ELEC 342

Lab Experiment: Lab-5: Synchronous Machine-Car Alternator

Section: L1B & L1D

Partners	Student ID #	% participation	Signatures
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Date Submitted: 30/11/2020

1. Data and Parameters

1.1 Task 1: Measuring the DC Resistance of Field and Stator Windings

Table 1: DC Resistance Measurement

<table>
<tr><td colspan="3">Stator phase resistance R_S, Ω</td><td colspan="3">Field winding resistance R_f, Ω</td></tr>
<tr><td colspan="2">Using DC source</td><td>Multimeter</td><td colspan="2">Using DC source</td><td>Multimeter</td></tr>
<tr><td>V_{dc}, V</td><td>I_{dc}, A</td><td rowspan="2">0.175- 0.04=0.135</td><td>V_{dc}, V</td><td>I_{dc}, A</td><td rowspan="2">3.5- 0.04=3.46</td></tr>
<tr><td>1.2</td><td>6.32</td><td>6.4</td><td>2.05</td></tr>
<tr><td colspan="2">Calculate R_S, Ω</td><td>0.0949</td><td colspan="2">Calculate R_f, Ω</td><td>3.12</td></tr>
</table>

Explain and state which values you will be using for the equivalent circuit:

- For the equivalent circuit, we will be using the calculated Rs and Rf values, as the multimeter values may have been less accurate due to wire resistance and other elements resulting in a higher resistance than calculated.

1.2A Task 2 A: Output Voltage vs. Speed Characteristic

Table 2: Output Voltage vs. Speed Characteristic (keep field current constant at about 2 A)

Measurement #	1	2	3	4	5	6
Field Current $I_f,\ A$	2.01	2.01	2.02	2.04	2.03	2.03
Phase Voltage $V_{s,ph}(ave,\ rms),\ V$	1.84	3.5	7.07	9.77	11.53	14.6
$T_m,\ Nm$	0.35	0.43	0.59	0.69	0.76	0.84
n, rpm	317	607	1235	1711	2000	2587
Frequency $f,\ Hz$	36.9	70.8	144.1	199.8	237.5	302
Calculate rotational losses P_{loss}	11.62	27.33	46.30	123.63	159.17	227.56

1.2B Task 2 B: Open-Circuit Characteristic (OCC)

Table 3: Open-Circuit Characteristic (keep speed constant at about 2000 rpm)

Measurement #	1	2	3	4	5	6
Field Current $I_f,\ A$	0	0.5	1	1.5	2	3
Phase Voltage $V_{s,ph}(ave,\ rms),\ V$	0.69	3.96	7.2	9.72	11.53	13.19
$T_m,\ Nm$	0.11	0.16	0.31	0.52	0.73	0.97
n, rpm keep it constant	2016	2014	2014	2017	2020	2018

1.3 Task 3: Short-Circuit Characteristic

Table 4: Short-Circuit Characteristic (keep speed constant at about 2000 rpm)

Measurement #	1	2	3	4	5	6
Field Current I_f, A	0	0.2	0.4	0.6	0.8	1
Phase Current $I_{s,ph}(ave,\ rms)$, A	1.34	4.31	7.47	10.96	14.44	18.01
T_m, Nm	0.1	0.12	0.17	0.28	0.46	0.69
n, rpm keep it constant	2012	2012	2012	2009	2012	2018

1.4A Task 4 A: Synchronization Procedure

Identify your bench with respect to Fig. B by circling the appropriate words and writing your and your partners' bench numbers below. You should perform this experiment with the group close to you from the left or from the right.

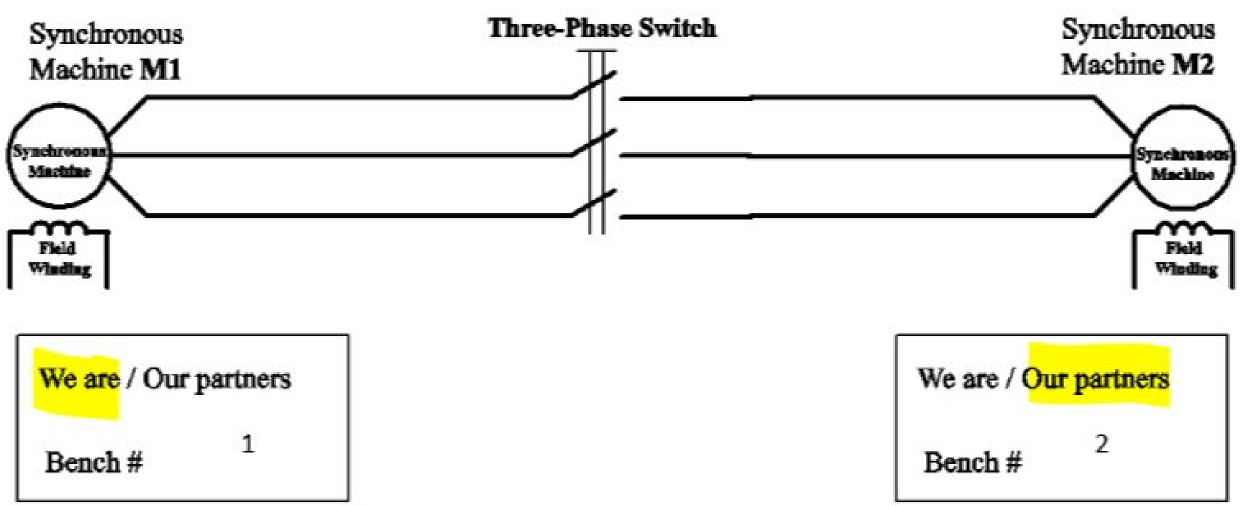


Fig. B. Synchronization test of left and right benches.

1.4B Task 4 B: Power Flow in Synchronized Operation

Table 5: Synchronization and Synchronous Operation

Measurement #	**Column 1** Before Synchronizing	**Column 2** When Synchronized	**Column 3** Increased/ Reduced Excitation	**Column 4** Left Bench DC Motor Off	**Column 5** Right Bench DC Motor Off
Machine M1 (circle we/partners)					
Field Current I_f, A	7.92	1.87	2.46		
Phase Current $I_{s,ph}(ave, rms)$, A	0.1	0.27	3.5		
Phase Voltage $V_{s,ph}(ave, rms)$, V	11.5	11.7	18.2		
Angle δ, deg	X	80	-88		
Total Real Power P_{tot}, W	3	1.8	0		
Calculated Total Reactive Power Q_{tot}, VAR	X	9.33	-190.98		
T_m, Nm	0.64	0.63	0.67		
n, rpm	2060	2101	2080		
Frequency f, Hz	240.2	245	292.7		
Machine M2 (circle we/partners)					
Field Current I_f, A	2.45	2.42	2.41		

Phase Current $I_{s,ph}(ave,\ rms),\ A$	0.1	0.3	3.48		
Phase Voltage $V_{s,ph}(ave,\ rms),\ V$	11.5	11.66	12.19		
Angle $\delta,\ deg$	X	-100	88		
Total Real Power $P_{tot},\ W$	X	X	6		
Calculated Total Reactive Power $Q_{tot},\ VAR$	X	-10.33	127.19		
$T_m,\ Nm$	0.57	0.54	0.62		
n, rpm	2056	2104	2082		
Frequency $f,\ Hz$	240	245.3	242.7		

Briefly record your observation/comments corresponding to each measurement test:

Column 1: Observations and/or Comments:
- Before synchronization
- The voltages and speeds/frequencies on both benches are very close
- Synchronization lamps are slowly flashing
- Angle delta, and real and reactive power are insignificant

Column 2: Observations and/or Comments:
- Synchronize with minimum power exchange
- 3-Phase Switch was turned off as the Synchronization lamps were off, and a transient was observed due to poor timing.
- On the second try, the transient observed was much smaller, as turning the lamps off was timed more accurately

Column 3: Observations and/or Comments:

- Increase and decrease excitation
- One of the alternators is under-excited and the other is over-excited

- The current and voltage waveforms are not quite sinusoidal
- Phase current is increasing, real power is near zero, the current is supplying reactive power, and the phase angle is at -90 degrees

Column 4: Observations and/or Comments:

- N/A

Column 5: Observations and/or Comments:

- N/A

2. Calculations and Analysis

2.5A Task 5 A: Determining Machine Parameters

- **Plot the following characteristics using measurements in Table 2, 3, and 4:**
  - **Open-circuit phase voltage vs. speed $V_{ph,oc,rms}(n)$ at field current 2A**

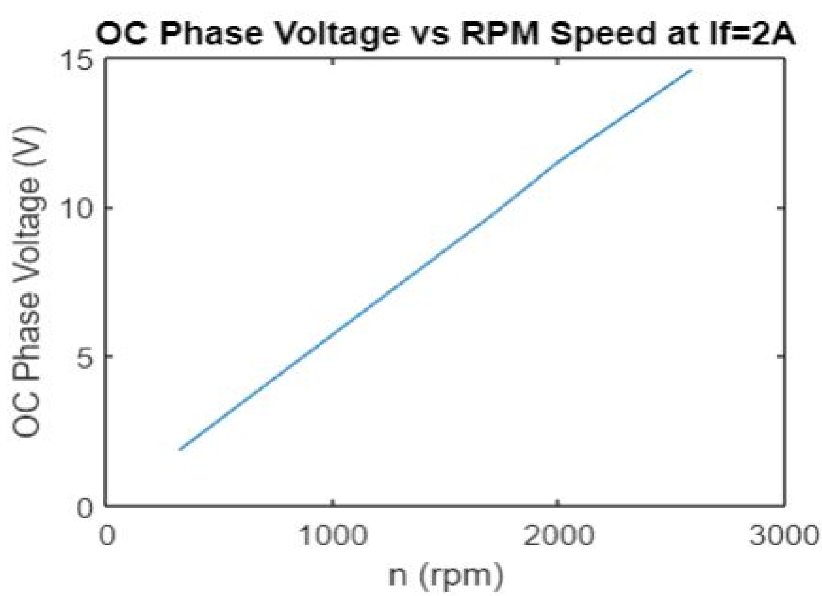


Figure 2.5-1: OC Phase Voltage vs RPM Speed at If=2A

- **Open-circuit phase voltage vs. field current** $V_{ph,oc,rms}(I_f)$ **at speed 2000 rpm**

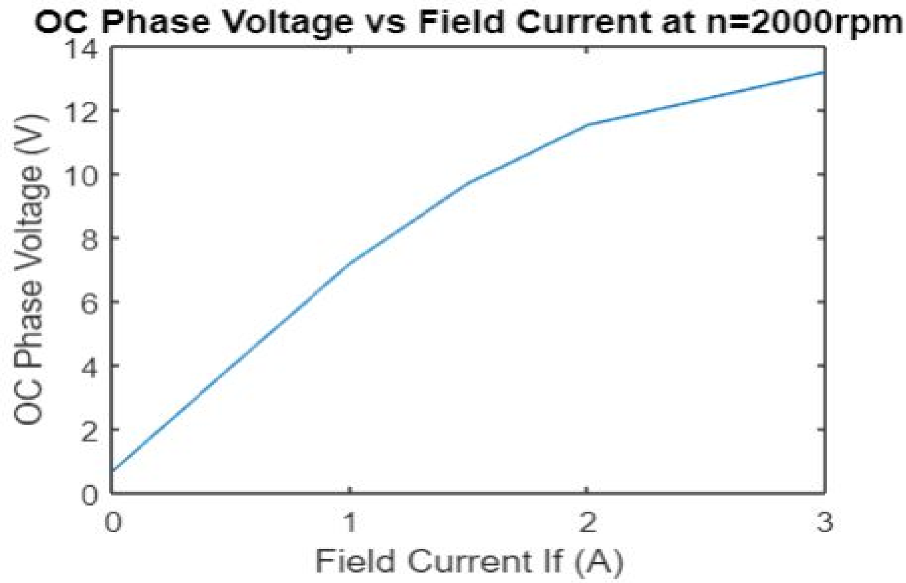


Figure 2.5-2: OC Phase Voltage vs Field Current at n=2000 rpm

- **Short-circuit phase current vs. field current** $I_{ph,sc,rms}(I_f)$ **at speed 2000 rpm**

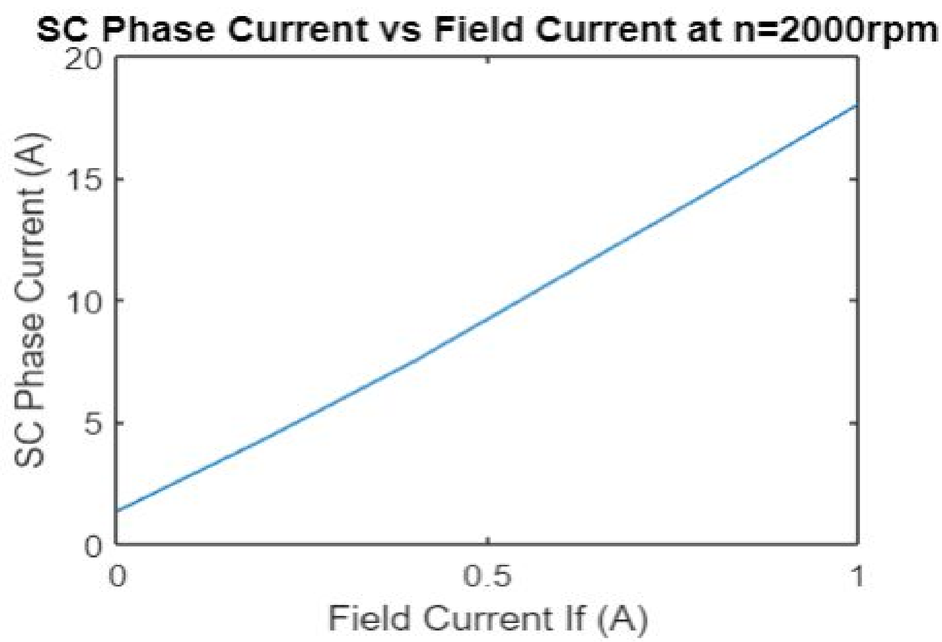


Figure 2.5-3: SC Phase Current vs Field Current at n=2000 rpm

- **Calculate the equivalent circuit parameters and write them down in Fig. A.**

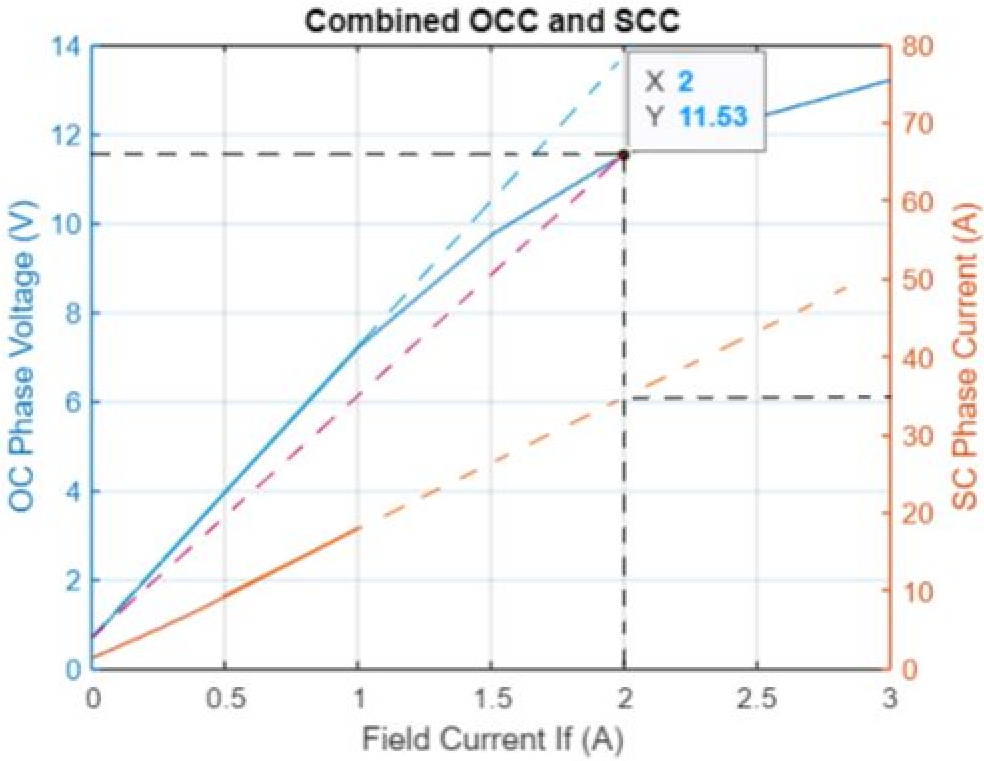


Figure 2.5-4: OCC and SCC Combined Plot

- $R_s = \frac{V_{dc}}{2 * I_{dc}} = 0.09494\ \Omega$
- $R_f = \frac{Vf_{dc}}{If_{dc}} = 3.1219\ \Omega$
- Using Table 2 Measurement 5: $n = 120\,\frac{fe}{P} \quad P = \frac{120*237.5}{2000} = 14$
- Using Table 2 Measurement 5:

  $P_{loss} = T_m * \omega_r = 0.84 * \frac{2000*2\pi}{60} = 175.9292\ W$
- From Figure 2.5-4: $Z_s = \frac{E_{f,\,rated}}{I_s'} = \frac{11.53}{34.54} = 0.3338\ \Omega$

  $X_s = \sqrt{Z_s^2 - R_s^2} = \sqrt{0.3338^2 - 0.09494^2} = 0.32\ \Omega$

  $L_s = \frac{X_s}{\omega_e} = \frac{0.32}{2\pi*237.5} = 0.214\ mH$

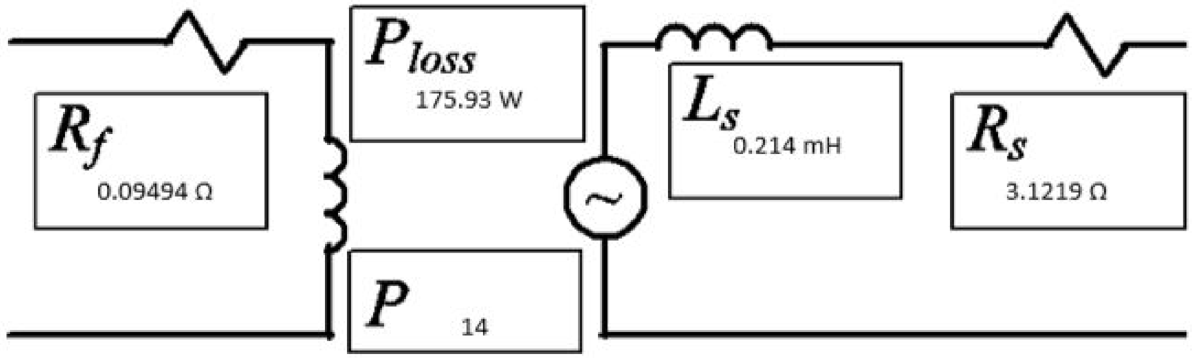


Fig. A. Synchronous Machine Equivalent Circuit. Fill-in the corresponding boxes with machine parameters including the number of magnetic poles P, and the rotational losses P_{loss} (at speed 2000rpm and field current 2A). Include the units.

- **Calculate the value of an equivalent resistor R_{loss} that may be connected in parallel to the back emf voltage source in equivalent circuit of Fig. A and will dissipate the power P_{loss}.**
  - Using Table 2 Measurement 5: $R_{loss} = \frac{P_{loss}}{I_s^2} = \frac{175.9292}{34.54^2} = 0.15\ \Omega$
- **Sketch this modified equivalent circuit in your report**

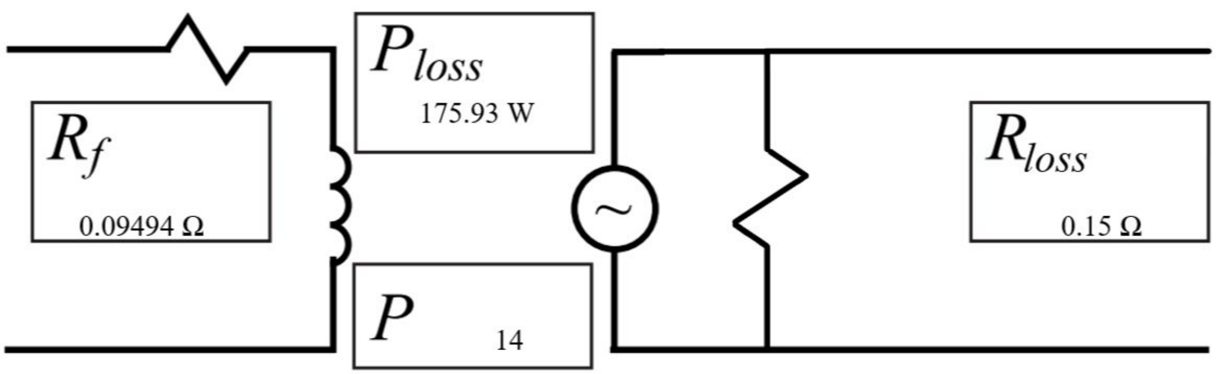
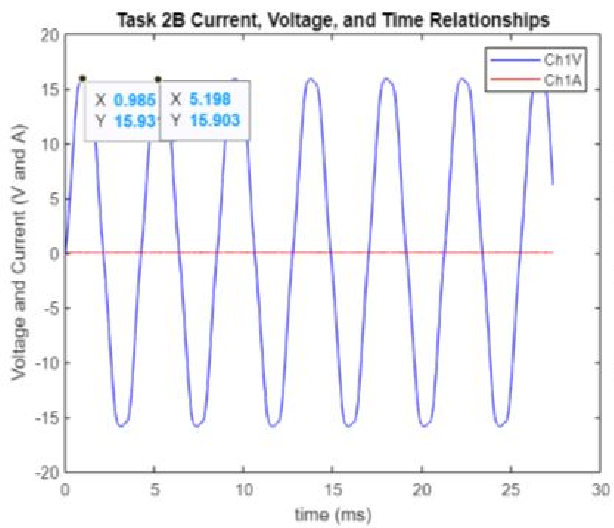


Fig. C. Synchronous Machine Equivalent Circuit with equivalent resistor R_{loss}.

2.5B Task 5 B: Additional Analysis and Questions

- **Plot the saved voltage and current waveforms and show the frequency.**
  - Task 2B Open Circuit Characteristics OCC
    - OCC Period: 5.198-0.985=4.213 ms Frequency: 237.36 Hz
  - Task 3 Short Circuit Characteristics SCC
    - SCC Period: 5.243-1.09=4.153 ms Frequency: 240.36 Hz



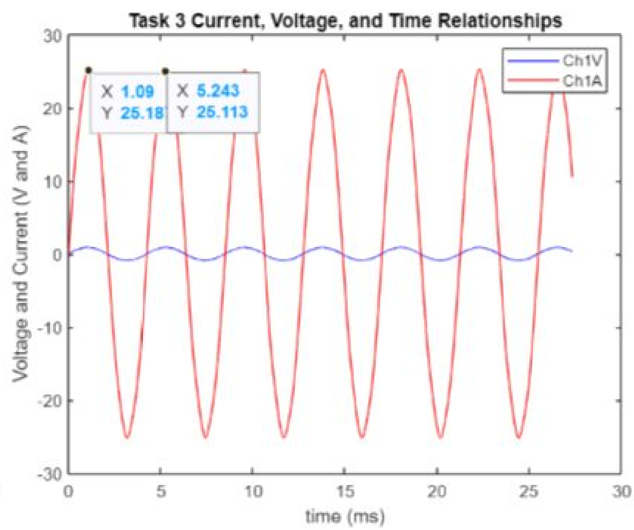
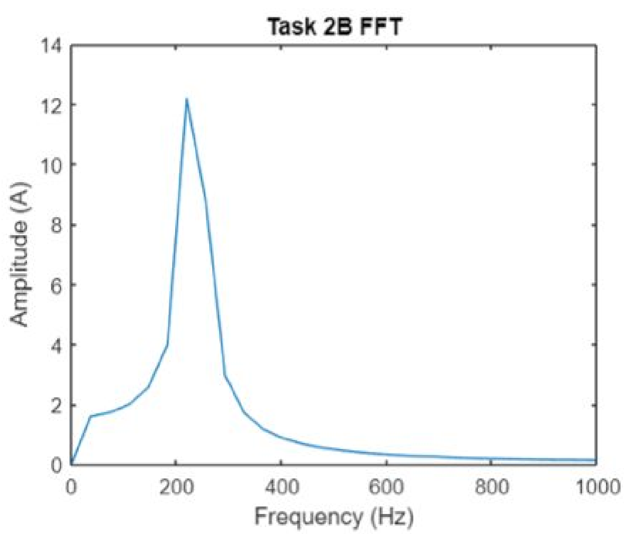


Figure 2.5-5: Open Circuit Characteristics (left) and Short Circuit Characteristics (right)

- **How close are these waveforms to sinusoidal? Calculate and plot the spectrum of harmonics to support your answer.**
  - These waveforms are very close to sinusoidal, as their spectrum of harmonics show very little inconsistencies.



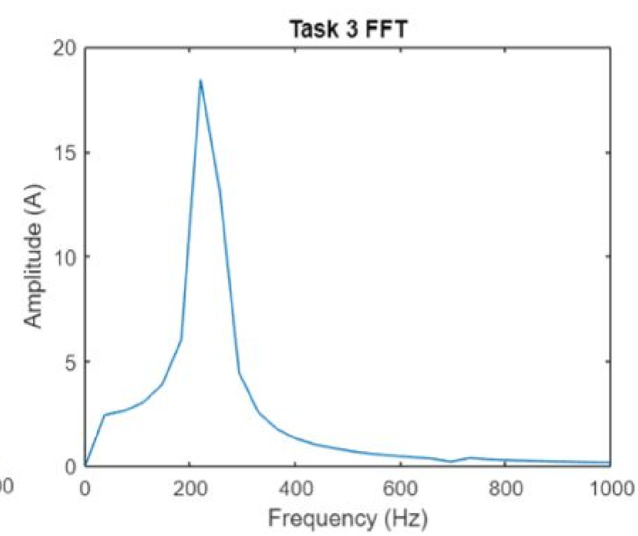


Figure 2.5-6: OCC FFT (left) and SCC FFT (right)

- **Based on the equivalent circuit parameters (Fig. A) and the induced excitation voltage E_f corresponding to field current of 2A (see OCC in Table 3), calculate and plot the power-angle characteristic and the torque-angle (for the ranger of angles -180 to +180 electrical degrees) characteristic for this Synchronous Machine. Here assume that $E_f = V_t$.**
    - $P = 3\frac{V_t E_f}{X_s} sin(\delta)$

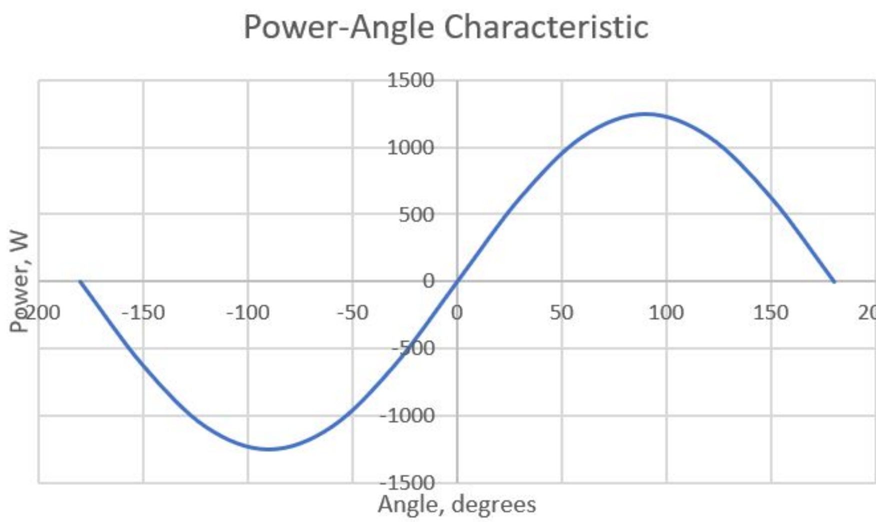


Figure 2.5-7: Power-Angle Characteristic

    - $T_e = \frac{3}{\omega_{syn}} \frac{V_t E_f}{X_s} sin(\delta)$

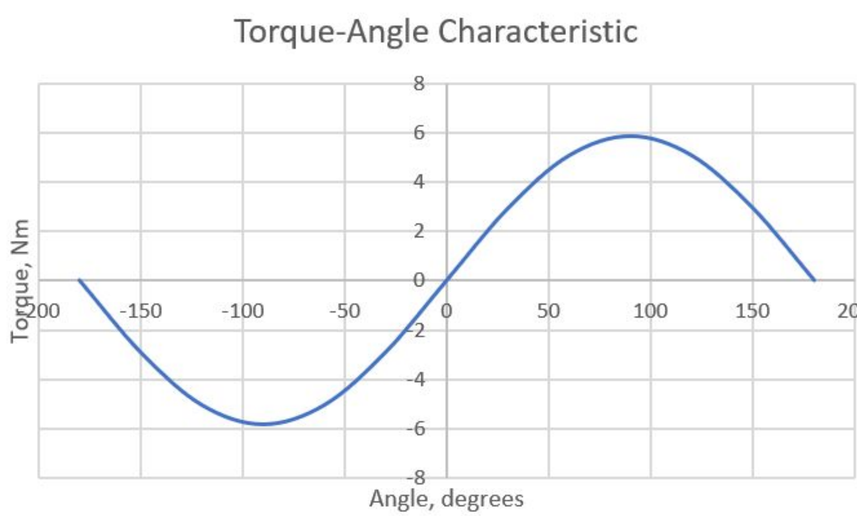


Figure 2.5-8: Torque-Angle Characteristic

- **What would be the maximum power and torque under this field current and given stator voltage? At what mechanical rotor angle will this be achieved?**
  - From Figure 2.5-7 and 2.5-8, we can see that both maximum power and maximum torque occur at the angle of 90 degrees, resulting in maximum power being 1246 W and maximum torque being 5.85 Nm.

- **Based on the equivalent circuit and losses presented in Fig. A, calculate and plot (using Matlab) the output voltage and efficiency of this Alternator vs. phase current at speed 2000 rpm and field current 2A when delivering power to a wye-connected resistive load. You can do this by varying the load resistor from very a large value, e.g. 100 to very small value, e.g. 0.1 Ohm per-phase, and taking approximately 20 to 30 points in this interval.**

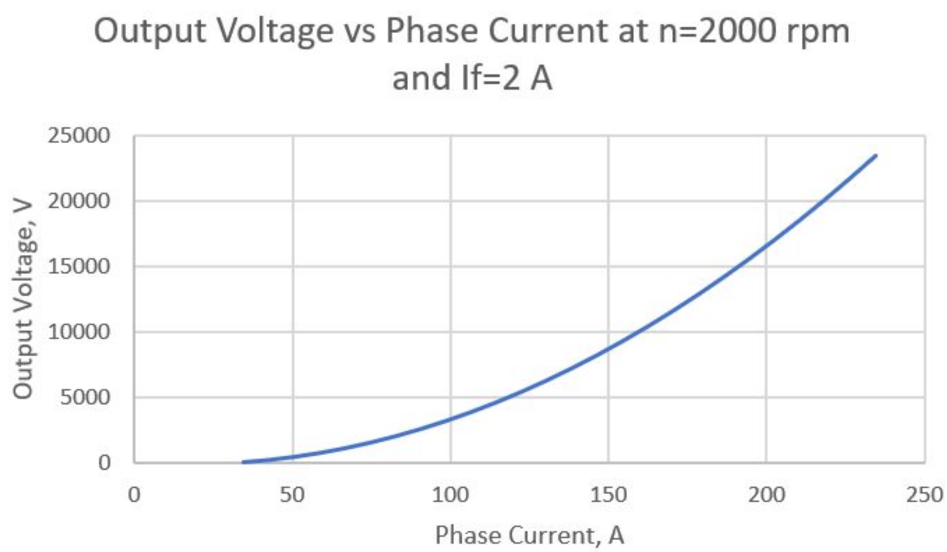


Figure 2.5-9: Output Voltage vs Phase Current When $n = 2000\ rpm$ and $I_f = 2\ A$.

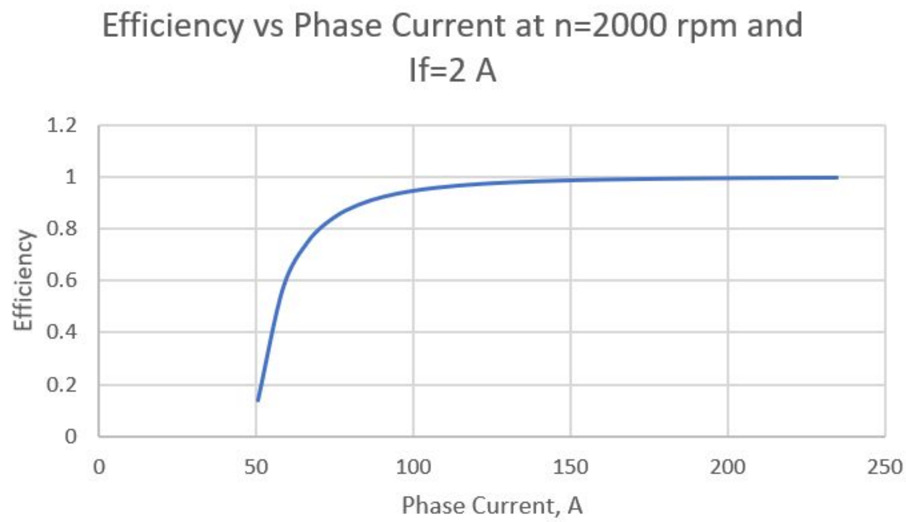


Figure 2.5-10: Efficiency of Alternator vs Phase Current When $n = 2000\ rpm$ and $I_f = 2\ A$.

- **Assume the generator is loaded with 1 Ohm per phase resistors, when it operates at speed 2000 rpm and field current 2A. Plot a phasor diagram representing a voltage equation for the generator under load condition.**
    - $V_t = E_f - (R_s + jX_s)I_s$ $\quad\quad E_f = V_t + (R_s + jX_s)I_s$
    - Assuming lagging PF

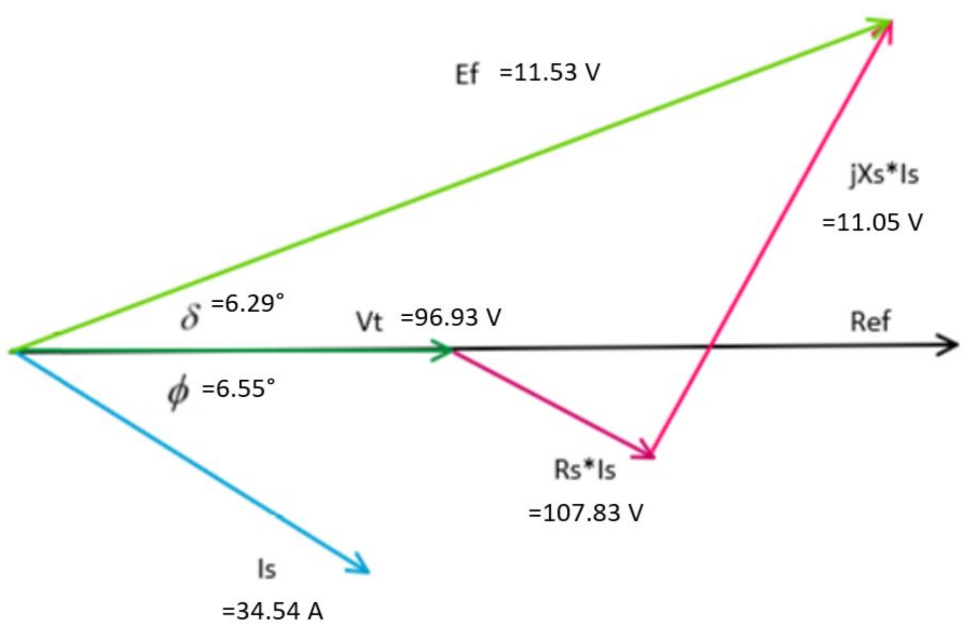


Figure 2.5-11: Generator Under Load Condition with Lagging PF

- **When this Alternator is in the vehicle, explain what principle is used to regulate its output voltage when the engine speed is changing?**
    - When the engine speed is changing, a voltage regulating circuit decreases the stator coil current as the output voltage increases and vice versa. If the output voltage is too low, the voltage regulator will increase the current flowing to the field coil.
- **Explain the causes of the rotational losses in this machine. Why are the losses so high for this Alternator? What recommendations can you provide to possibly improve the efficiency of such a generator?**
    - A lot of power is lost as resistive loss in windings due to the high current for the winding size. At higher speeds, core losses also increase.
    - To improve the efficiency of such a generator, conductors allowing greater fill of the windings in the alternator can be used. Operating the alternator at a higher voltage may further increase the efficiency.

3. Conclusion

This lab explored the characteristics of a Car Alternator, also known as a synchronous machine.The small synchronous machine's output voltage regulation was observed by controlling the field current, and its voltage and current waveforms were analysed as the alternator was loaded. The synchronization of two remote ac sources/generators were improvised, and finally, its equivalent parameters were calculated. By recording a set of measurements, the parameters of the synchronous machine per-phase equivalent circuit connected in a symmetric Y winding were determined. A steady-state model of the Car Alternator was developed, and the synchronization of the two synchronous machines was performed. A synchronized AC link was successfully established, and the power flow was observed and altered from one side to the other.

Appendix A: Task 5B Waveforms OCC and SCC

```
d = importdata("Task2CStepb.txt");
d = importdata("Task2CStepb.txt");

t = d.data(:,1)/1000;    % ms
c = d.data(:,4);     % current
L = length(t);
Ts = mean(diff(t));     % sampling interval (s)
Fs = 1/Ts;          % sampling freq
vc = c - mean(c);   % sub 0hz component

% Fourier Transform
Y = fft(vc);
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);
f = Fs*(0:(L/2))/L;
plot(f,P1)
xlim([0 1000])
xlabel('Frequency (Hz)')
ylabel('Amplitude (A)')
```

Appendix B: Task 5B Harmonic Spectrum

```
task2B = importdata("Lab5Task2B.txt");

time1 = task2B.data(:,1)/1000;    % ms
V1 = task2B.data(:,2);     % current
L1 = length(time1);
Ts1 = mean(diff(time1));     % sampling interval (s)
Fs1 = 1/Ts1;          % sampling freq
vc1 = V1 - mean(V1);   % sub 0hz component

% Fourier Transform
Y = fft(vc1);
P2 = abs(Y/L1);
P1 = P2(1:L1/2+1);
P1(2:end-1) = 2*P1(2:end-1);
f = Fs1*(0:(L1/2))/L1;

figure(1)
plot(f,P1)
xlim([0 1000])
xlabel('Frequency (Hz)')
ylabel('Amplitude (A)')
title('Task 2B FFT');
```