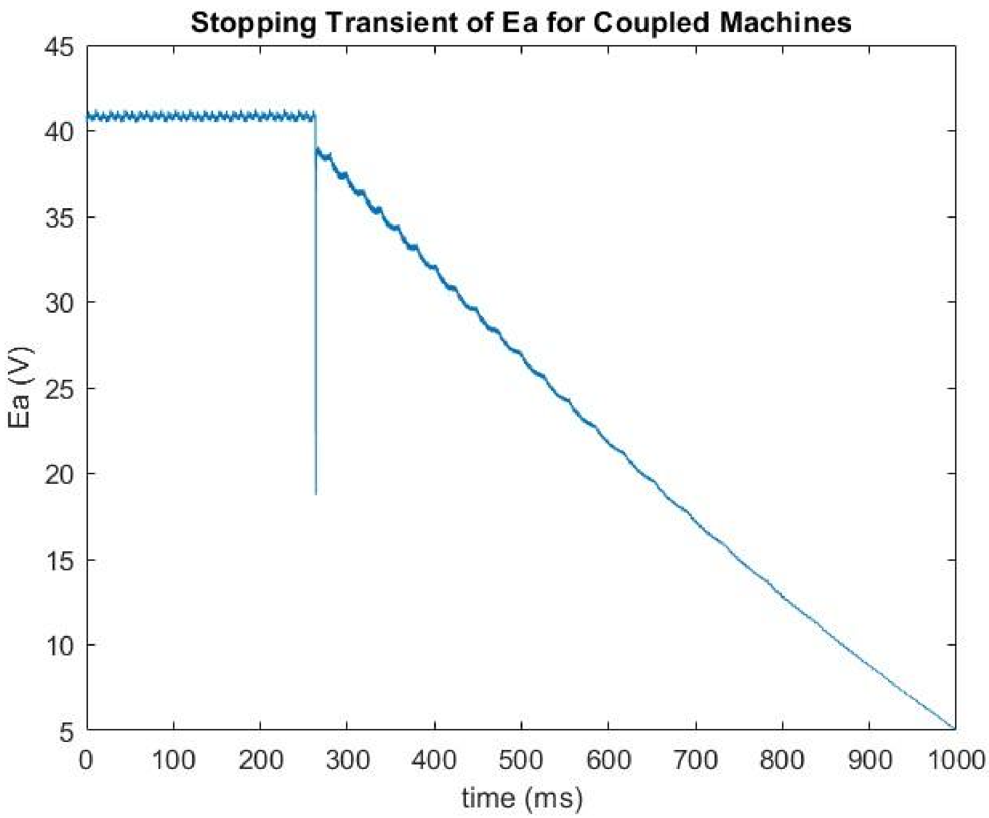
$d\omega_r / dt = (dE_a / dt) / K_t = -39.158 / 0.2295091 = -170.615\ rad/s^2$

We take $\omega_r = 900$ rpm which is approximately the midpoint of the graph in part 3.
$\therefore\ T_{fric}\ (\omega_r) = 0.232825$ Nm

$\therefore\ J_{rotor} = T_{fric}\ (\omega_r) / (d\omega_r / dt) = 0.232825 / -170.615 = -1.3646 * 10^{-3}\ Kg/m^2$

5)



Now, $T_{fric}\ (\omega_r) = 0.232825$ Nm (from before)

$\therefore\ dE_a / dt = (36.986 - 15.83) / \{(304.704 - 732.064) * 10^{-3}\} = - 49.50393$

$\therefore\ d\omega_r / dt = (dE_a / dt) / K_t = - 49.50393 / 0.2295091 = - 215.694851$

$\therefore\ J_{combined} = T_{fric}\ (\omega_r) / (d\omega_r / dt) = 0.232825 / - 215.694851 = - 1.07942 * 10^{-3}\ Kg/m^2$

The values of $J_{combined}$ and J_{rotor} are very similar to each other, which is expected since the two motors are meant to be identical models with the same level of internal friction.

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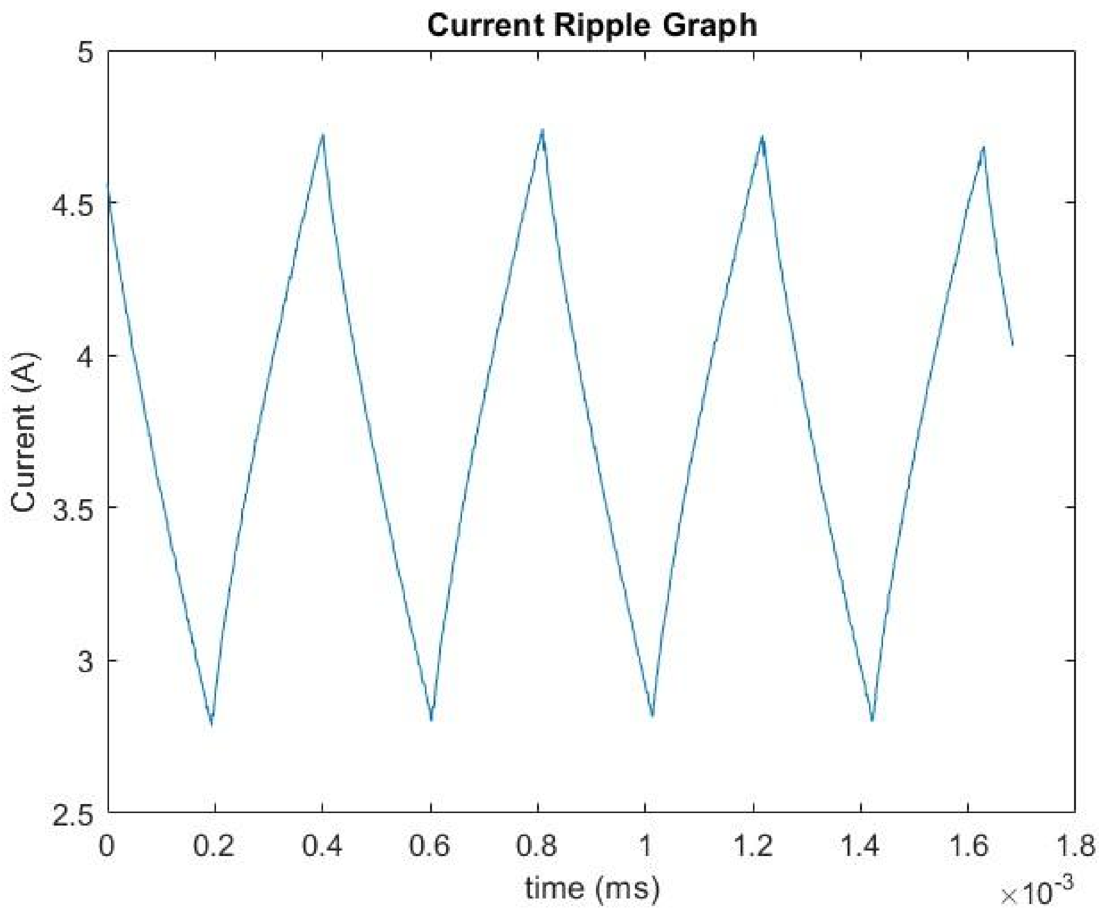
6)



For Less Accurate equation:

$V_a = L_a \frac{\Delta i_a}{\Delta t} + E_a$

From the current ripple graph,

$\Delta i_a = 4.742 - 2.842 = 1.9\, A$ $and\ \Delta t = 0.000809 - 0.0006 = 0.000209$ s

n = 7.916113532658694e+02.

$E_a = k_t * n * 2\pi/60 = 0.2295 * 791.611 * 2\pi/60 = 19.0249\, V$

$V_a = d * V_{dc} = 0.5 * 45.1 = 22.55\, V$

$L_a = 0.3822\, mH$

For more Accurate Equation:

$V_a = L_a \frac{\Delta i_a}{\Delta t} + E_a + R_a I_a$

I_a = 3.781602575896964 A

R_a = 0.7713

$L_a = 0.06\, mH$

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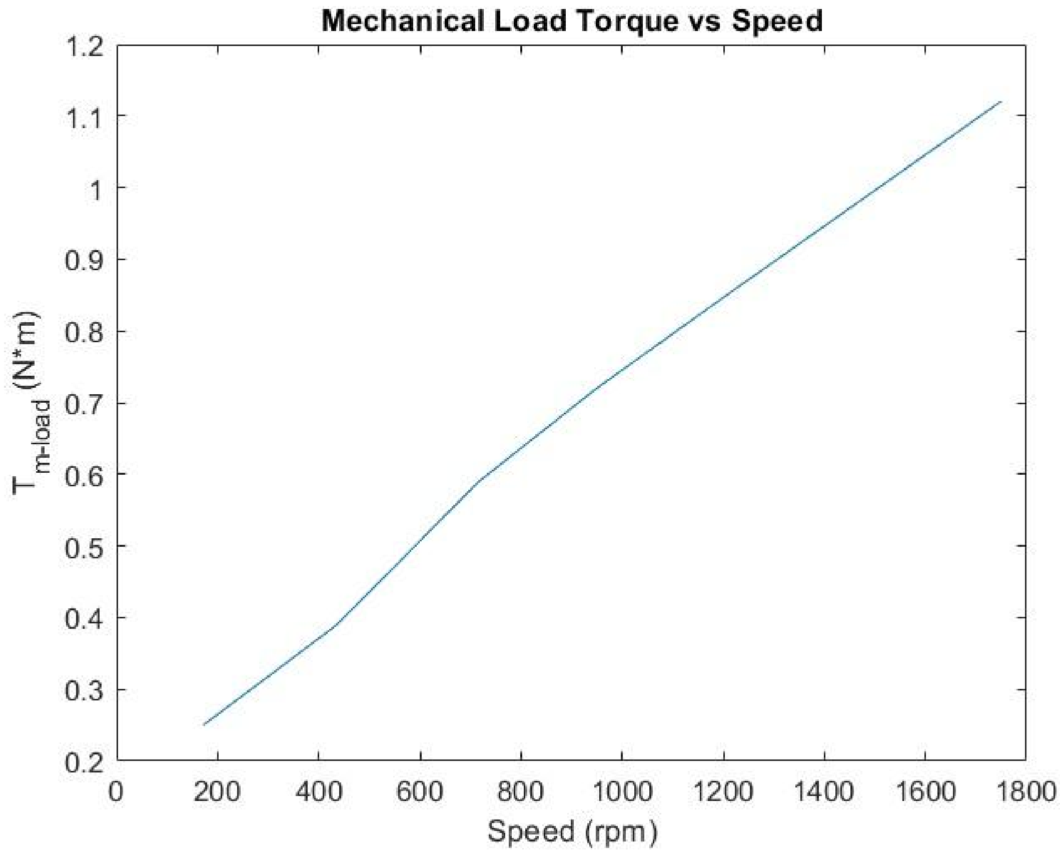
7) Refer to Fig. A. for filled out PM DC Machine parameters.



8)

Since the plot is linear,

$T_e = k_t * I_a$

$\omega_r = \frac{V_a - I_a R_a}{k_t}$

$T_e = k_t \frac{V_a - \omega_r k_t}{R_a}$, As we can observe the data is linear therefore, it confirms the linear relationship

Task 5B: Equivalent Circuit vs Measured Comparison

1) We use the measured torque values from Task 2A and graph it with respect to the speed in rpm. We also calculated the values of torque to compare with the measured torque values.
   We use the formula TM = $Ea_1 * I_1/(2*pi*n/60)$ - $T_{friction.}$

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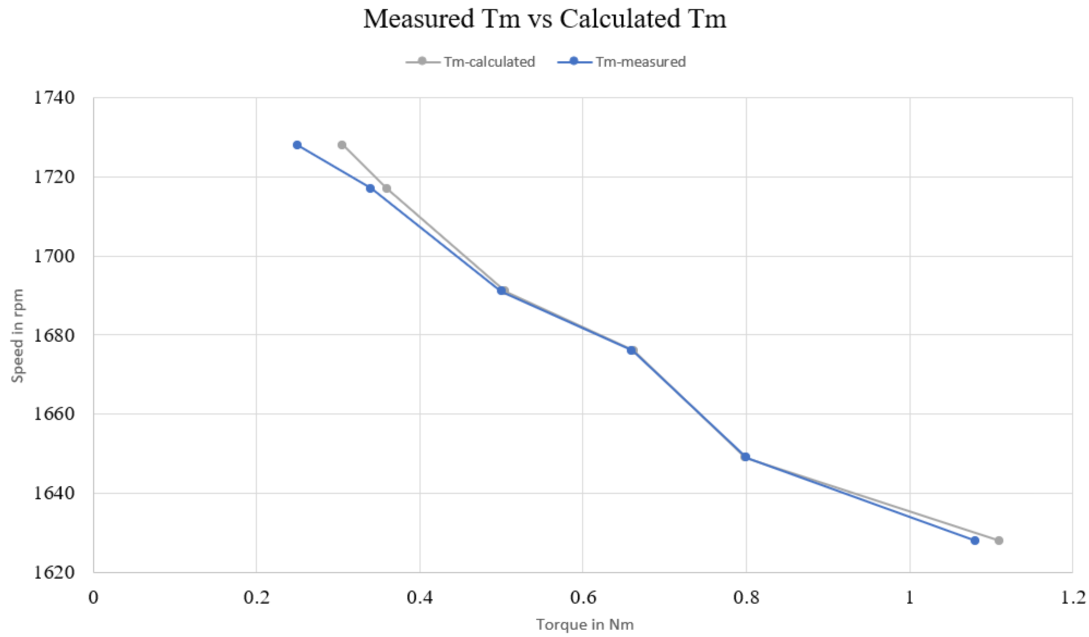

After superimposing both plots we see the calculated torque is very close to the measured torque we got in Task 2A. There is little difference in the produced rpm due to the fact that there are losses such as mechanical and electrical losses that cause variation in the speed. Thus the speed-voltage regulation would also show this same trend due to linear relation.

2) Below represents the voltage predicted vs voltage measured for Table 4- voltage adjustment test values we also have to take into account $t_{friction}$ for the prediction. We can see that there is a direct proportionality between the speed and voltages in table 4. Also comparing with the predicted voltage line we can see it's pretty much just a few deviations due to the fact that the losses are taken into account.

   The orange line represents the voltages measured in Table 3 with the load test where we kept the voltage about constant (around 42.3 V) and changed the load thus keeping the speed also fairly constant, hence the small deviation line.

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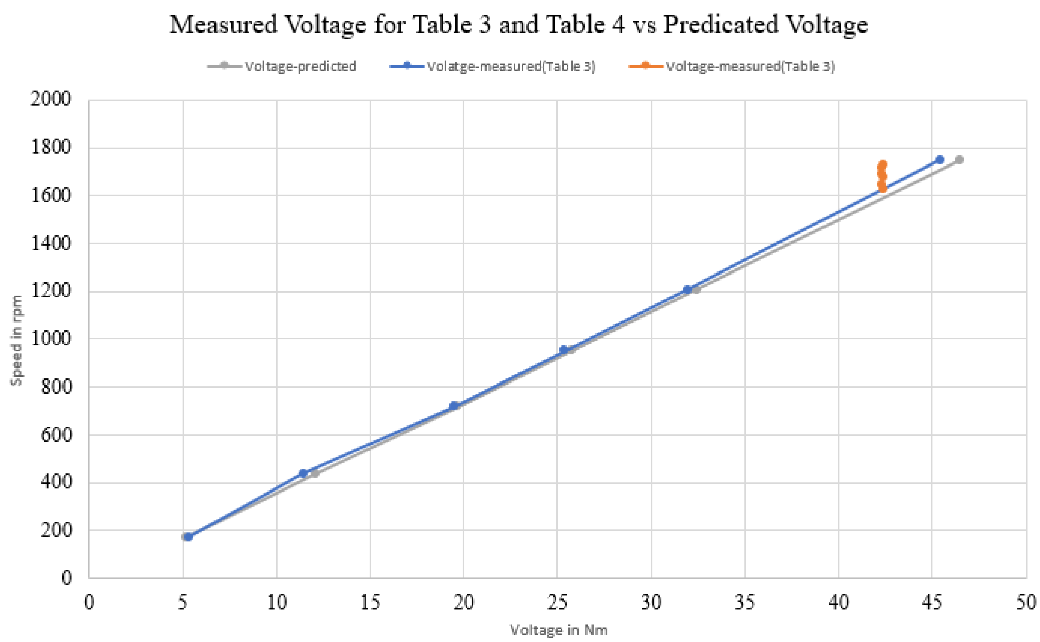
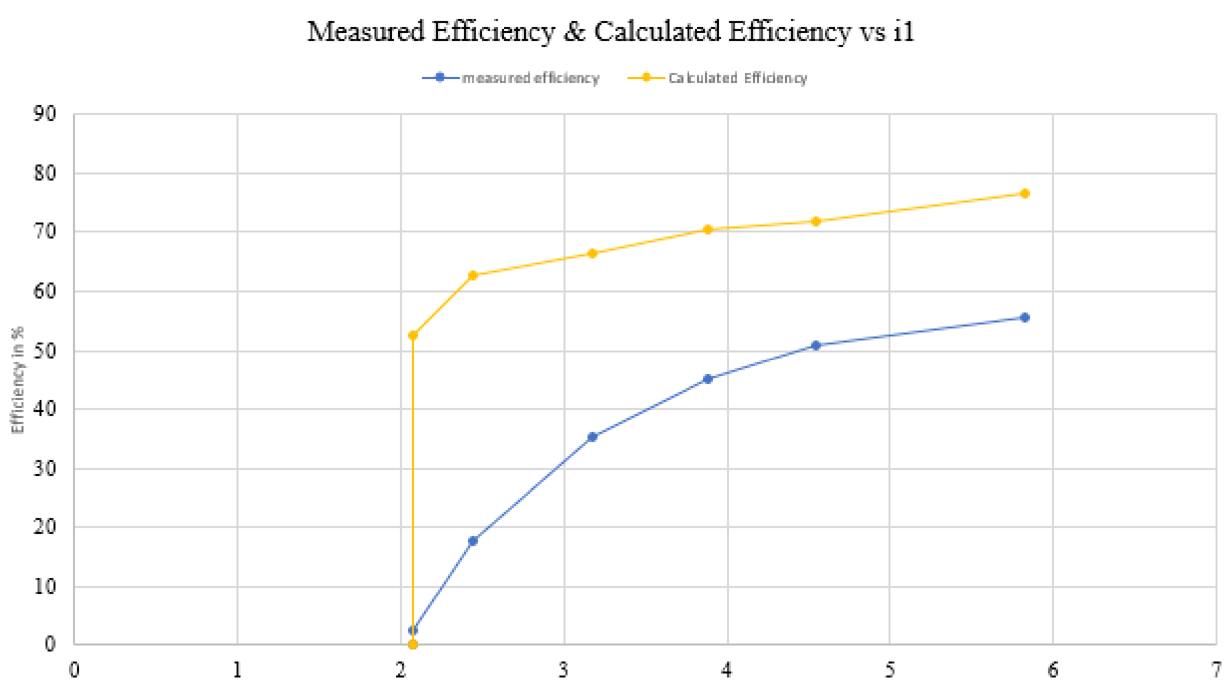


3)



We plotted the measured efficiency and the calculated efficiency of the values of Table 3 vs the i1 current and infer that the calculated efficiency (including measured friction) is much higher as compared to the measured efficiency due to the excess friction in a nonideal motor. The efficiency seems to peak around 5.83 A, but with this linearity, the efficiency could be much higher on higher i1 currents.

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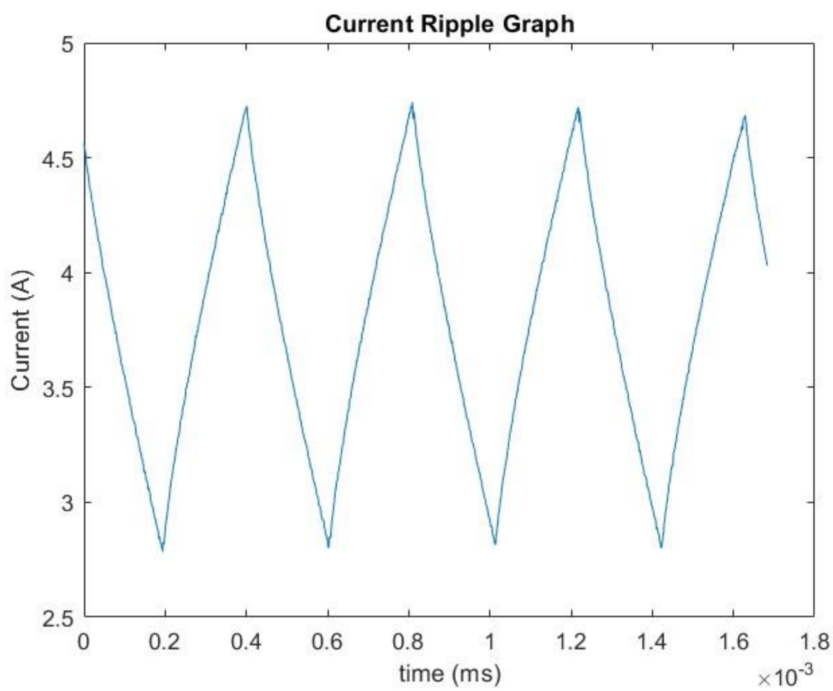
Task 5D: General Questions

1) The equivalent circuit gives a very good approximation as the final results obtained are pretty similar to the measured values. The error margin is very low.

2) The variable resistance method is highly inefficient due to significant power losses in the resistors. In low-voltage robotics / automotive applications, the adjustable voltage method is the most efficient approach, as it minimizes power loss and maximizes efficiency. However, for larger motors and high-voltage automotive applications, adjusting the voltage can be dangerous. Therefore, the safest and most effective option is to use an inverter.

3) The required graphs are shown below:



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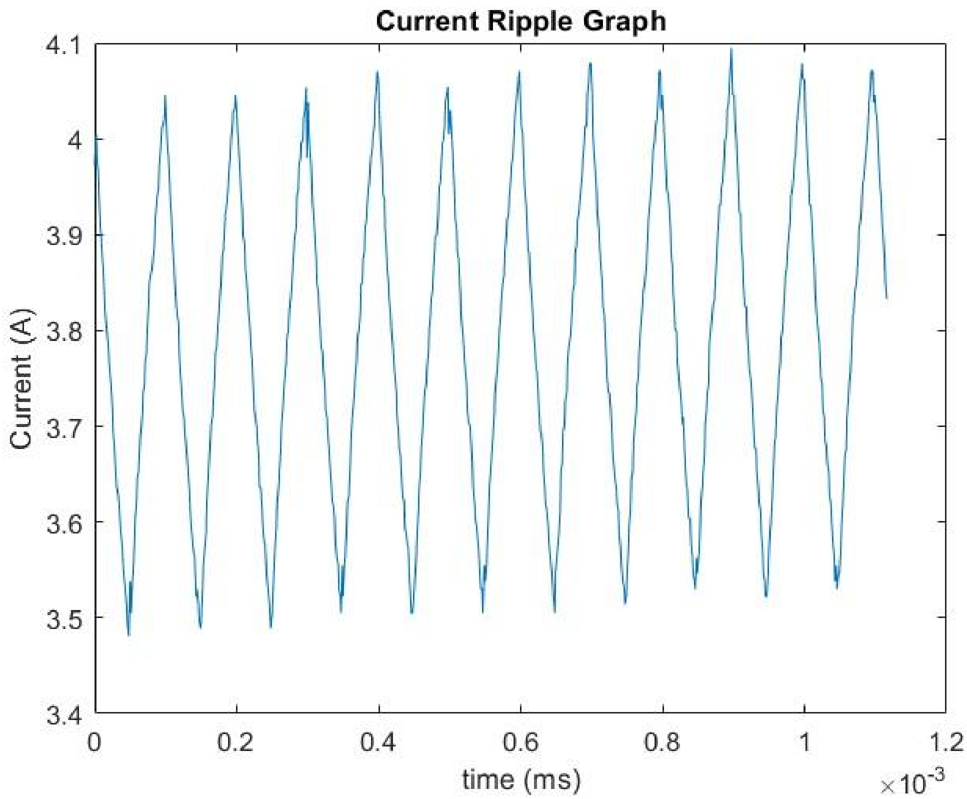

From the above graphs, it is evident that a higher switching frequency decreases the current ripple.

4) The combined efficiency of the motor and inverter is the lowest among all the components. This result suggests that the efficiency of the inverter is constrained by the efficiency of the motor. Moreover, as the load increases, additional losses in the form of power come into the act, which results in a decrease in efficiency.

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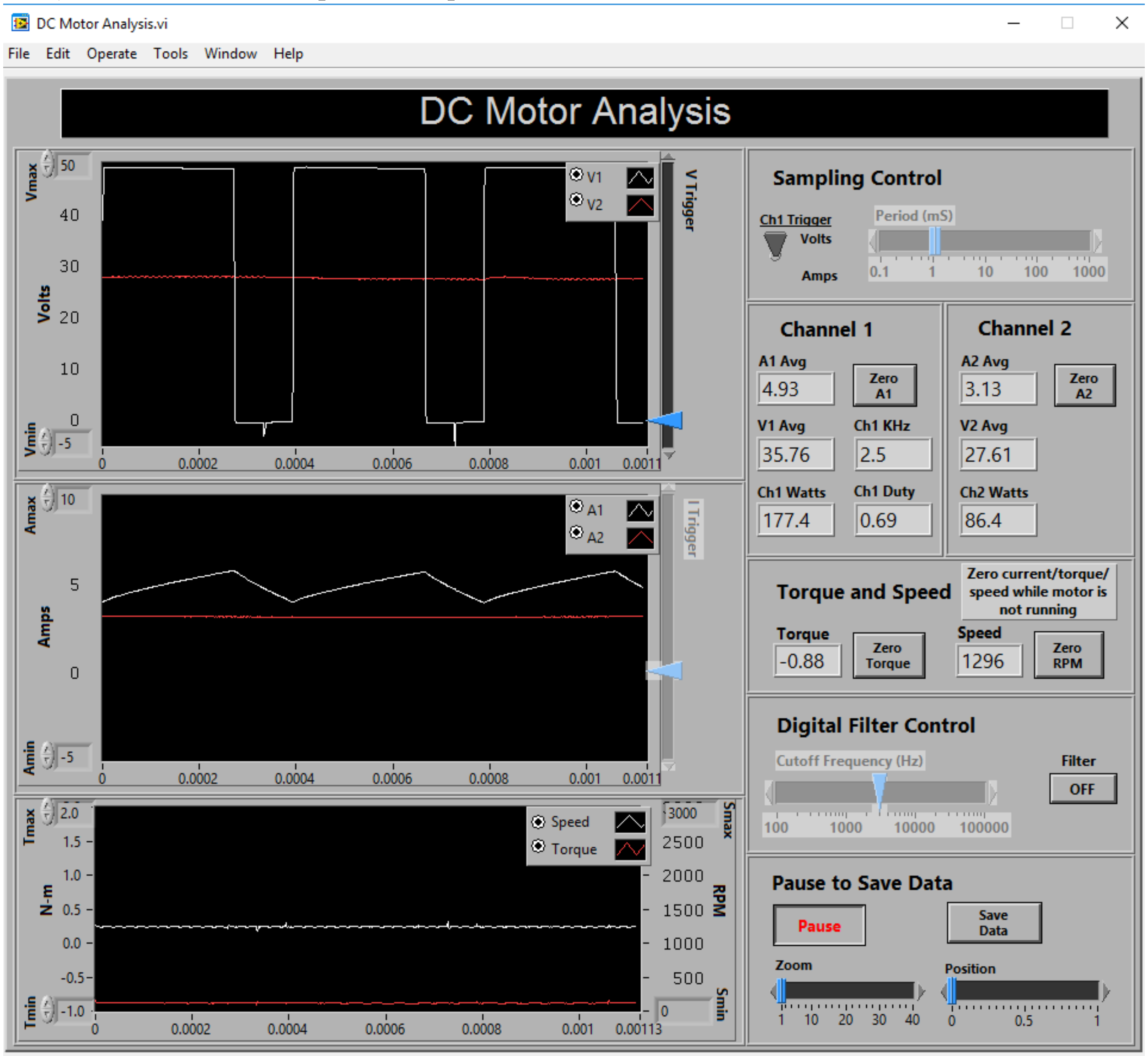
5) Task 4B Forward Operation capture:



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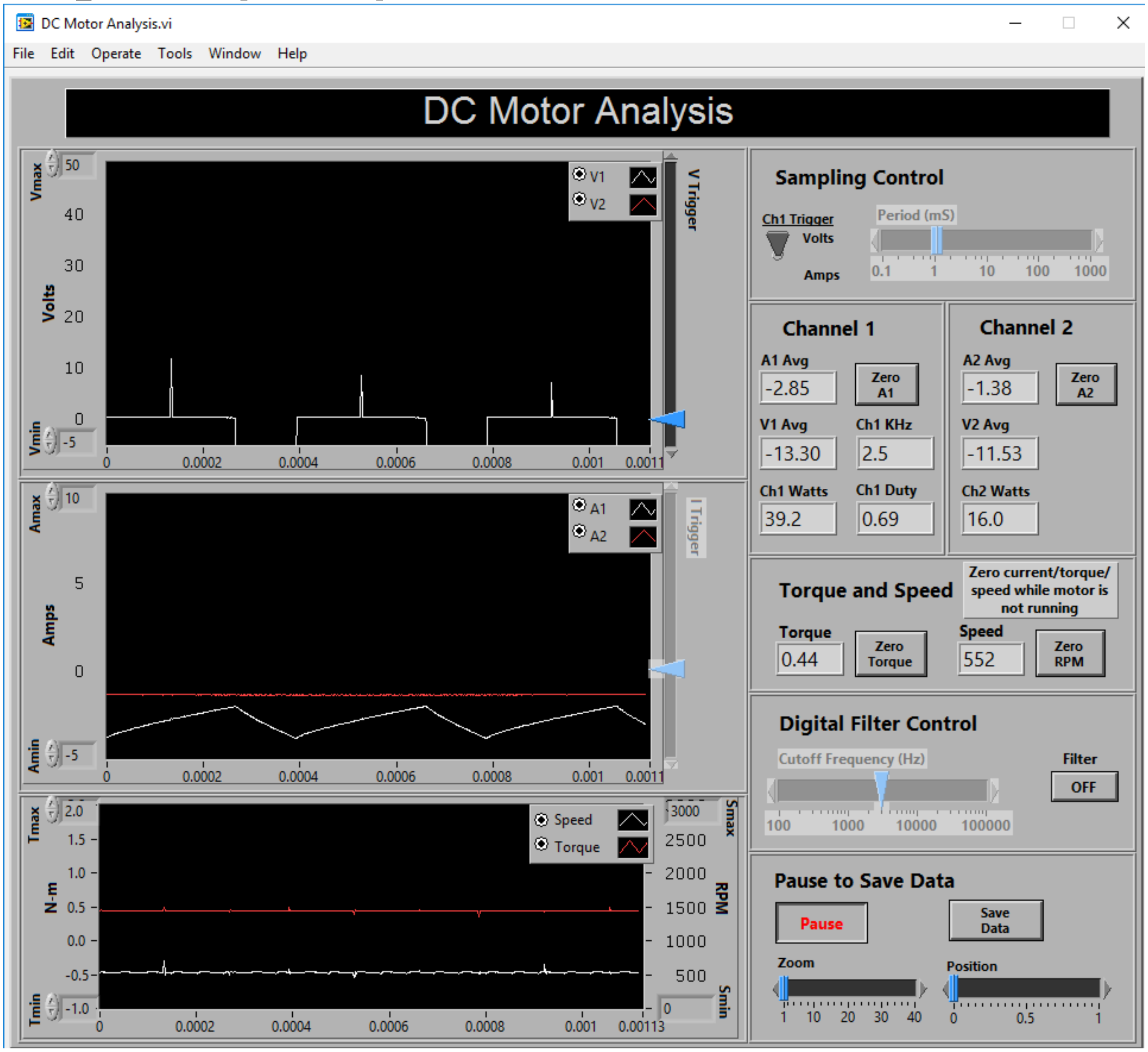
Task 4_B Reverse Operation Capture:



From the captured waveforms, we can observe that Voltage And Current during the forward operation are positive while it gets to the negative side in reverse operation. but the peak values are similar for both graphs.

Summary:
In this laboratory, a significant amount of time was dedicated to exploring different motor configurations and methods of operation. Throughout the course of our work, we gained an understanding of several important concepts, such as conducting tests to measure a motor's performance under different conditions, adjusting motor speed through changes in voltage, duty cycle, and resistance, estimating moment of inertia, calculating various constants and equations relevant to motor comparisons, and creating equivalent motor models in Simulink for simulation purposes. Overall, this laboratory provided us with valuable insights into the behavior of motors and equipped us with the knowledge necessary to make informed decisions about motor selection and characteristics in future projects, research, and employment opportunities.

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Appendix

Matlab Code for Task 5A:

```
clear all;
clc;

%%% Task 5A_3 %%%
T_fric = [0.172131798   0.204263067 0.224918883 0.236394336 0.243279608
0.245574699];
n = [209    443    725    979    1266   1602];
figure(6)
plot(n, T_fric, 'Linewidth', 2);
xlabel('n (rpm)');
ylabel('T_{fric} (N*m)');
title('Friction Torque vs Motor Speed Graph (No-Load)');

%%% Task 5A_4 %%%
in_data = importdata('TASK1_C.data');
Ea = in_data.data(:,2);
time = in_data.data(:,1);
kt = 0.229509064;
figure(1)
plot(time,Ea);
xlabel('time (ms)');
ylabel('Ea (V)');
title('Stopping Transient of Ea');
figure(2)
plot(time,Ea*60/(2*pi*kt));
xlabel('time (ms)');
ylabel('Wr (rpm)');
title('Stopping Transient of Wr');

%%% Task 5A_5 %%%
task1d_data = importdata("task_1d");
Ea = task1d_data.data(:,2);
time = task1d_data.data(:,1);
kt = 0.2178;
figure(3)
plot(time,Ea);
xlabel('time (ms)');
ylabel('Ea (V)');
title('Stopping Transient of Ea for Coupled Machines');

%%% Task 5A_6 %%%
task3a_data = importdata("task3b_data");
I_1 = task3a_data.data(:,4);
time = task3a_data.data(:,1)./1000;
V1 = task3a_data.data(:,2);
Kv = 0.22502;
Wr = task3a_data.data(:,6).*(2*pi/60);
n = task3a_data.data(:,6);
avg_n = mean(n)
avg_I_1 = mean(I_1)
didt = diff(I_1) ./ diff(time)
VLa = V1 - Kv .* Wr
didt_mean = mean(abs(didt))
La = abs(VLa(1:end-1)) ./ didt_mean
format long
```


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```
La_final = mean(La)
%more accurate version
VLa_2 = V1 - Kv .* Wr - I_1*0.7395;
La_2 = abs(VLa_2(1:end-1)) ./ didt_mean;
format long
La_2_final = mean(La_2);
figure(4)
plot(time, I_1);
xlabel('time (ms)');
ylabel('Current (A)');
title('Current Ripple Graph');

%%% Task 5A_8 %%%
Tm = [0.25 0.39 0.59 0.72 0.85 1.12];
n = [172,436,717,950,1207,1749];
figure(5)
plot(n, Tm);
xlabel('Speed (rpm)');
ylabel('T_{m-load} (N*m)');
title('Mechanical Load Torque vs Speed');
```


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