ECSE 362 - Fundamentals of Power Engineering

Lab 4: The Synchronous Machine

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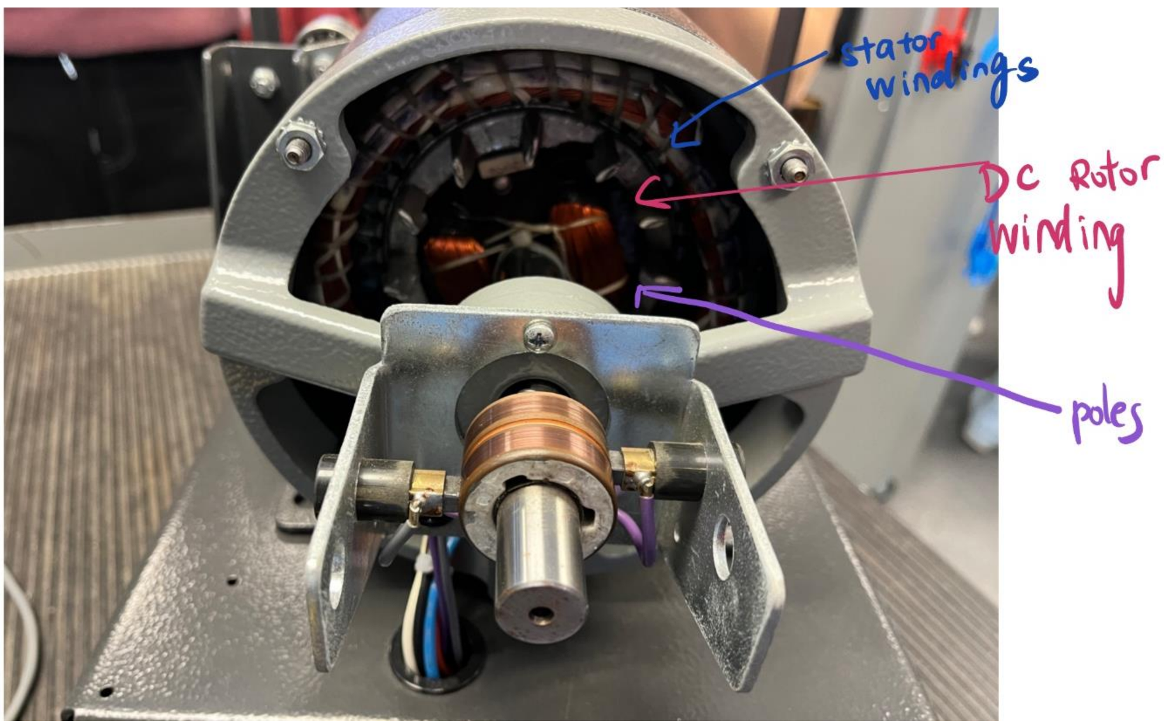
Lab section: 003

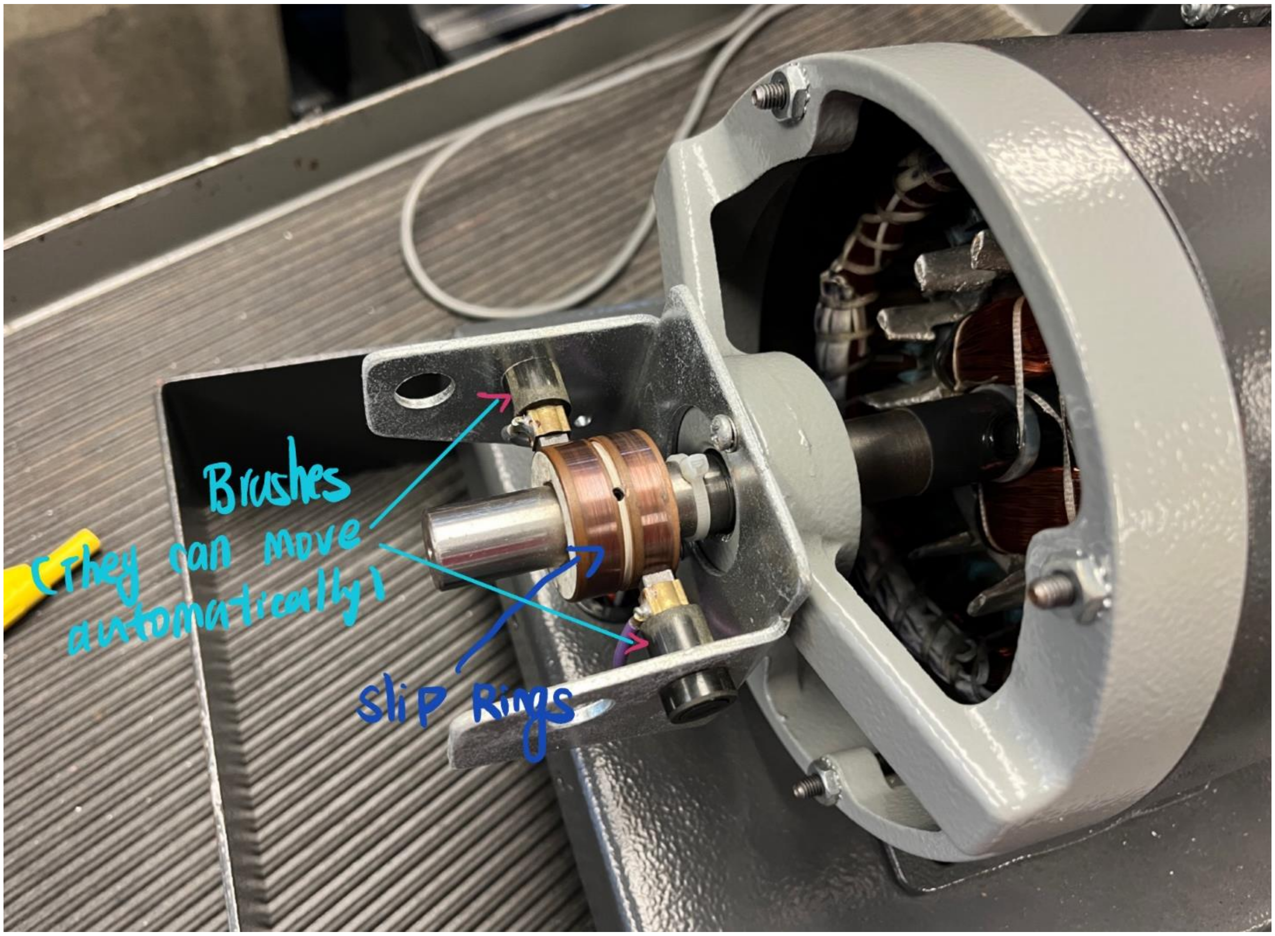
Introduction

The lab is split into 7 main sections. For the first section, the team focused on the examination of the construction of the three-phase synchronous machine where we identify Stator/Rotor windings, poles, and slip rings. During the second section, the team learned about field excitation effect and plotted AC stator current against DC rotor excitation current and power factor against DC rotor excitation current graphs. In the third section, the focus is now on the maximum loading and pull-out torque. The fourth and fifth section is dedicated to determining the characteristics of the synchronous generation. The remaining two sections allow the team to learn how to synchronize an alternator to the electric utility system.

1. Synchronous Machine Construction and Characteristics

2)





3) Viewing from the front face of the module:

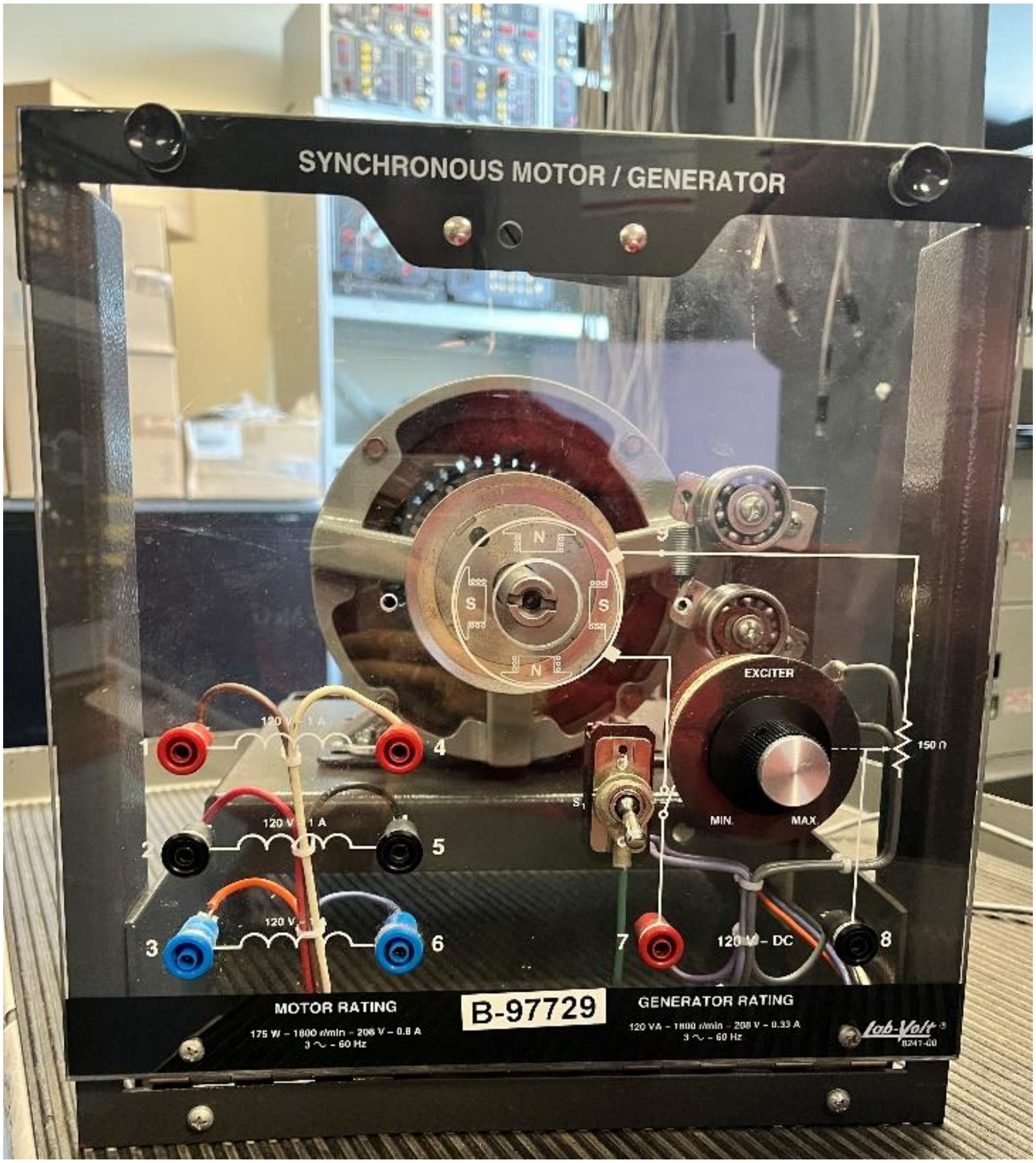
(i) $V_{rated\ stator} = 208V$

(ii) $V_{rated\ stator} = 0.8\ A$

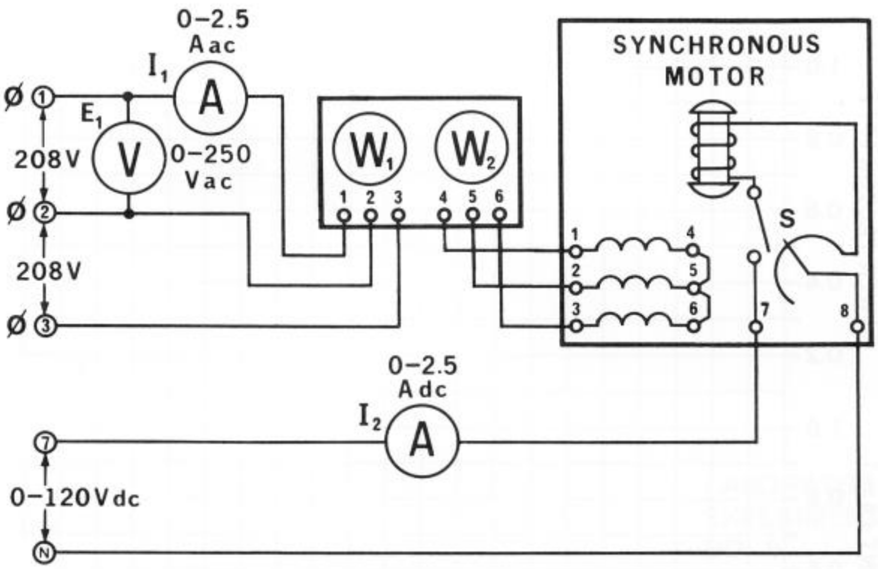
(iii) Terminals 7 and 8 are voltage ports for the rotor windings

(iv) $V_{rated\ rotor} = 208V$

(v) Rated speed: 1800 rpm | Rated power: 120VA

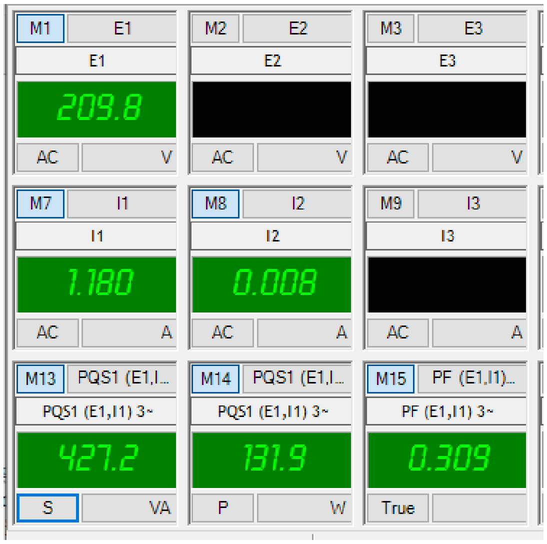

SYNCHRONOUS MOTOR / GENERATOR
EXCITER
MIN.
MAX.
150 Ω
120 V – DC
MOTOR RATING
175 W – 1800 r/min – 208 V – 0.8 A
3 ∿ – 60 Hz
B-97729
GENERATOR RATING
120 VA – 1800 r/min – 208 V – 0.33 A
3 ∿ – 60 Hz
Lab-Volt

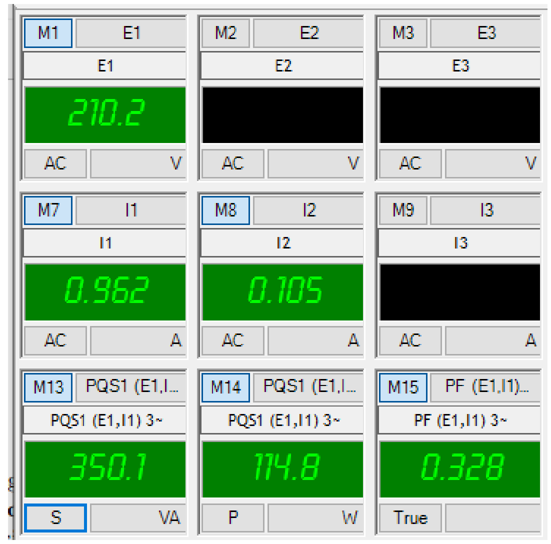
2. Field Excitation Effects

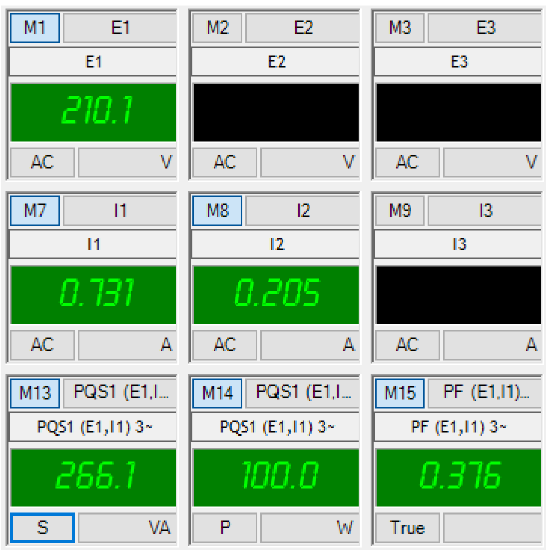


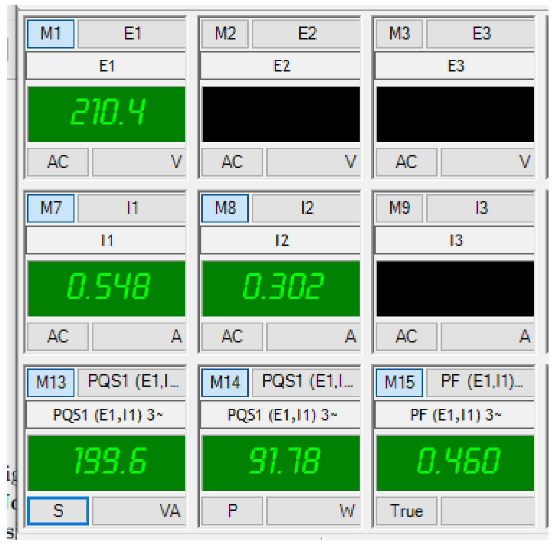
3. Measurements and screenshots:

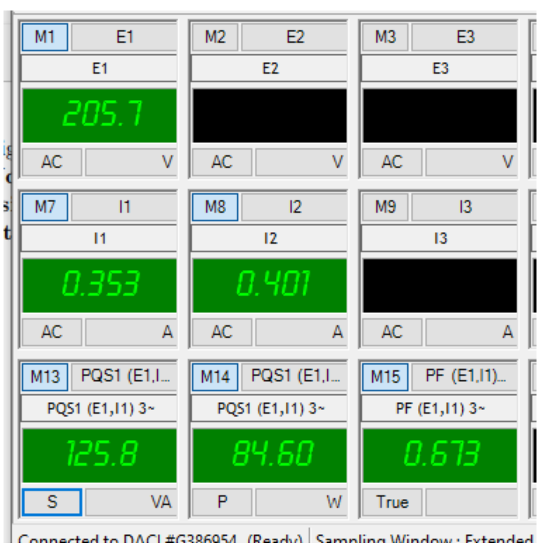
Table 1					
I2	E1	I1	S	P	pf
0	208	1.18	427.2	131.9	0.309
0.1	208	0.962	350.1	114.8	0.328
0.2	208	0.731	266.1	100	0.376
0.3	208	0.548	199.6	91.78	0.46
0.4	208	0.353	125.8	84.6	0.673
0.5	208	0.265	95.85	83.39	0.87
0.6	208	0.236	86.07	83.47	0.97
0.7	208	0.323	116.9	86.17	0.737
0.8	208	0.445	161.2	88.73	0.55

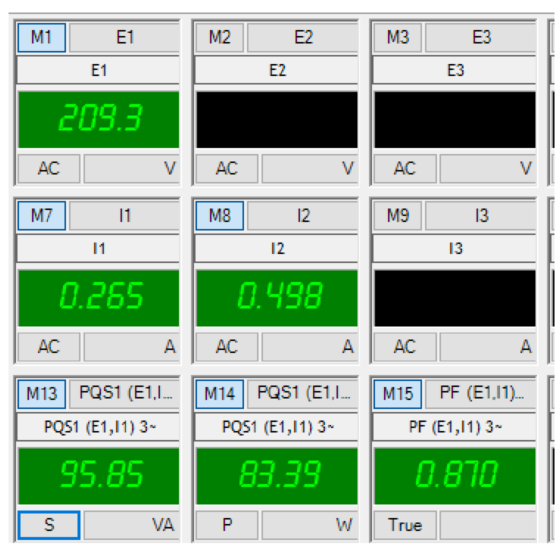

M1 E1
E1
209.8
AC V
M2 E2
E2
AC V
M3 E3
E3
AC V
M7 I1
I1
1.180
AC A
M8 I2
I2
0.008
AC A
M9 I3
I3
AC A
M13 PQS1 (E1,I...
PQS1 (E1,I1) 3~
427.2
S VA
M14 PQS1 (E1,I...
PQS1 (E1,I1) 3~
131.9
P W
M15 PF (E1,I1)...
PF (E1,I1) 3~
0.309
True

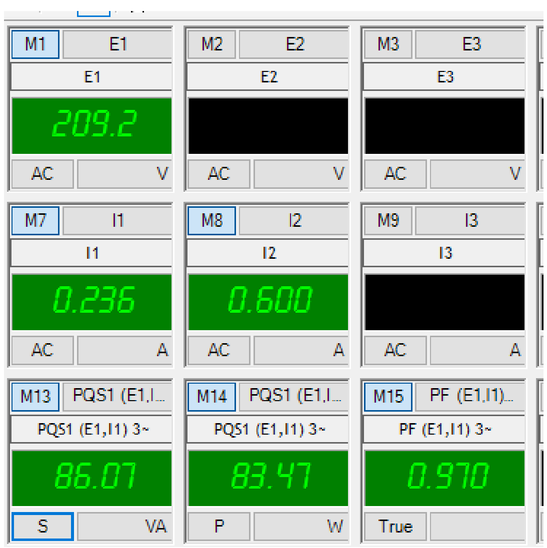

M1 E1
E1
210.2
AC V
M2 E2
E2
AC V
M3 E3
E3
AC V
M7 I1
I1
0.962
AC A
M8 I2
I2
0.105
AC A
M9 I3
I3
AC A
M13 PQS1 (E1,I...
PQS1 (E1,I1) 3~
350.1
S VA
M14 PQS1 (E1,I...
PQS1 (E1,I1) 3~
114.8
P W
M15 PF (E1,I1)...
PF (E1,I1) 3~
0.328
True

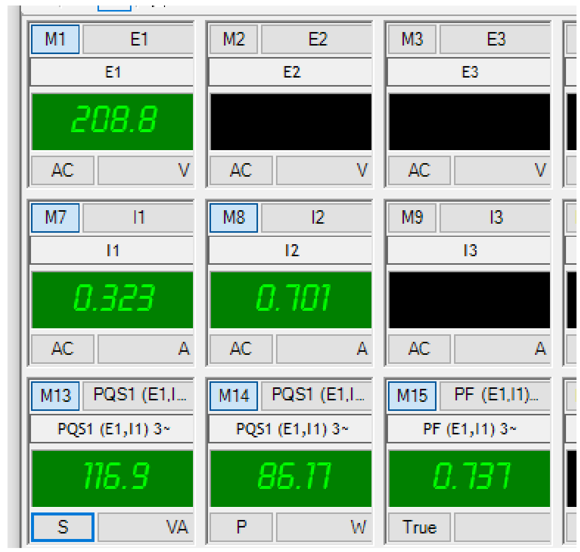

M1 E1
E1
210.1
AC V
M2 E2
E2
AC V
M3 E3
E3
AC V
M7 I1
I1
0.731
AC A
M8 I2
I2
0.205
AC A
M9 I3
I3
AC A
M13 PQS1 (E1,I...
PQS1 (E1,I1) 3~
266.1
S VA
M14 PQS1 (E1,I...
PQS1 (E1,I1) 3~
100.0
P W
M15 PF (E1,I1)...
PF (E1,I1) 3~
0.376
True

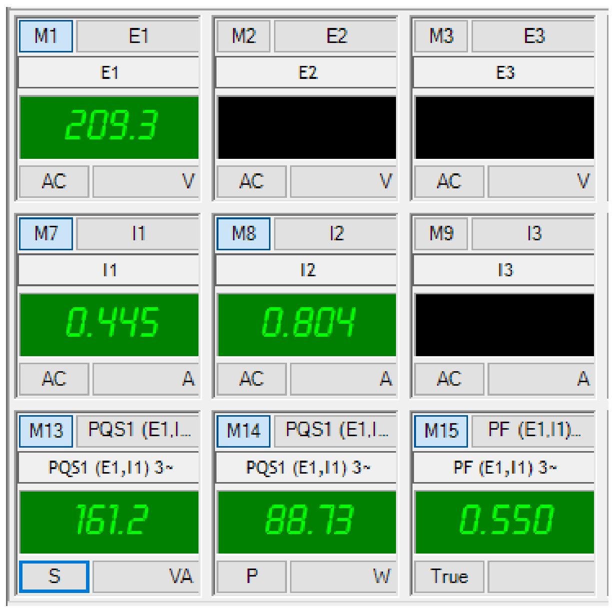

M1 E1
E1
210.4
AC V
M2 E2
E2
AC V
M3 E3
E3
AC V
M7 I1
I1
0.548
AC A
M8 I2
I2
0.302
AC A
M9 I3
I3
AC A
M13 PQS1 (E1,I...
PQS1 (E1,I1) 3~
199.6
S VA
M14 PQS1 (E1,I...
PQS1 (E1,I1) 3~
91.78
P W
M15 PF (E1,I1)...
PF (E1,I1) 3~
0.460
True


M1 E1
E1
205.7
AC V
M2 E2
E2
AC V
M3 E3
E3
AC V
M7 I1
I1
0.353
AC A
M8 I2
I2
0.401
AC A
M9 I3
I3
AC A
M13 PQS1 (E1,I...
PQS1 (E1,I1) 3~
125.8
S VA
M14 PQS1 (E1,I...
PQS1 (E1,I1) 3~
84.60
P W
M15 PF (E1,I1)...
PF (E1,I1) 3~
0.673
True


M1 E1
E1
209.3
AC V
M2 E2
E2
AC V
M3 E3
E3
AC V
M7 I1
I1
0.265
AC A
M8 I2
I2
0.498
AC A
M9 I3
I3
AC A
M13 PQS1 (E1,I...
PQS1 (E1,I1) 3~
95.85
S VA
M14 PQS1 (E1,I...
PQS1 (E1,I1) 3~
83.39
P W
M15 PF (E1,I1)...
PF (E1,I1) 3~
0.870
True







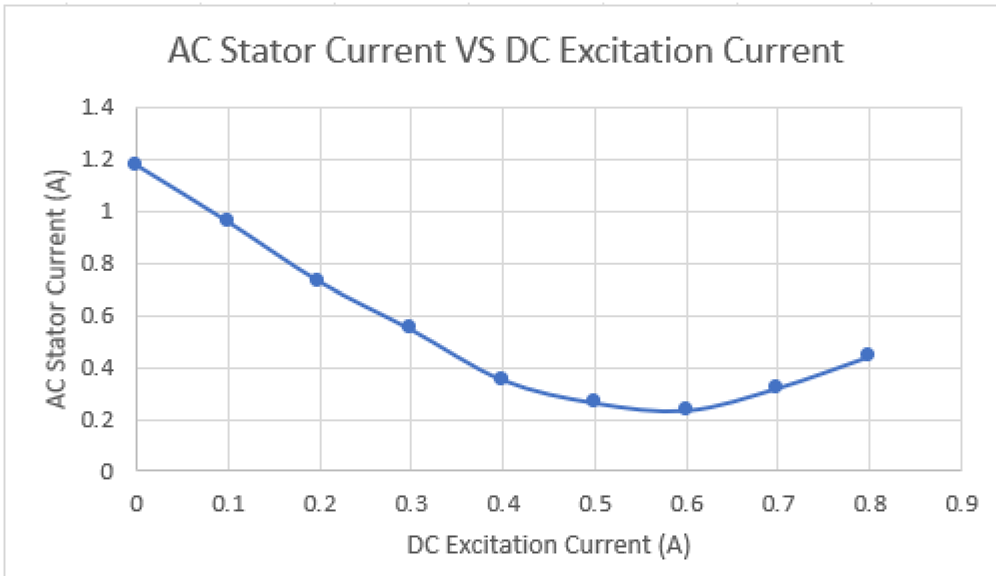
5) $Q = \sqrt{427.2^2 - 131.9^2} = 406.3\ var$ | pf = 0.309 lagging

6) $Q = -\sqrt{161.2^2 - 88.73^2} = -134.58$ var | pf = 0.55 leading

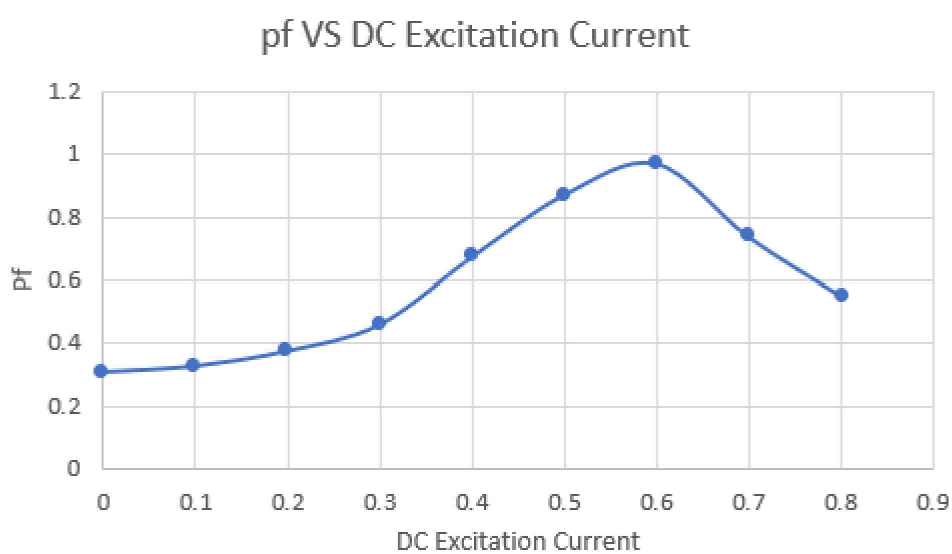
7) $Q = \sqrt{86.07^2 - 83.47^2} = 20.99$ var | pf = 0.97 lagging

Supplementary questions:

(a)



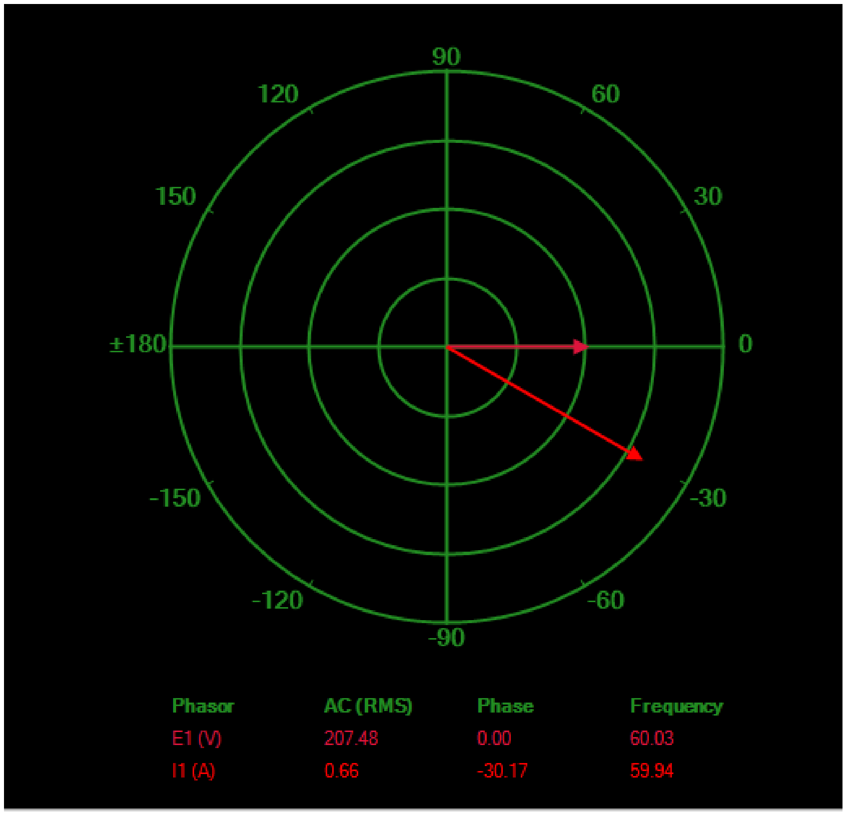
(b)

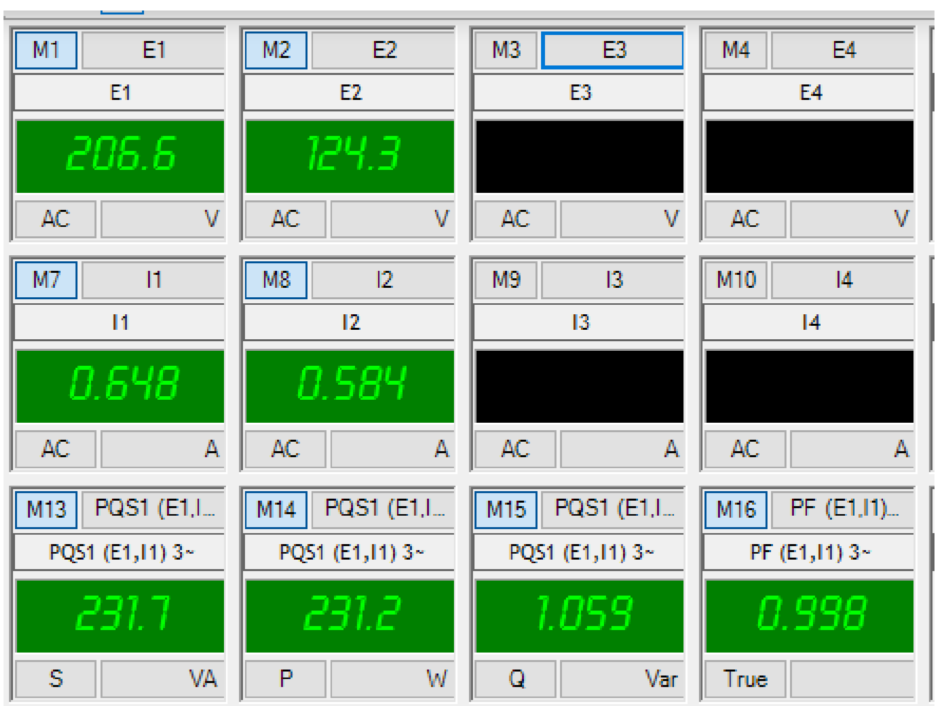


c) As DC excitation increases, the AC stator current decreases. When it reaches its minimum of 0.236 A when DC current equals to 0.6 A, the AC stator current would increase until DC excitation current reaches it maximum. With the increase of DC excitation current, the power factor would increase till its maximum at 0.97 when DC current equals to 0.6A and AC current equals to 0.236A. Then it would start to decrease till maximum DC current reached.

3. Maximum Loading and Pull-Out Torque

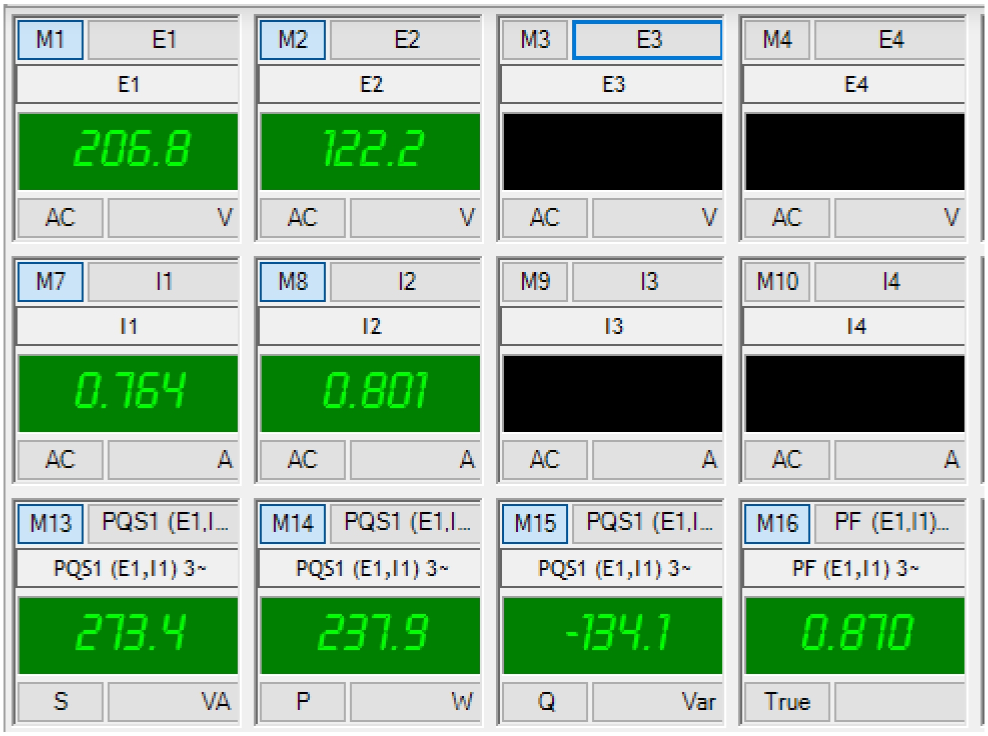
3) Machine current lags machine voltage by 30 degrees.





4) Max torque: 1.924 Nm, RPM drops to ~1400

5) Because Q is negative following generator convention, the power factor would be leading.



6) Pull-out torque at I2 = 0.8 A is T = 2.347 Nm

Supplementary questions

1) (a) 231.7 VA

(b) 213.2 W

(c) 1.059 var

(d) 0.998 lagging

(e) $P = E_2 \times I_2 = 124.3 \cdot 0.584 = 72.59\ W$

(f) $P_{mech} = P_{elec} = 231.2W$

(g) Full load torque: $P_{full\ load} = 186\ W$ (1/4 horsepower)

$$\mu = \frac{P_{out}}{P_{in}} = \frac{231.2}{231.2 + 72.59} \times 100 = 76.1\ \%$$

2) Pull out torque = **2.347 Nm** | Full load torque = **1.924 Nm** | Ratio = 2.347/1.924 = **1.22**

3) (a) 273.4 VA

(b) 237.9 W

(c) -134.1 var

(d) 0.870 leading

(e) $P_{dc} = EI = 122.2 \times 0.801 = 97.88\, W$

(f) Mechanical output power = 237.9 W

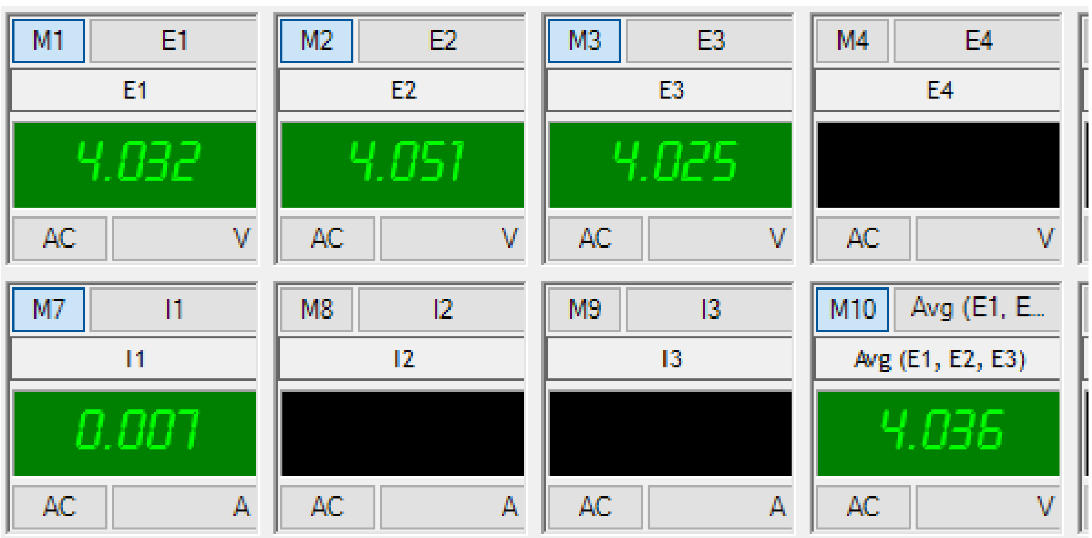
4) Negative

5) As the degree of DC excitation increases, the strength of the magnetic field increases. The force it created leads the motor to create.

4. The Three-Phase Alternator

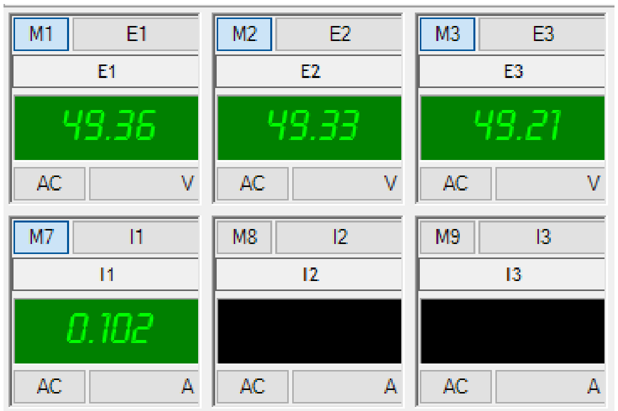
Alternative instructions: Remove the Squirrel Cage entirely. Dynamometer to CW Prime Mover/Brake. Synchronous speed 1800 rpm. Note for switch S: up is close (1), down is open (0).

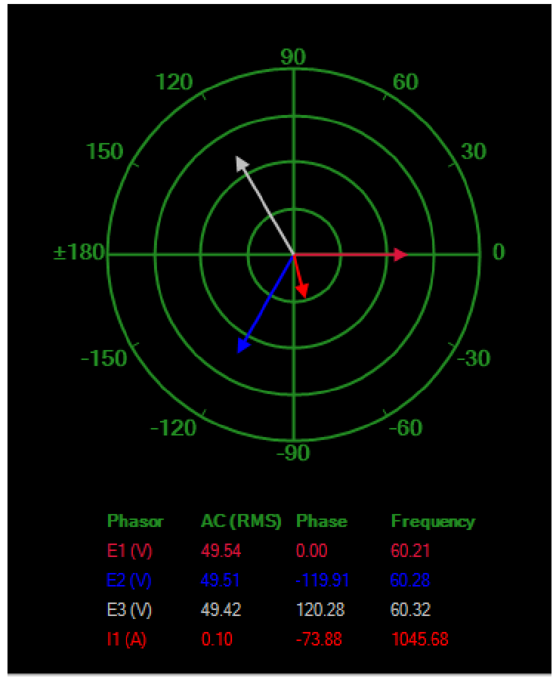
3.



There is an AC voltage generated without DC excitation due to the lingering magnetization in the stator/rotor from previous lab sections.

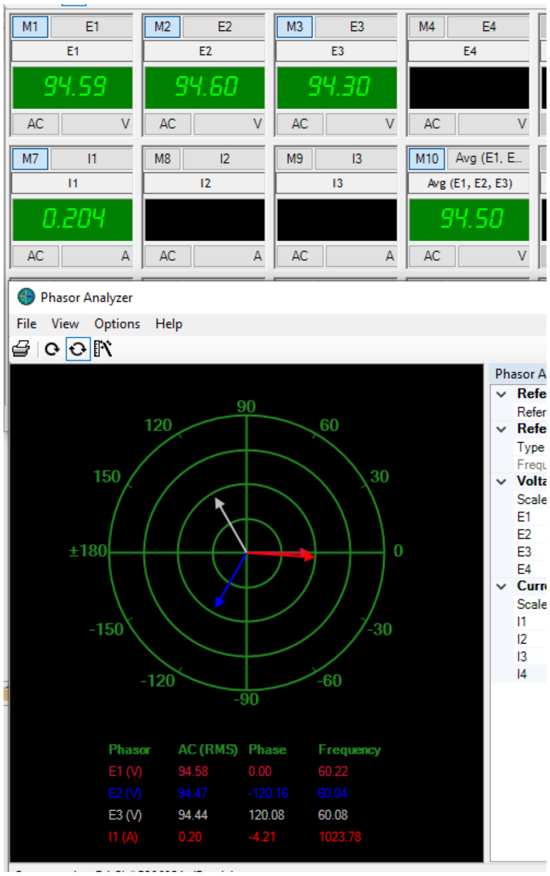
4. Measurements for E1, E2, E3, and proof that they are 3-phase balanced:

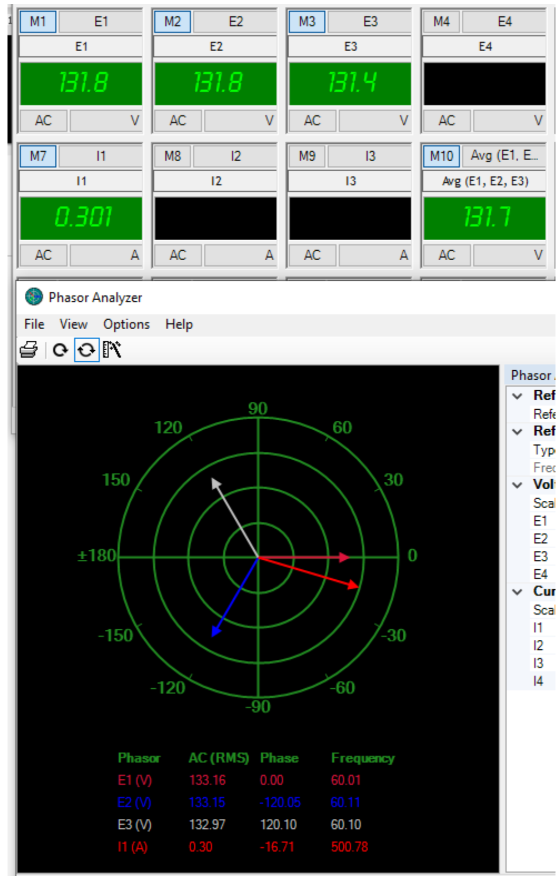


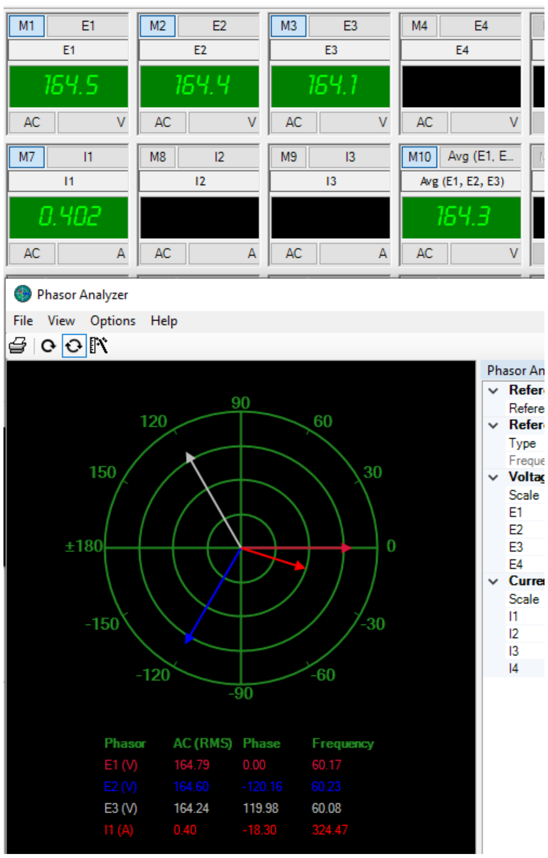


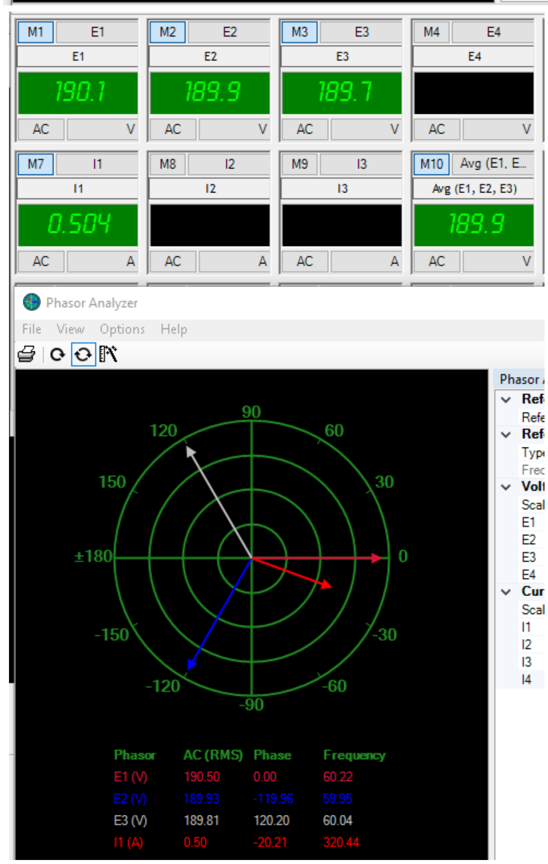
5. Table 2, with the first entry from Step 3. Measurements and screenshots are below.

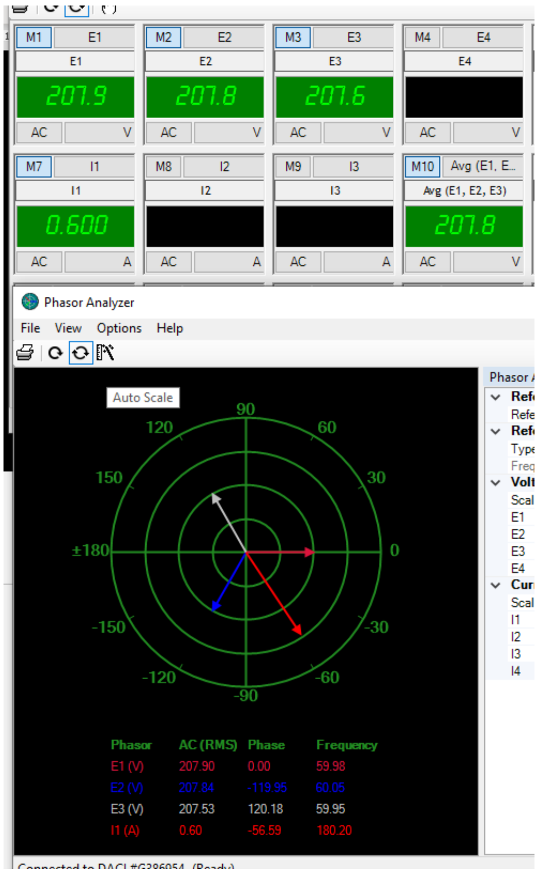
Table 2				
I1	E1	E2	E3	Eavg
0	4.032	4.051	4.025	4.036
0.1	49.36	49.33	49.21	49.3
0.2	94.59	94.6	94.3	94.5
0.3	131.8	131.8	131.4	131.7
0.4	164.5	164.4	164.1	164.3
0.5	190.1	189.9	189.7	189.9
0.6	207.9	207.8	207.6	207.8
0.7	222.9	222.6	222.5	222.7
0.8	233.4	233.2	233	233.7
0.9	241.4	241	240.9	241.7

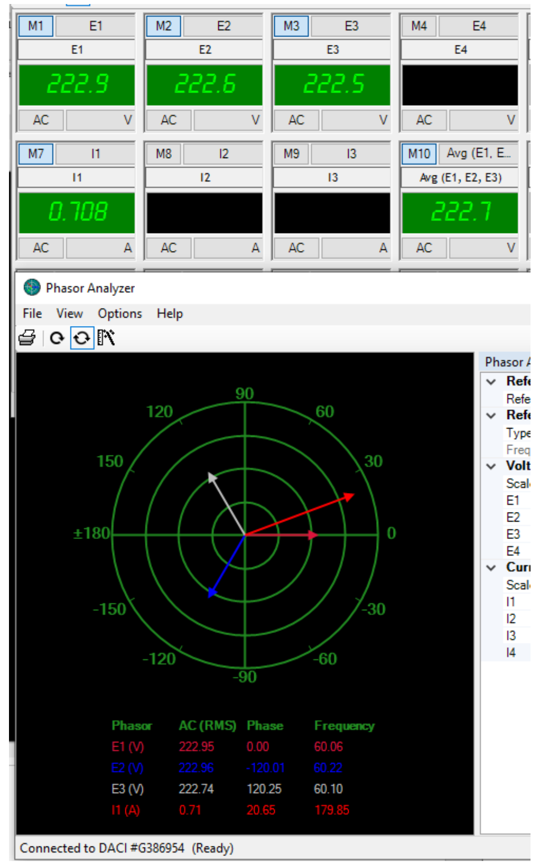

M1 E1
94.59
M2 E2
94.60
M3 E3
94.30
M4 E4
M7 I1
0.204
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
94.50
Phasor Analyzer
File View Options Help
Phasor | AC (RMS) | Phase | Frequency
E1 (V) 94.58 0.00 60.22
E2 (V) 94.47 -120.16 60.04
E3 (V) 94.44 120.08 60.08
I1 (A) 0.20 -4.21 1023.78

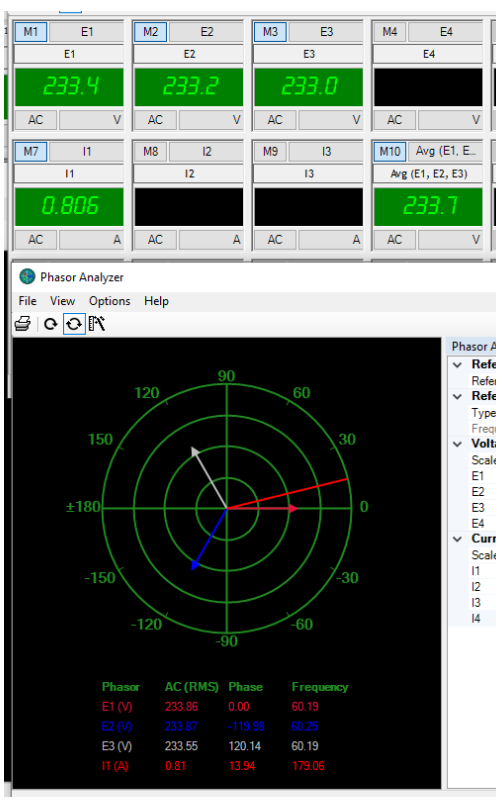

M1 E1
131.8
M2 E2
131.8
M3 E3
131.4
M4 E4
M7 I1
0.301
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
131.7
Phasor Analyzer
File View Options Help
Phasor | AC (RMS) | Phase | Frequency
E1 (V) 133.16 0.00 60.01
E2 (V) 133.15 -120.05 60.11
E3 (V) 132.97 120.10 60.10
I1 (A) 0.30 -16.71 500.78

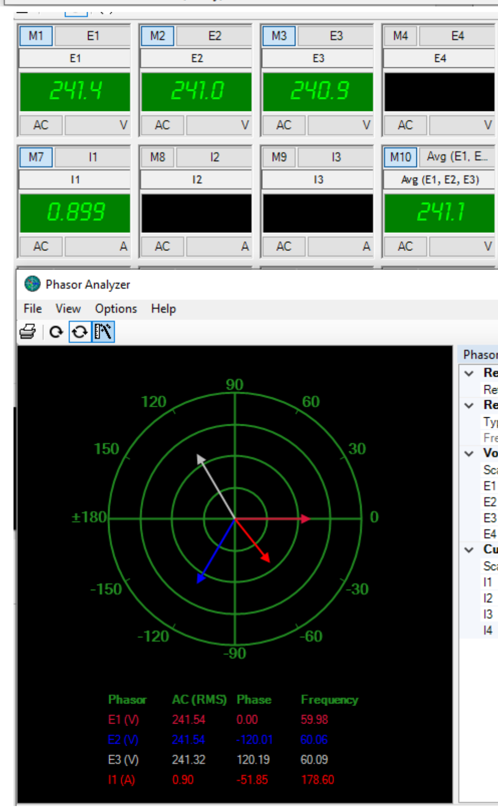

M1 E1
164.5
M2 E2
164.4
M3 E3
164.1
M4 E4
M7 I1
0.402
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
164.3
Phasor Analyzer
File View Options Help
Phasor | AC (RMS) | Phase | Frequency
E1 (V) 164.79 0.00 60.17
E2 (V) 164.60 -120.16 60.23
E3 (V) 164.24 119.98 60.08
I1 (A) 0.40 -18.30 324.47


M1 E1
190.1
M2 E2
189.9
M3 E3
189.7
M4 E4
M7 I1
0.504
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
189.9
Phasor Analyzer
File View Options Help
Phasor | AC (RMS) | Phase | Frequency
E1 (V) 190.50 0.00 60.22
E2 (V) 189.93 -119.96 59.95
E3 (V) 189.81 120.20 60.04
I1 (A) 0.50 -20.21 320.44


M1 E1
207.9
M2 E2
207.8
M3 E3
207.6
M4 E4
M7 I1
0.600
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
207.8
Phasor Analyzer
File View Options Help
Auto Scale
Phasor AC (RMS) Phase Frequency
E1 (V) 207.90 0.00 59.98
E2 (V) 207.84 -119.95 60.05
E3 (V) 207.53 120.18 59.95
I1 (A) 0.60 -56.59 180.20


M1 E1
222.9
M2 E2
222.6
M3 E3
222.5
M4 E4
M7 I1
0.708
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
222.7
Phasor Analyzer
File View Options Help
Phasor AC (RMS) Phase Frequency
E1 (V) 222.95 0.00 60.06
E2 (V) 222.96 -120.01 60.22
E3 (V) 222.74 120.25 60.10
I1 (A) 0.71 20.65 179.85
Connected to DACI #G386954 (Ready)


M1 E1
233.4
M2 E2
233.2
M3 E3
233.0
M4 E4
M7 I1
0.806
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
233.7
Phasor Analyzer
File View Options Help
Phasor AC (RMS) Phase Frequency
E1 (V) 233.86 0.00 60.19
E2 (V) 233.87 -119.98 60.25
E3 (V) 233.55 120.14 60.19
I1 (A) 0.81 13.94 179.06

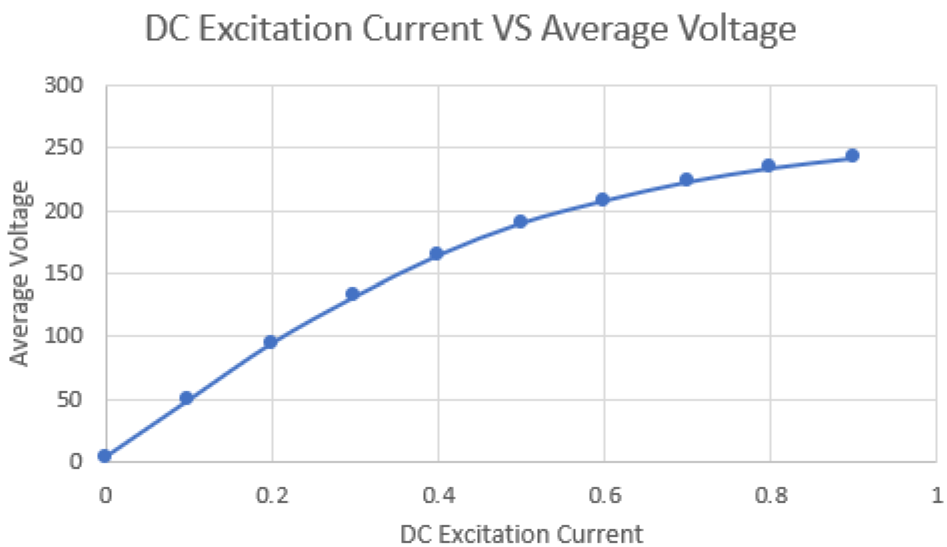

M1 E1
241.4
M2 E2
241.0
M3 E3
240.9
M4 E4
M7 I1
0.899
M8 I2
M9 I3
M10 Avg (E1, E2, E3)
241.1
Phasor Analyzer
File View Options Help
Phasor AC (RMS) Phase Frequency
E1 (V) 241.54 0.00 59.98
E2 (V) 241.54 -120.01 60.06
E3 (V) 241.32 120.19 60.09
I1 (A) 0.90 -51.85 178.60

7. (v) I_2 peaked to **2.856 A** at the moment of switch closure when performing a short circuit.

(vi) At steady state, I_1 = **0.585 A** and I_2 = **1.320 A**.

Supplementary questions

1. (a)



(b) 164.3 V

(c) 181.9 V

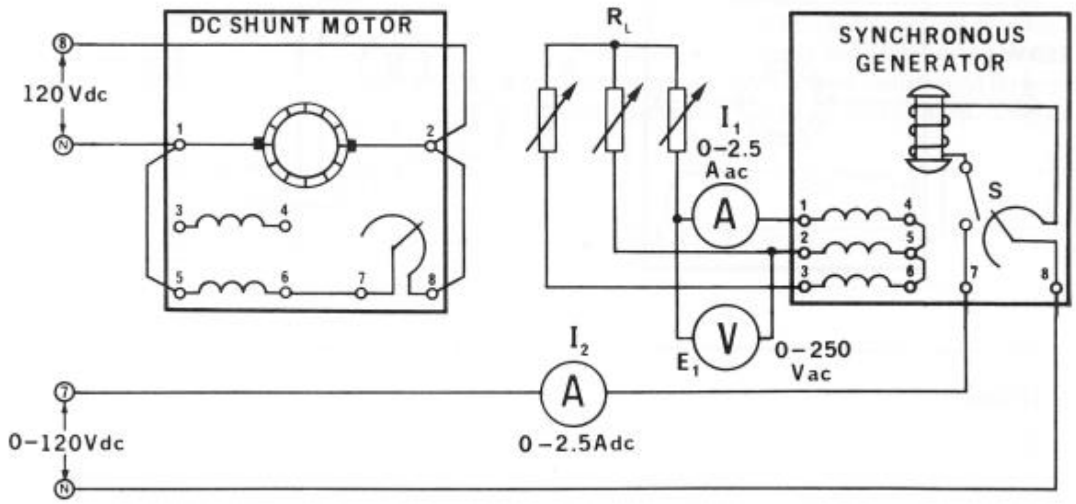
(d) Saturation happens. As magnetic flux density in the core approach max, increase in DC current only results in small increase in flux density. Therefore, there will be a smaller increase in stator voltage.

2. $Z_{base} = \frac{V^2}{S} = \frac{208^2}{120} = 360.5\ \Omega$

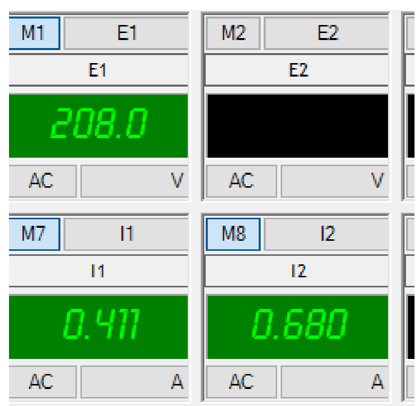
$$Z = \frac{V}{I} = \frac{208\ V}{2.856A} = 72.83\ \Omega$$

$$Z_{p.u} = \frac{Z}{Z_{base}} = \frac{72.83}{360.5} = 0.202\ p.u$$

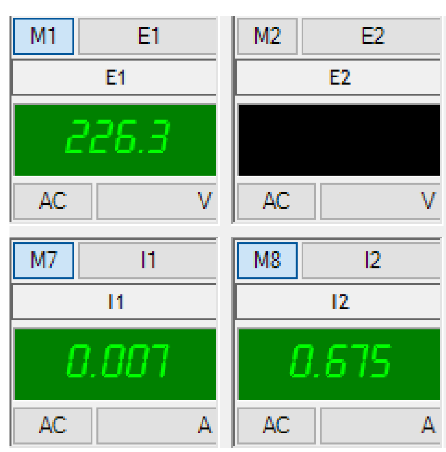
5. The Alternator Under Load



3) With resistive load:

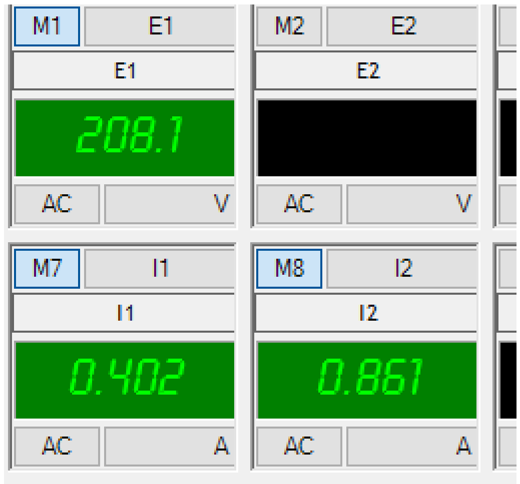


No load: removing resistive load increases induced voltage (MMF) and rotational speed (rpm)

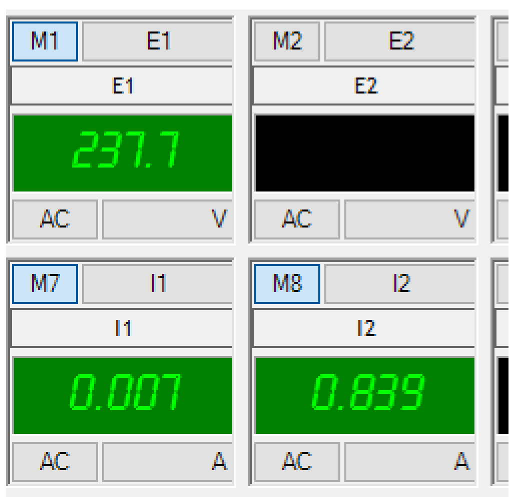


$$Voltage\ regulation = \frac{|E_{fl} - E_{nl}|}{E_{fl}} \times 100 = \frac{|208 - 226.3|}{208} \times 100 = 8.8\ \%$$

4. Inductive load ($Z_L = 300\Omega$) measurements:



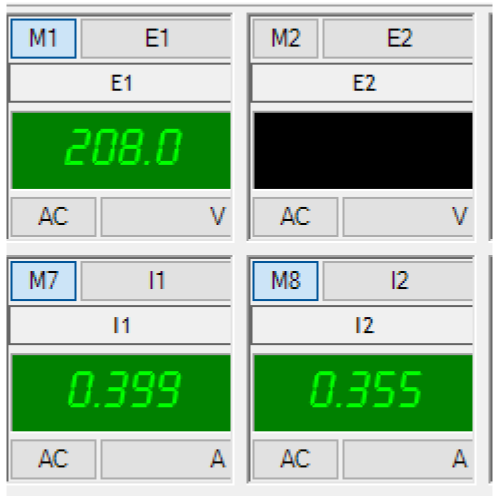
No load measurements: remove inductive load leads to increase MMF, increase voltage, rotational speed stay the same



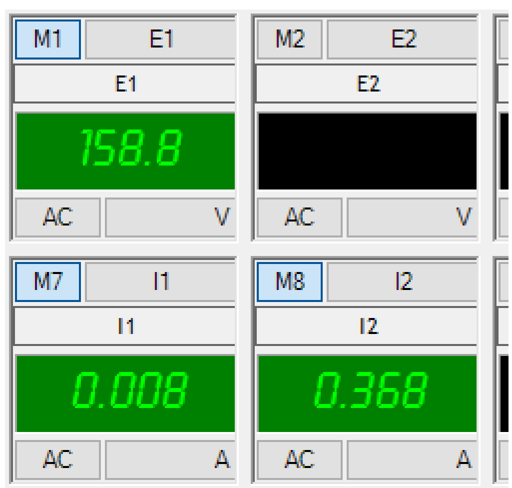
$$Voltage\ regulation = \frac{|E_{fl} - E_{nl}|}{E_{fl}} \times 100 = \frac{|208 - 237.7|}{208} \times 100 = 14.3\ \%$$

Oppose the rotor MMF because of the lagging power factor of inductive load.

5. Capacitive load ($Z_C = 300\Omega$) measurement:



No load measurement: Remove capacitive load leads to voltage drops while rotational speed stays the same.



$$Voltage\ regulation = \frac{|E_{fl} - E_{nl}|}{E_{fl}} \times 100 = \frac{|208 - 158.8|}{208} \times 100 = 23.7\ \%$$

Aids the rotor MMF because of the leading power factor of capacitive load.

6. Alternator Synchronization

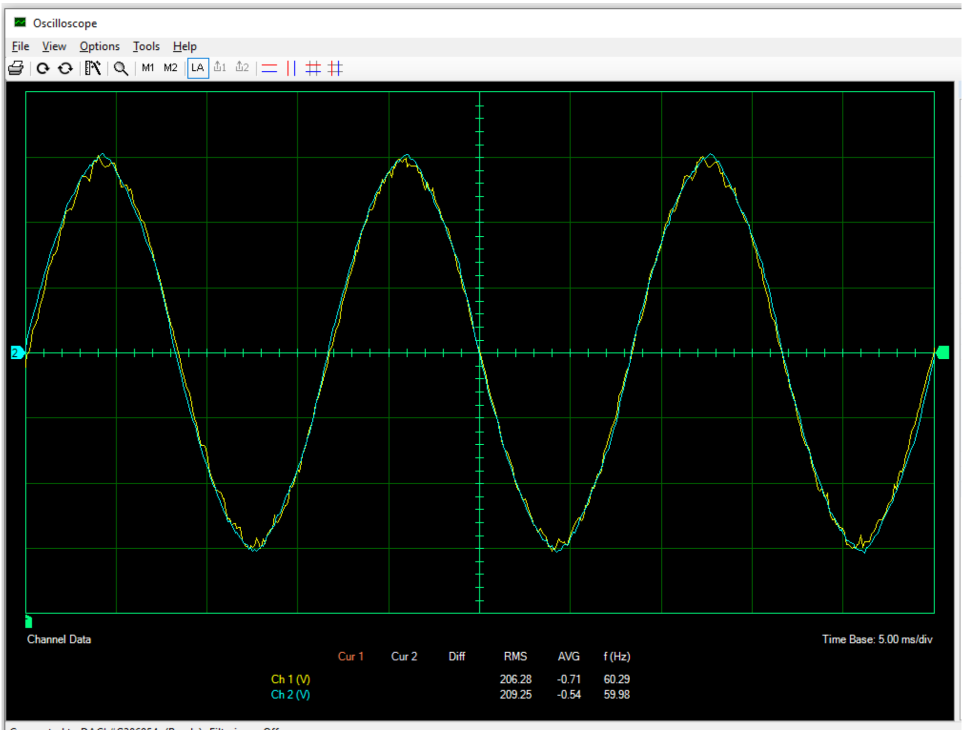


Figure: Voltages from the generator and the grid are in phase
(CH1: The generator, CH2: The grid)

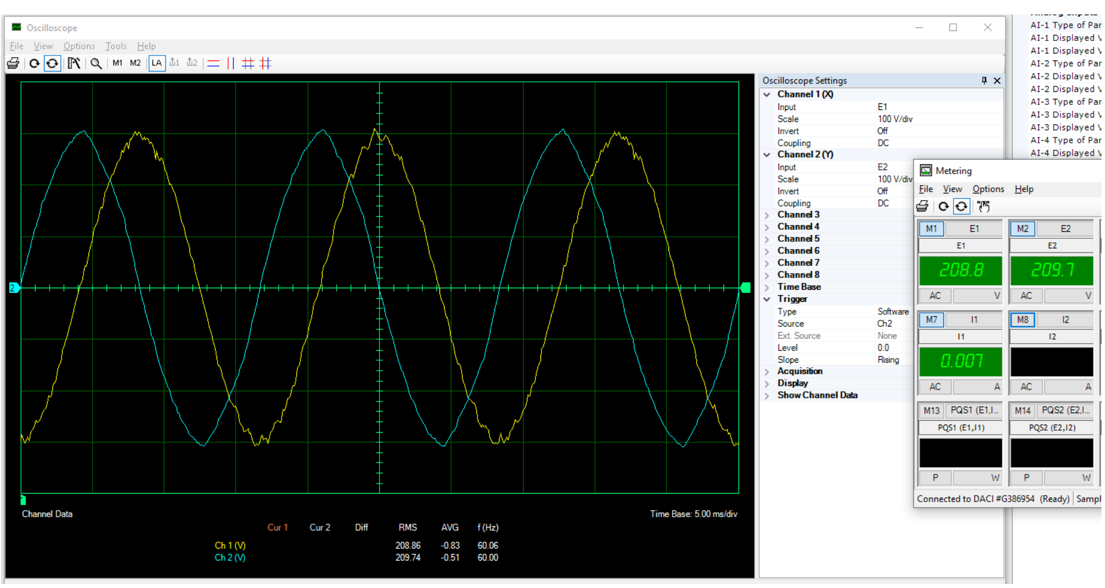


Figure: Voltages from the generator and the grid are out of phase
(CH1: The generator, CH2: The grid)

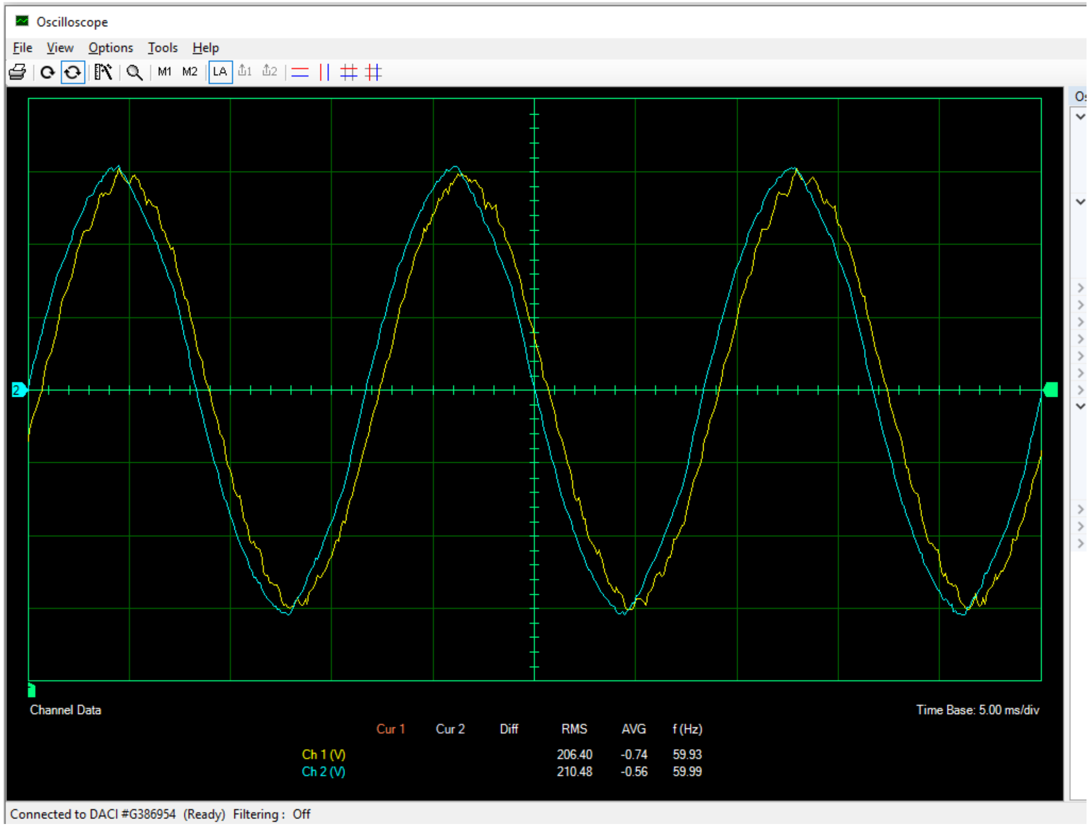


Figure: Voltages from the generator and the grid are close to be in phase
(CH1: The generator, CH2: The grid)

1800rpm gives the lowest light blinking frequency, deviate from it increases the blinking light frequency. When the voltages have the same phase value, the bulb is dark. When they are out of phase, the bulb is bright.

5. Close the synchronizing switch when all three lights are …

- Dark: I_1 peaked at **0.491A** at the moment of closure

- Dimmed: I_1 peaked at **0.617A** at the moment of closure

- Bright: I_1 peaked at **2.058A** at the moment of closure, along with an audible loud bang.

6. I_1 starts at 0.007 A and spiked to 0.416A during moment of closure.

7. Lights blink in a direction (shining from right to left),

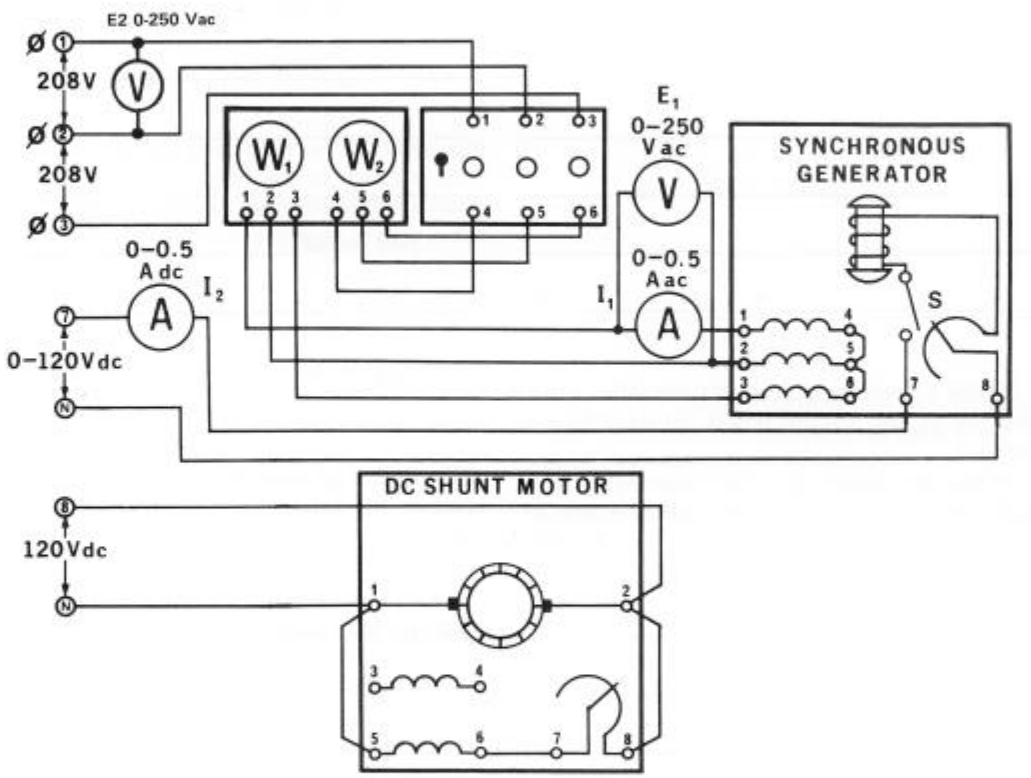
When we do counterclockwise, angle become 0, 120, -120 (phase b and c are flipped)

We can swap cable in terminal B and C, and it will blink altogether again.

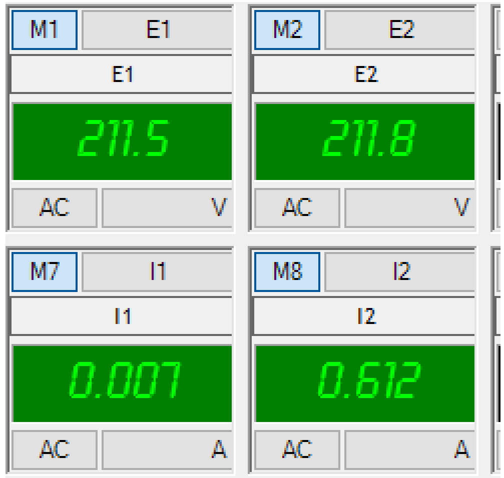
Supplementary questions

1. Must have equal line voltage, frequency, phase sequence, phase angle, and waveform.

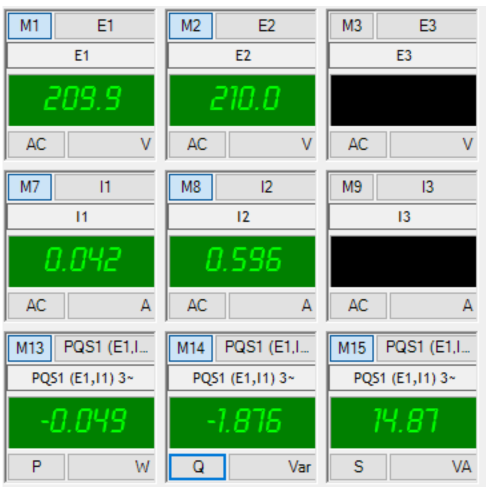
7. Alternator Power



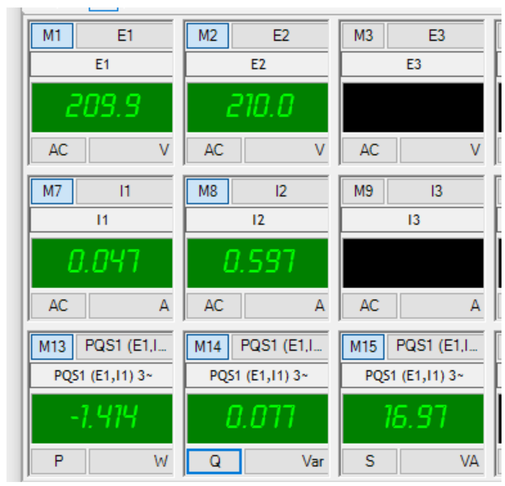
3. The alternator is now "floating" on the power line. It is neither receiving nor delivering power to the line. After synchronization, here are the measurements of E_1, I_1, and I_2 (E_2 is the grid's line voltage)



P and Q ~ 0 here:



or

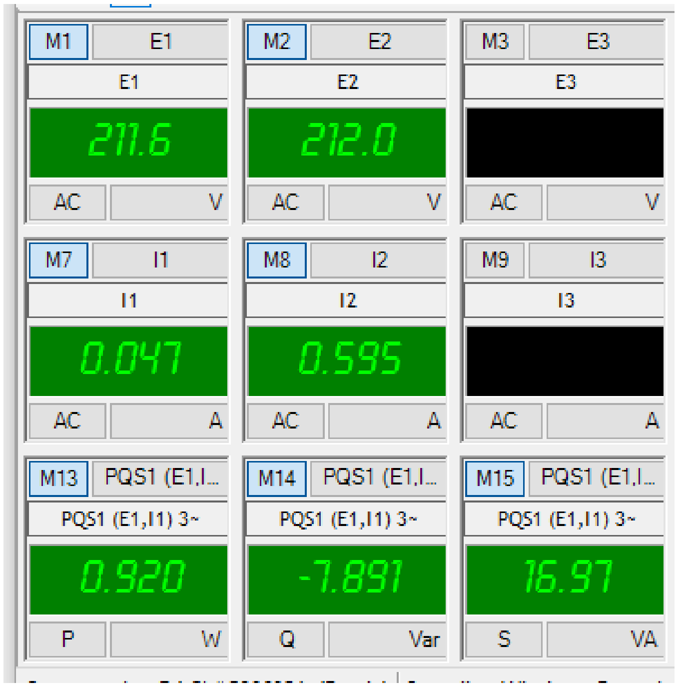


4. Slowly increased till I1 = 0.33A,

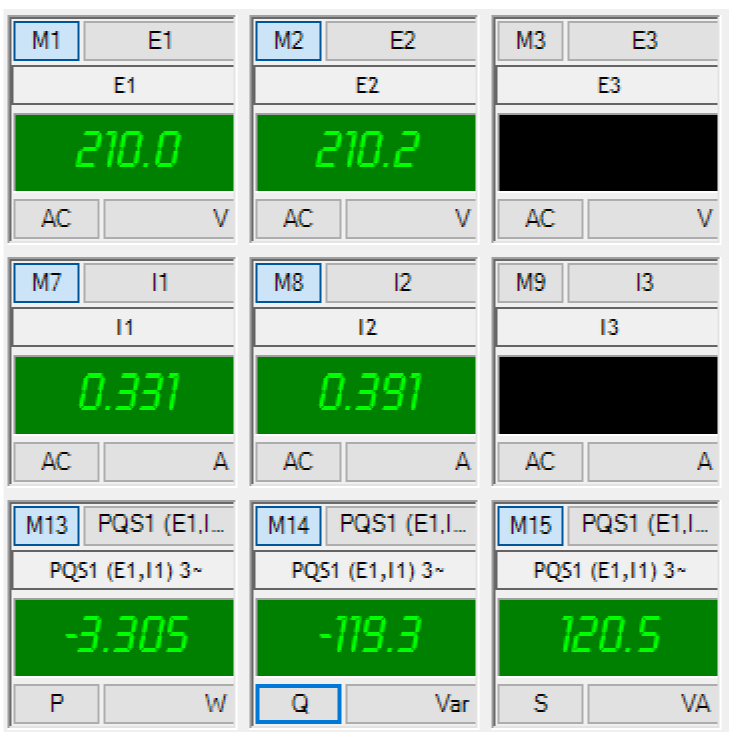
4.i.

An increase in DC excitation leads to both reactive and active power to increase.

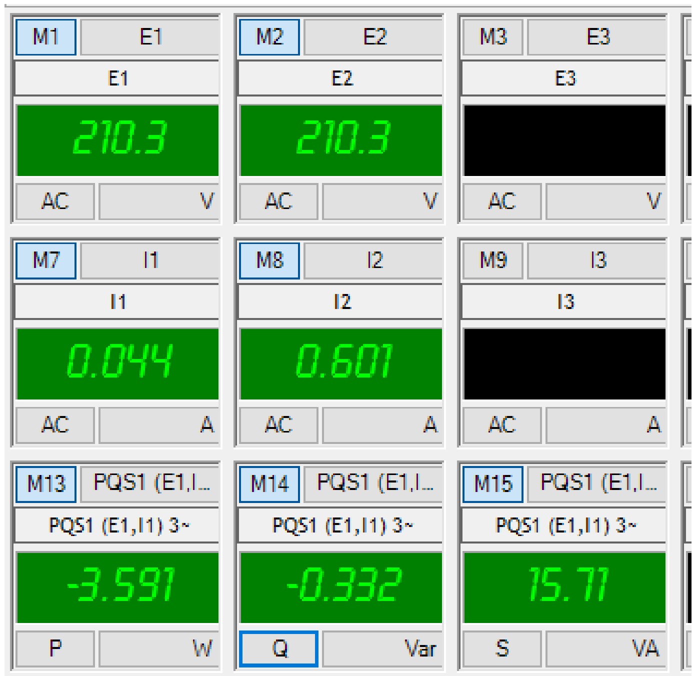
5. P = 0W or reach as closely to 0 as possible because of losses in the machine.



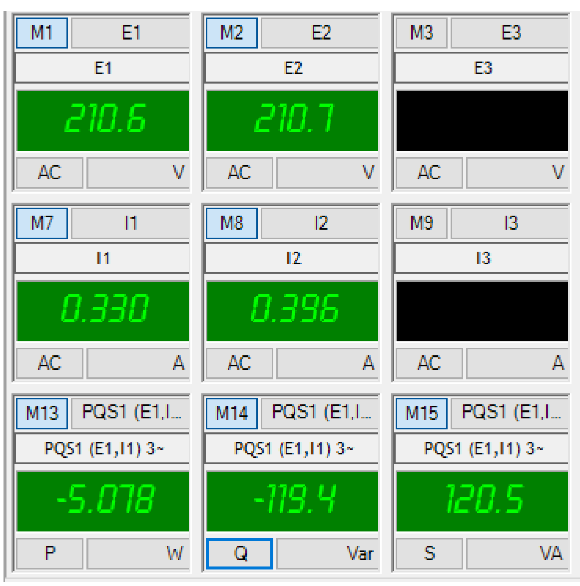
6. A decrease in DC excitation affect mainly the **reactive** power delivered by the alternator. The nature of the reactive power is different from Step 4.

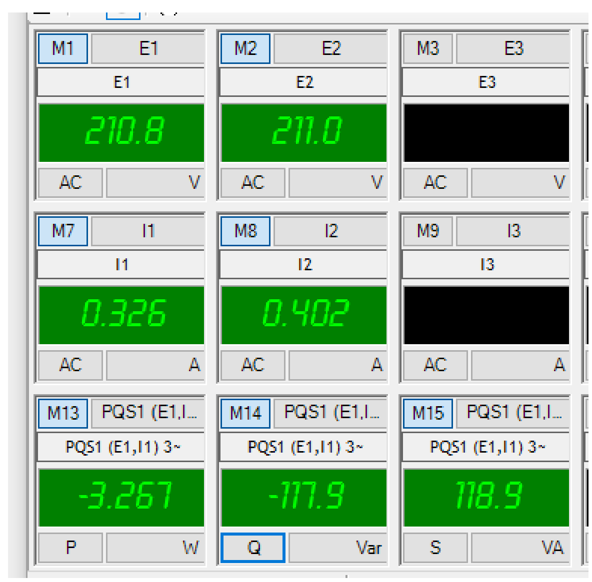


7. S = 0VA or reach as closely to 0 as possible due to loss.

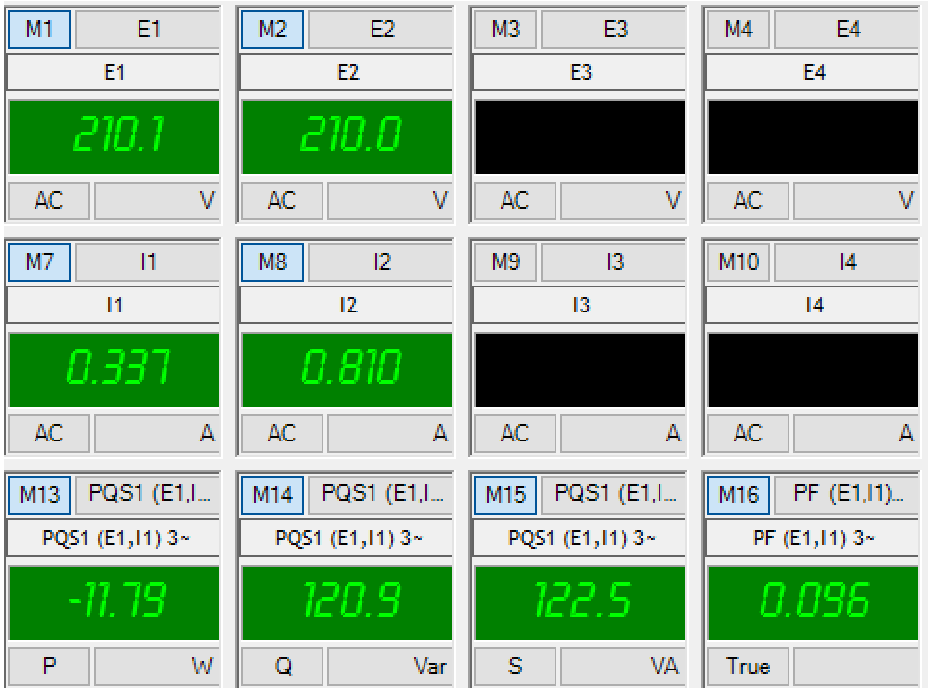


8. Decrease DC excitation voltage to get I_1 = 0.33A. An increase in torque leads to both P and Q to decrease (in source convention).





10. Here, $Q = 120.9\ var$ following generator convention, i.e., it's an inductive load on the alternator.



11. Here, $Q = -120.6\ var$ following generator convention, i.e., it's a capacitive load on the alternator.