ELEC 342

Lab Experiment: 4

Section: L1B & L1D

Bench #: N/A

Partners	Student ID	% participation	Signatures
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Date Performed: 9/11/2020

Date Submitted: 16/11/2020

1. Data and Parameters

1.0 Setting-Up the Experimental Part

Table 1: Motor Nameplate Information and Nominal Characteristics

Info/ Parameter	Nominal/Rated Value	Comments
NEMA Class	B	
Horse Power	0.25	
Speed	1750 rpm	
Number of Poles	4	See Table in Module 5 Notes for n = 1750
Line Current	6.6 A	Assume motor is composed of 2 windings, internally connected in parallel
Line Voltage	34 V	
Calculations corresponding to full load		
Efficiency	73.59%	See Table 6
Power Factor	0.4304	PF = P_NL/(I_NL*V_NL), See Table 4

How can you explain the voltage and current information? Briefly explain why the motor has two sets of values.

- This motor is internally connected in parallel and is composed of two windings, therefore having two sets of values.

Table 2: Nominal/rated phase voltage and current assuming Y-connected winding

V_1(rms), V	I_1(rms), A
19.6299	6.6

Table 3: Stator winding DC resistance measurement (Do not exceed 5A dc current)

	Measurements (line-to-line)		Calculation
Using DC source	V_{DC}, V	I_{DC}, A	$R_{1,DC} = 0.5V_{DC}/I_{DC}$, Ω
	1.7	4.07	0.2088
Using Multimeter	R_{total}, Ω		$R_{1,DC} = 0.5R_{total}$, Ω
	0.4 - 0.04 = 0.36		0.18

1.1A Task 1A: Measuring No-Load Rotational Losses

Table 4: No-load measurement (motor is free-spinning)

Average phase voltage **V_{NL}(rms), V**	Average phase current **I_{NL}(rms), A**	Average phase power factor angle **φ_{NL}, deg**	Total real power **P_{NL}, W**	Calculate rotational losses **P_{rot}, W**
20.05	6.2	-81.7	53.5	29.4212

1.2 Task 2: Blocked-Rotor Test

Table 5: Blocked-rotor measurement (motor is not spinning)

Average phase voltage **V_{BR}(rms), V**	Average phase current **I_{BR}(rms), A**	Average phase power factor angle **φ_{BR}, degrees**	Total real power **P_{BR}, W**	Stall torque **T_{BR}, N·m**
4.6	6.95	-54.4	55.8	0.07

1.3A Task 3A: Load Characteristic - Speed Regulation under Nominal Voltage

Table 6: Load test measurement (Task 3A): (under nominal voltage, 20-23V)

Measurement #	**1**	**2**	**3**	**4**	**5**	**6**	**7**
V_{ph}(ave, rms), V	20.18	20.18	20.17	20.14	20.17	20.16	20.18
I_1(ave, rms), A	6.32	6.53	6.75	7.01	7.37	7.68	7.85
φ_{pf} (ave), degrees	-77.2	-72.2	-67.4	-63.4	-59.4	-56.1	-54.6
P_{in}(total), W	86	122	157	191	226	258	275
n, rpm	1762	1755	1748	1742	1736	1729	1726
T_m,N·m	0.17	0.34	0.53	0.7	0.88	1.04	1.12
Calculations (w_syn = 183.2596)							
P_m, W	31.37	62.49	96.99	127.69	159.98	188.30	202.38
s (slip)	-0.0069	-0.0029	0.0014	0.0046	0.008	0.012	0.014
Using last measurement, calculate SR **SR = $(n_1-n_{7,load})/n_{7,load}$**				0.0139			
Using last measurement, calculate efficiency of the motor **$\eta = P_m/P_{in}$, %**				73.59%			

1.3B Task 3B: Speed Control by Adjusting Voltage

Table 7: Motor speed control by varying voltage (Task 3B): (motor may stall at low voltage)

Measurement #	1	2	3	4	5
V_{ph}(ave, rms), V	20.18	17.05	14.20	12.09	11.29
I_1(ave, rms), A	7.81	7.58	7.97	8.99	9.63
φ_{pf} (ave), degrees	-54.7	-47.5	-40.6	-36.9	-36
P_{in}(total), W	274	263	258	260	262
n, rpm	1759	1740	1704	1647	1684
T_m,N·m	1.14	1.13	1.12	1.10	1.05
Calculations					
P_m, W	209.98	205.90	199.91	189.69	185.11
s (slip)	-0.0051	0.0057	0.026	0.059	0.038
Using last measurement, calculate SR **SR = $(n_1 - n_{last,load})/n_{last,load}$**			0.0392		

1.3C Task 3C: Load Characteristic - Speed Regulation under Low Voltage

Table 8: Load test measurement (Task 3C): (under low voltage, 12-14V)

Measurement #	1	2	3	4	5	6	7
V_{ph}(ave, rms), V	14.12	14.05	14.11	14.13	14.12	14.15	14.10
I_1(ave, rms), A	4.41	4.84	5.41	6.05	6.74	7.48	7.87
φ_{pf} (ave), degrees	-70.8	-61.8	-54.4	-49.7	-44.9	-41.9	-40.5
P_{in}(total), W	62	97.2	133.4	168	202.5	236.6	253.2
n, rpm	1788	1772	1759	1743	1727	1713	1705
T_m,N·m	0.16	0.34	0.51	0.68	0.84	0.99	1.06
Calculations							
P_m, W	29.97	63.12	93.94	124.12	151.94	177.62	189.20
s (slip)	-0.022	-0.013	-0.0051	0.004	0.013	0.021	0.026

1.4A Task 4A: Speed Control by Varying the Frequency

Table 9: VFD (Task 4A): Motor speed control by varying frequency at V_{DC} = 45V

Measurement #	1	2	3	4	5	6
f_{AC}, Hz	10	20	40	60	80	95
$I_{inv.DC}$, A	0.89	1.65	3.59	6.05	9.73	13.88
V_{ph}(ave, rms), V	3.65	7.5	14.94	19.16	19.58	19.58
I_1(ave, rms), A	5.91	6.83	7.58	7.44	9.31	12.91
φ_{pf} (ave), degrees	-60.1	-65.9	-64.31	-52.2	-38.6	-37.4
$P_{in.\,AC}$(total), W	31.7	62.4	144.8	253	412.0	578
n, rpm	291	592	1179	1761	2285	2580
T_m,N·m	0.31	0.45	0.77	1.06	1.34	1.45
s (slip)	0.8337	0.6617	0.3263	-0.0063	-0.3057	-0.4743

Calculations

Calculate values corresponding to different frequencies	Inverter input power P_{inDC}, W	Input power at induction motor terminals P_{inAC}, W	Output mechanical power P_m, W	Efficiency of the inverter P_{inAC}/P_{inDC}	Efficiency of the motor P_m/P_{inAC}
f_{AC} = 10Hz	40.05	31.7	9.45	79.15%	29.98%
f_{AC} = 60Hz	272.25	253	195.48	92.93%	77.26%
f_{AC} = 95Hz	624.6	578	391.76	92.54%	67.78%

2. Calculations and Analysis

2.5A Task 5A: Determining Motor Parameters

1) **Calculate the equivalent circuit parameters (except the rotor resistance, R′₂).**
   - $R1 = \frac{Vdc}{2*Idc} = \frac{1.7}{2*4.07} = 0.2088\Omega$
   - **No-Load Test**
     - $Prot = P_{NL} - 3*R_1 I_{NL}{}^2 = 53.5 - 3*0.2088*6.2^2 = 29.4212W$
     - $Avg\ Phase\ Voltage\ V1 = 20.05V$
     - $Q_{NL} = \sqrt{(3I_{NL}V_1)^2 - P_{NL}{}^2} = \sqrt{(3*6.2*20.05)^2 - 53.5^2} = 369.0725VA$
     - $X1 + Xm = X_{NL} = \frac{Q_{NL}}{3*I_{NL}{}^2} = \frac{369.0725}{3*6.2^2} = 3.2\Omega$
   - **Blocked-Rotor Test**
     - $R_{BR} = R1 + R2' = \frac{P_{BR}}{3I_{BR}2} = \frac{55.8}{3*6.95^2} = 0.3851\Omega$
     - $Avg\ Phase\ Voltage\ V1 = 4.6V$
     - $X_{BR} = X1 + X2' = \sqrt{(V1/I_{BR})^2 - R_{BR}{}^2} = \sqrt{(4.6/6.95)^2 - 0.3851^2} = 0.5383\Omega$
     - $X1 = X2' = \frac{X_{BR}}{2} = \frac{0.5383}{2} = 0.2692\Omega$
     - $Xm = X_{NL} - X1 = 3.2 - 0.2692 = 2.9308\Omega$
     - $R2' = R_{BR} - R1 = 0.3851 - 0.2088 = 0.1763\Omega$

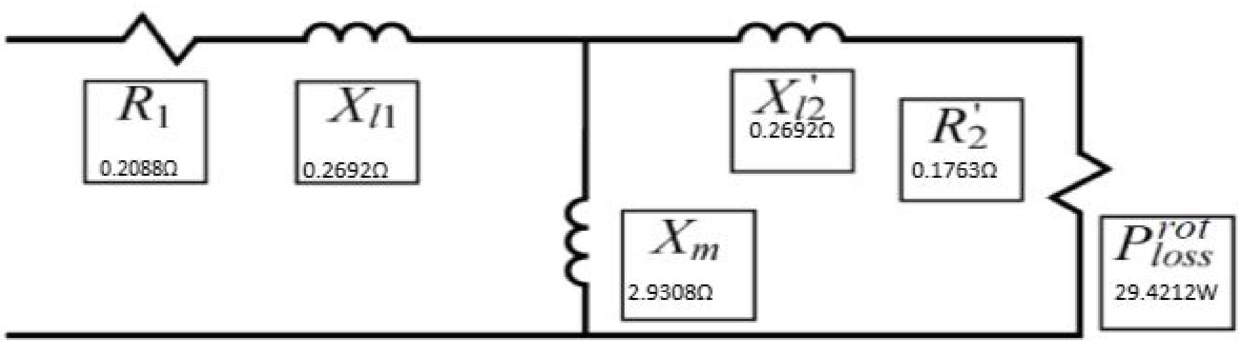

Figure 2.25-1 **Fig. A. Induction Machine Equivalent Circuit. Fill in the corresponding boxes with machine parameters. Make sure to include the units.**

Complete Table 1 for the condition when the motor was loaded to the nominal output power defined by the mechanical speed and torque.

- See Table 1

2) **The rotor resistance can also be estimated from the measured load torque-speed characteristic. In particular, using the equation** $T_e = 3\frac{V_1^2}{\omega_{syn}} \cdot \frac{(R_2'/s)}{(R_{1th}+(R_2'/s))^2+(X_{1th}+X_2')^2}$ **, it can be noted that at very small values of slip the torque is almost linearly/proportional to slip and may be approximated as** $T_e \approx 3\frac{V_1^2}{\omega_{syn}} \cdot \frac{(R_2'/s)}{(R_2'/s)^2} = 3\frac{V_1^2}{\omega_{syn}} \cdot \frac{s}{R_2'}$ **. Based on this approximation, a new value for R'_2 can be calculated using several points from the measured load torque-speed characteristic. Calculate this value and compare it to the value found in part 1).**

- Assume Te = Tm
- n_syn = 1750 rpm, w_syn = 183.2596 rad/sec
- Since Torque slip s is very small: $T_e = Tm \approx 3\frac{V_1^2}{\omega_{syn}} * \frac{s}{R_2'}$
- Using Measurement 7 of Table 6: $1.12 = 3 * \frac{20.18^2}{183.2596} * \frac{0.014}{R_2'}$ $R2' = 0.08333\Omega$

Choose one that in your opinion is more accurate, state and justify your choice and write it in Fig. A.

- R2' = 0.1763 is more accurate than R2'= 0.08333 as it is a closer value to R1 = 0.2088 Ω, and is also more related to the other components calculated from the equivalent circuit.

2.5B Task 5B: Equivalent Circuit vs. Measured Comparison

1) **Use the per-phase equivalent circuit of Induction Machine (Fig. A) and calculate the torque-speed characteristic $T_e(n)$ using the voltage from Table 6. Use about 15 to 25 equally-spaced (from 0 to 1800 rpm) points and superimpose on the same plot both calculated (theoretical) characteristic, as well as the measured characteristic from Table 6.**

- $T_e = 3\frac{V_{1th}^2}{\omega_{syn}} \cdot \frac{(R_2'/s)}{(R_{1th}+(R_2'/s))^2+(X_{1th}+X_2')^2}$
- $V_{1th} = \frac{X_m V_1}{\sqrt{R_1^2+(X_{l1}+X_m)^2}} = 18.43V$
- $Z_{1th} = \frac{jX_m(R_1+jX_{l1})}{R_1+j(X_{l1}+X_m)} = 0.1744 + 0.2579j\ \Omega$
- $R_{1th} = 0.1744\ \Omega$ & $X_{1th} = 0.2579\ \Omega$

- Since slip is very small as n approaches 1800 rpm, measured T_m from Table 6 can be treated as T_e.

Provide two plots: one with the scale from 0 to 1800 rpm, and the second one where you zoom-in to show all the measured points. Comment on the results.

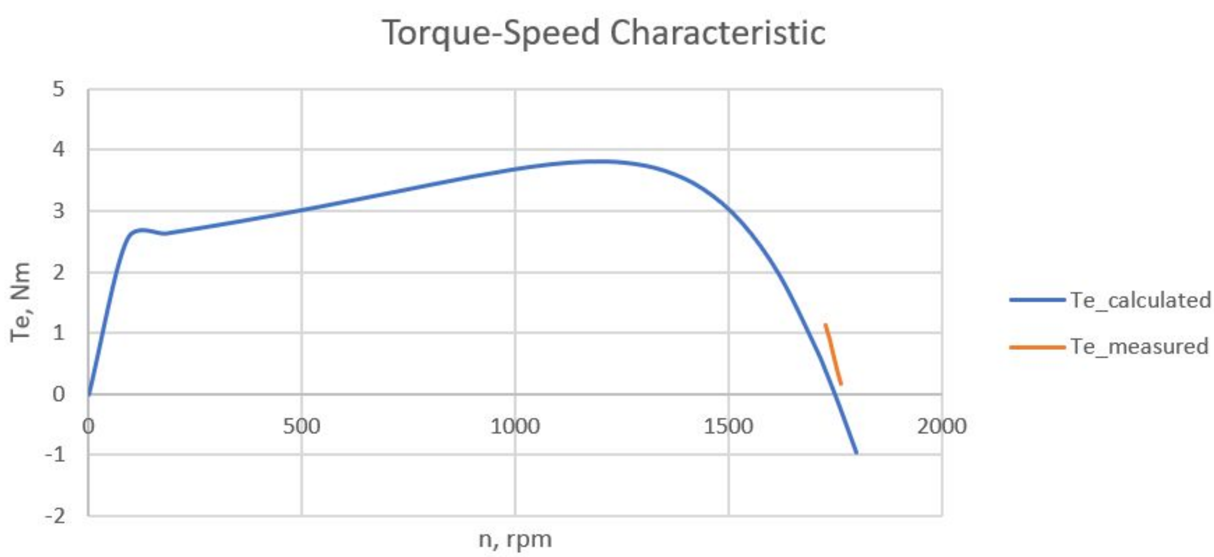

Figure 2.25-2 Torque-Speed Characteristic using measurements in Table 6

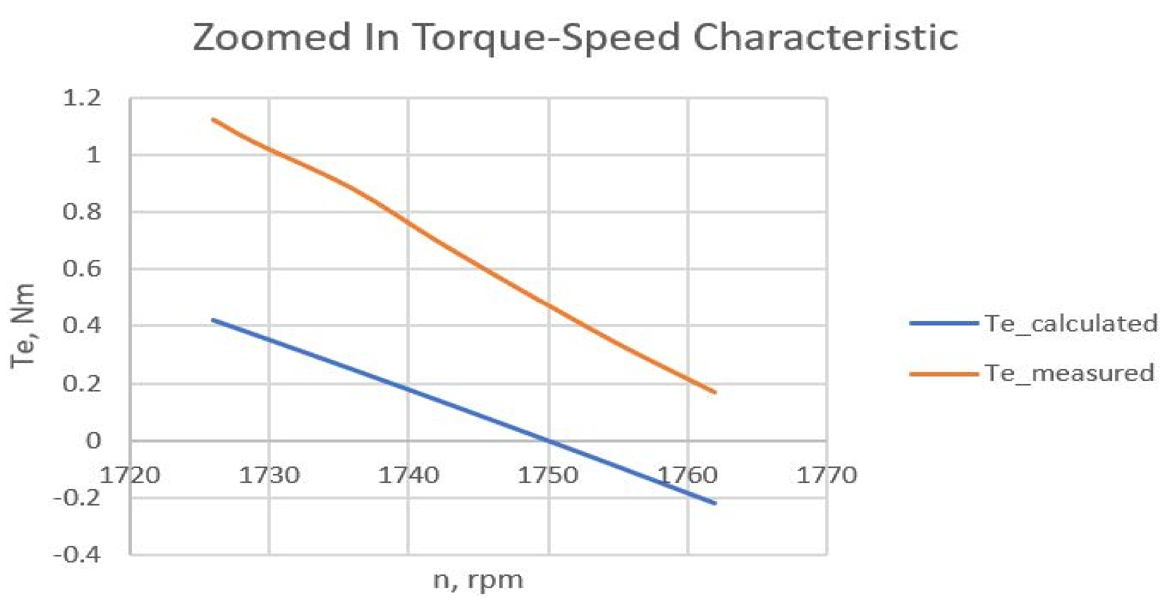

Figure 2.25-3 Zoomed In Torque-Speed Characteristic

- For values of n that were measured in the lab, the calculated values of torque are generally lower than the measured values, but they follow the same linear trend of decreasing with increasing n.

2) Using the data in Table 6, calculate the motor efficiency as a function of the torque $\eta(T_m)$.

- $\eta = \frac{P_{out}}{P_{in}} = \frac{T_m\omega_r}{P_{in}} = \frac{1.12*1726\pi}{30*275} = 0.7361 = 73.61\%$ (using the last measurement point from Table 6)

Then, calculate the same characteristic using the equivalent circuit.

- $P_{in} = 3V_1 I_1 cos(\varphi) = 3 * 20.18 * 7.85 * cos(-54.6) = 275.3\ W$
- $P_{ag} = 3I_2'^2\frac{R_2'}{s} = 3 * 2.62^2 * \frac{0.1763}{0.014} = 259.33\ W$
- $P_m = P_e - P_{rotational\ loss} = P_{ag}(1-s) - P_{rotational\ loss}$
  $= 259.33(1-0.014) - 29.4212 = 226.28W$
- $\eta = \frac{P_{out}}{P_{in}} = \frac{P_m}{P_{in}} = \frac{226.28}{275.3} = 82.19\%$

Plot/superimpose the two curves: one calculated using the measured data, and one calculated using the equivalent circuit. Comment on the results.

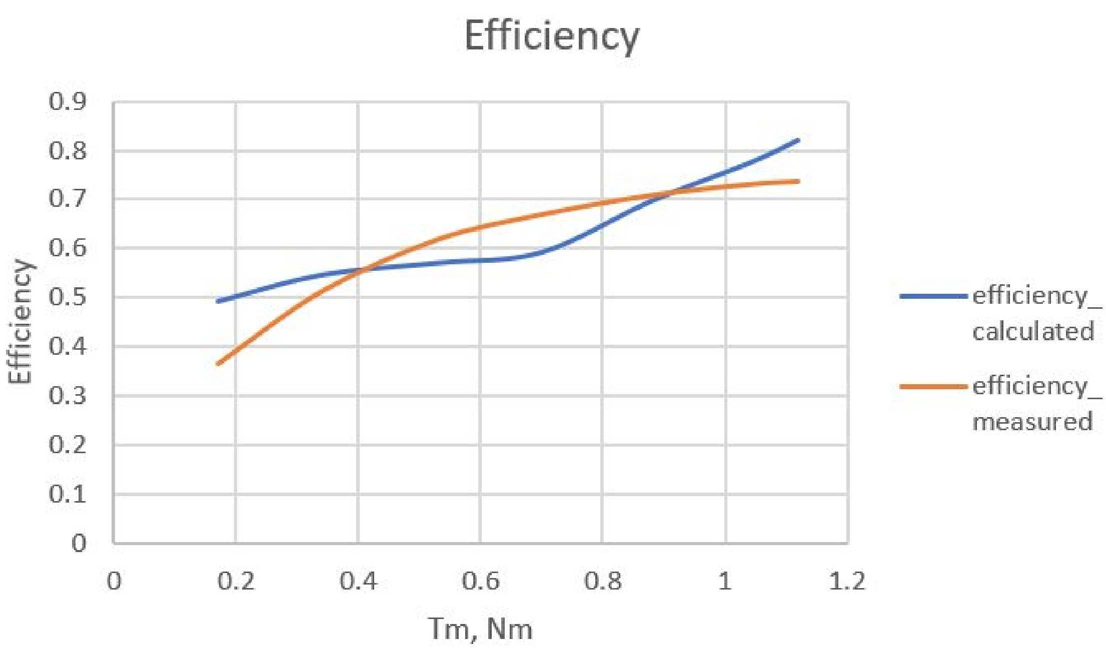

Figure 2.25-4 Efficiency vs Tm

3) Using the data in Table 6, plot the motor power factor as a function of the torque PF(T_m). Show two curves: one calculated using the measured data, and one calculated using the equivalent circuit. Comment on the results.

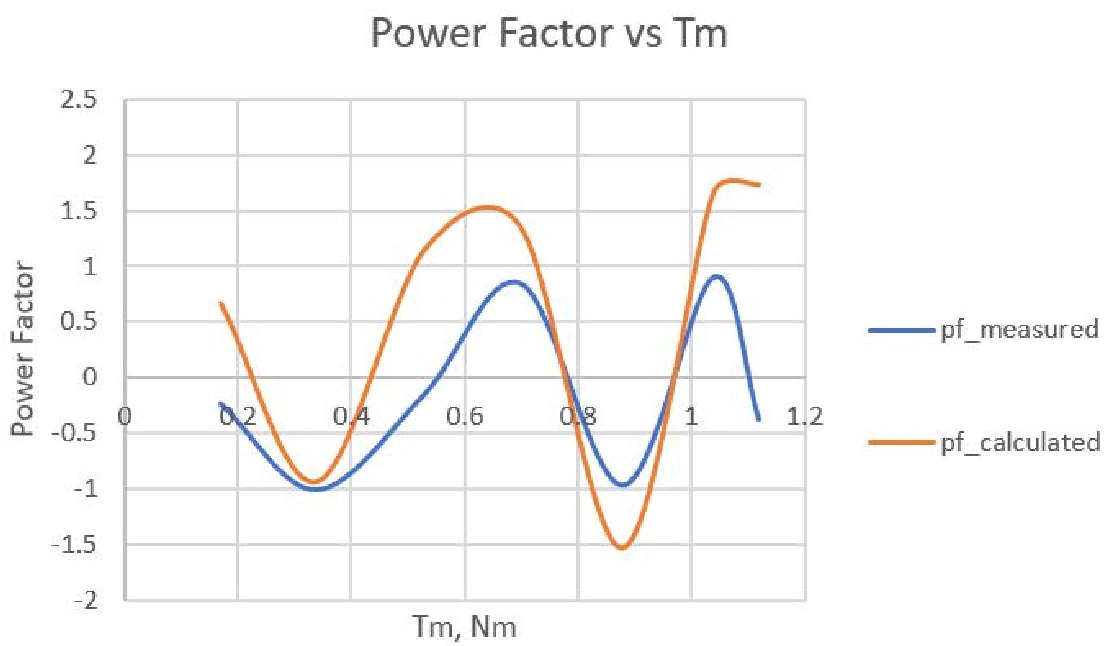

Figure 2.25-5 PF vs Tm

- From the graph, the measured power factor from Table 6 follows a sine wave trend where the calculated values are a bit off but still have the sine wave shape.

4) Find the maximum and the minimum voltages for which you took measurements in Table 7.

- Maximum voltage: 20.18V
- Minimum voltage: 11.29V
- See Table 7

For these two voltages, plot two theoretical torque-speed characteristics using equation $T_e = 3\frac{V_{1th}^2}{\omega_{syn}} \cdot \frac{(R_2'/s)}{(R_{1th}+(R_2'/s))^2+(X_{1th}+X_2')^2}$ and the equivalent circuit parameters. Superimpose both plots on the same graph with data points corresponding to the measured speed and torque in Table 7. Make comments on the speed regulation.

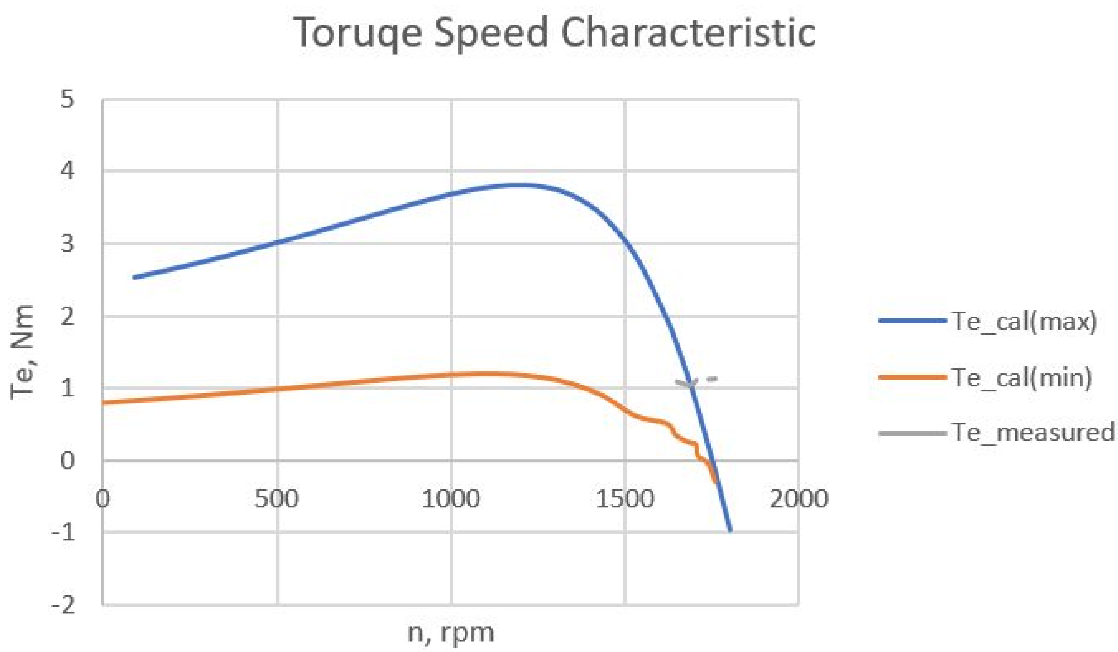

Figure 2.25-6 Torque Speed Characteristic using measurements in Table 7

- Both calculated values of torque have similar shapes where the torque corresponding to the minimum voltage measured in Table 7 has small fluctuations for bigger speed n.

5) **What can you say and conclude about the accuracy of equivalent circuit compared to your measurements?**

    - The accuracy of the equivalent circuit compared to the measurements is quite good, as the motor/constant value is near that of the one obtained from measured values, and the component values are consistent with the measured data

2.5C Task 5C: Starting Transients

1) **First, on one graph plot the voltage and current saved in Task 1 B. Then, plot on another graph the phase voltage and current recorded in Task 1C.**

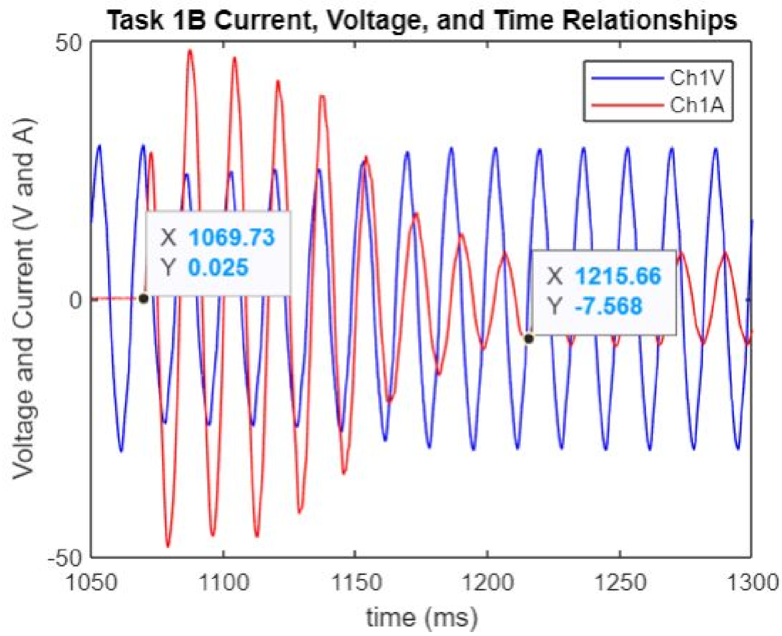

Figure 2.5-7: Task 1B Current, Voltage, and Time Relationships

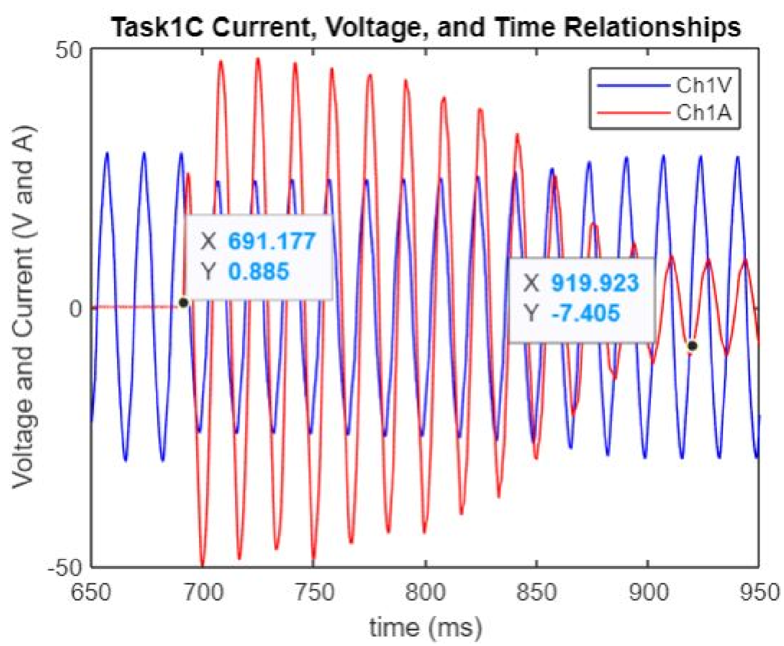

Figure 2.5-8: Task 1B Current, Voltage, and Time Relationships

- See Appendix B for Matlab Code

2) **Show how long the transient lasts in each case.**

- In Task 1B from Figure 2.5-1, the transient lasts approximately: $t_{trans,B} = 1215.66 - 1069.73 = 145.93\ ms$
- In Task 1C from Figure 2.5-e, the transient lasts approximately: $t_{trans,C} = 919.923 - 691.177 = 228.746\ ms$

Write your conclusion to why this may represent a problem for the remaining power network. Extrapolate your conclusions to large induction motors on industrial sites.

- As the ratio of inrush current can range from 5 to 100 times that of its normal full-load current, the surge can cause component damage and failure within the equipment, including blown fuses and tripped circuit breakers. For large induction motors on industrial sites, this may also severely limit the number of devices connected to a common power source

3) **Based on the equivalent circuit parameters that you have determined (see Fig. A) and the recorded voltage and current transients in Task B and C, determine/estimate the impedance Z of the AC power supply.**

- Using the equivalent circuit parameters to find equivalent (input) impedance:
  - $Z1 = R1 + jX1 + \frac{jX_m(R2'/s + jX2')}{R2'/s + j(Xm + X2')}$
  - $Z1 = 0.2088 + j0.2692 + \frac{j2.9308\ (0.1763\ /\ 1 + j0.2692)}{0.1763\ /\ 1 + j(2.9308 + 0.2692)} = 0.2867 < 1.225\ \Omega$
- Using the recorded voltage and current transients to find total impedance:
  - From Figures 2.5-3 and 2.5-4, $Z1 = \frac{V1}{I1} = \frac{24.311}{47.253} = 0.5145\ \Omega$
- AC power supply impedance:
  - $Z = Z_{total} - Z_{input} = 0.5145 - 0.2867 = 0.2278\ \Omega$

2.5D Task 5D: Variable Speed Operation

1) **What are the advantages and disadvantages of controlling the Induction Motor speed using the method of Task 3B? Briefly explain.**

- Task 3B controls the speed by adjusting the input Voltage. This method allows a large range of speeds and is highly efficient, however requires the use of power electronics to vary the input Voltage and the frequency.

2) **What are the advantages and disadvantages of controlling the Induction Motor using the VFDs based on your experience in Task 4?**

   - Task 4 operates the Induction Motor using the VDF to modulate AC output with variable frequency and amplitude with the Constant Torque Operation control mode. The VFD allows for a smoother start, acceleration, and deceleration time, with more efficient stopping method and reversal of motor. Harmonics are reduced, and power factor is increased. There are little disadvantages to using VFD, however at lower frequencies, the motor power efficiency drops considerably. Furthermore, harmonics can cause overheating of transformers and the motor, causing fuses to blow and circuit breakers to trip.

3) **Consider the chain of the components that you had in Task 4 including the following: AC Source, VFD, Induction Machine, Mechanical Coupling, Mechanical Load. Take one measurement in Task 4 and assign the energy conversion efficiency at each energy conversion stage in the above chain (Complete Table 9).**

   - At f = 60 Hz:
     - $P_{inDC} = V_{DC} * I_{invDC} = 45 * 0.89 = 272.25\ W$
     - $s = \frac{(n_{syn} - n_r)}{n_{syn}} = \frac{(1750-1761)}{1750} = -0.0063$
       $\omega_{rm} = \omega_{syn} * (1 - s) = 183.26 * (1 + 0.0063) = 184.41\ rad/s$
     - $P_m = T_m * \omega_{rm} = 1.06 * 184.41 = 195.48\ W$
     - Into VFD: 100% of AC Source Power
     - Into Induction Machine: $P_{inAC}/P_{inDC} = \frac{253}{272.25} = 92.93\%$
     - Additional Losses:
       - For Stator Copper Losses:
         $P_{SCL} = 3 * I1^{2} * R1 = 3 * 7.44^{2} * 0.2088 = 34.6735\ W$
       - Into Mechanical Coupler:
         $\eta_{couple} = \frac{P_{inAC} - P_{SCL}}{P_{inAC}} = \frac{253-34.6735}{253} = 86.29\%$
     - Into Mechanical Load: $\eta_{load} = P_m/P_{inAC} = \frac{195.48}{253} = 77.26\%$
   - See Appendix A for Energy Conversion Efficiency Chain of Components Diagram

   Comment on where most of the energy is being lost and how the efficiency changes with motor speed and frequency.

   - Most of the efficiency is lost at the Mechanical Coupling stage, where only 77.26% of the Power proceeds to the Mechanical Load.
   - As we move away from the designed frequency or frequency is lowered, the speed and motor power efficiency drops considerably.

3. Conclusion

This lab explored the characteristics of a small industrial ¼ HP 34V Induction Motor by identifying its equivalent circuit parameters. The start up transient was observed as the motor was connected to a 60 Hz AC source and started from stall, and its load characteristics when supplied from a fixed frequency 3-phase AC source were determined.The motor speed was controlled by adjusting the source voltage magnitude at a fixed frequency, and motor control was demonstrated using Variable Frequency Drive (VFD) in a wide range of speeds below and above the nominal speed in order to observe the energy conversion efficiency of different stages as the motor is driven by the VFD. Finally, the Induction Motor's equivalent circuit parameters of the per-phase steady-state were calculated and analysed assuming a symmetric Y-connected winding. This model was used to successfully predict torque-speed and load characteristics, comparing them to the measured data.

Appendix A: Chain of Components

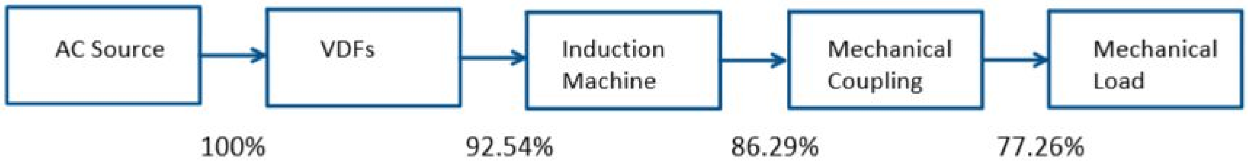

Figure 4-1: Task 4 Chain of Components Energy Conversion Efficiency at f = 60 Hz

Appendix B: Task 5C Matlab Code Transient Plots

```
task1B = importdata("Task1B.txt");
task1C = importdata("Task1C.txt");

Btime = task1B.data(:,1);   %time in ms
BV1 = task1B.data(:,2);
BI1 = task1B.data(:,5);

Ctime = task1C.data(:,1);   %time in ms
CV1 = task1C.data(:,2);
CI1 = task1C.data(:,5);

figure(1);                  %plot
%subplot(2,1,1);
plot(Btime, BV1,'b',Btime, BI1,'r');
set(gca,'XLim',[1050 1300]);
set(gca,'YLim',[-50 50]);
%set(gca,'XTick',[0 1 2 3])
xlabel('time (ms)');
ylabel('Voltage and Current (V and A)');
title('Task 1B Current, Voltage, and Time Relationships');
legend('Ch1V','Ch1A')

figure(2)
%subplot(2,1,1);
plot(Ctime, CV1,'b', Ctime, CI1,'r');
set(gca,'XLim',[650 950]);
set(gca,'YLim',[-50 50]);
%set(gca,'XTick',[0 1 2 3])
xlabel('time (ms)');
ylabel('Voltage and Current (V and A)');
title('Task1C Current, Voltage, and Time Relationships');
legend('Ch1V','Ch1A')
```