ECSE 362 - Fundamentals of Power Engineering

Lab 3: The Power Transformer

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Lab section: 003

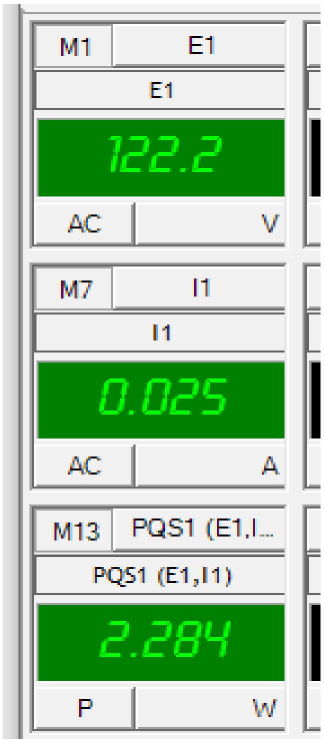
Introduction

The experiment is split into three main sections. The goal of the first section is to examine the voltage regulation and equivalent circuit of a single-phase transformer. This includes conducting open circuit, short circuit, and voltage regulation tests. The second section is dedicated to exploring connections in three-phase transformers, specifically investigating Y-Y, Δ-Y, Y-Δ, and Δ-Δ configurations. In the third and final section, we delve into special transformer connections, with a focus on experimenting with the open Δ connection.

1. Single-phase transformer voltage regulation and equivalent circuit

1.1. Open-circuit (OC) test

3. Measure and record all voltages and currents. Measure and record the active power consumed by the transformer.



5. Calculate the shunt impedance

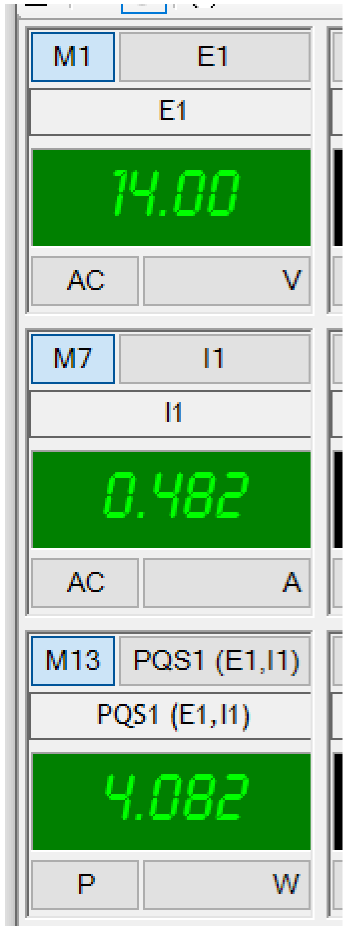
$$Z = \frac{V}{I} = \frac{122.2}{0.025} = 4888\ \Omega$$

1.2. Short-circuit (SC) test

1. Calculate the rated current of the transformer

60VA/120V = 0.5A

4. Measure and record all voltages and currents. Measure and record the active power consumed by the transformer



6. Calculate the series impedance of the transformer. Express your results both in ohms with respect to the low and the high voltage side and in per unit of the transformer ratings.

$V_{base,\,low} = 120V \quad V_{base,\,high} = 208V \quad S_{base} = 60\,VA \quad I_{base} = 0.5A$

$Z_{base,\,low} = \frac{120^2}{60} = 240\,\Omega \quad Z_{base,\,high} = \frac{208^2}{60} = 721.06\,\Omega$

$V_{L,\,p.u.} = \frac{14}{120} = 0.12\ p.u. \quad V_{H,\,p.u} = \frac{14}{208} = 0.067\ p.u.$

$Z_{eq,\,low} = \frac{14}{0.482} = 29.05\,\Omega = \frac{29.05}{240}\ p.u = 0.121\ p.u \quad Z_{eq,\,high} = 29.05\,\Omega = \frac{29.05}{721.06} = 0.040\ p.u.$

7. Which component of the impedance (resistive or reactive) is the dominant one?

Reactive component is the dominant one.

8. Using the same measurements, assume that the rated voltage between terminals 5 and 6 is 240Vac. Recalculate the equivalent series impedance in ohms of the transformer as seen from the high voltage side.

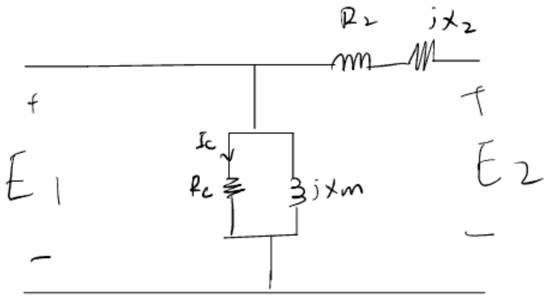
voltage side.

$V_b = 240V \quad S_b = 60\ VA \quad Z_b = \frac{240^2}{60} = 960\,\Omega$

$Z = 0.04 \cdot 960 = 38.4\,\Omega$

1.3. Voltage regulation

1. Draw the equivalent circuit for the transformer in ohms and in per-unit of the transformer's ratings



$Z_{OC} = 4888$

$R_c = \frac{V^2}{P} = \frac{122.2^2}{2.284} = 6538\ \Omega$

$I_{cL} = \frac{122.2}{6538} = 0.0187\ A$

$I_{mL} = 0.025 - 0.0187 = 0.0063\ A$

$X_m = \frac{V_L}{I_L} = \frac{122.2}{0.0063} = 19397\ \Omega$

In per unit: $Z_{base} = \frac{E_{base}^2}{S_{base}} = \frac{120^2}{60} = 240\ \Omega$

$R_{cL} = \frac{6538}{240} = 27.2$ p.u

$X_{mL} = \frac{19397}{240} = 80.8$ p.u.

$P_{SC} = I^2 R_{eq}$

$R_2 = \frac{P}{I^2} = \frac{4.082}{0.482^2} = 17.57\ \Omega$

$Z = \frac{V}{I} = 29.05\ \Omega$

$X_2 = \sqrt{Z^2 - R^2} = \sqrt{29.05^2 - 17.57^2} = 23.13\ \Omega$

In per unit: $R_2 = \frac{17.57}{240} = 0.0732$ p.u.

$X_2 = \frac{23.13}{240} = 0.0964$ p.u.

From high voltage side: $Z_{base} = \frac{208^2}{60} = 721.06$ p.u.

$R_c = \frac{6538}{721.06} = 9.067$ p.u.

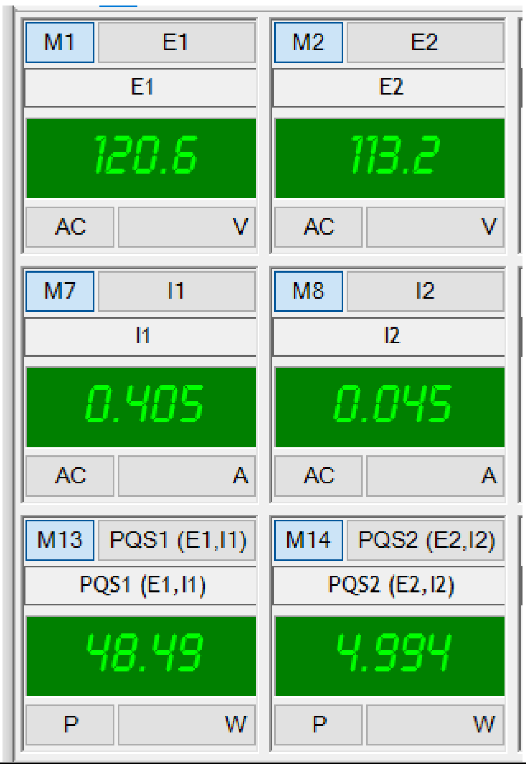
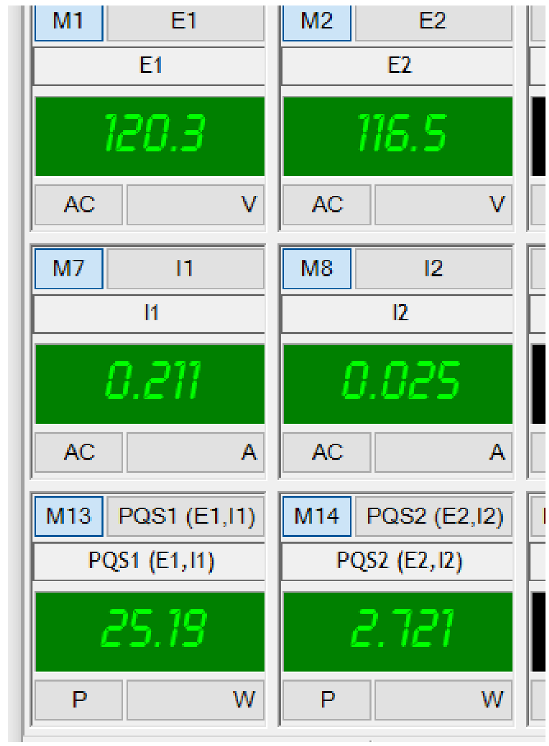
$X_m = \frac{19397}{721.06} = 26.9$ p.u.

$R_2 = \frac{17.57}{721.06} = 0.0244$ p.u.

$X_2 = \frac{23.13}{721.06} = 0.0321$ p.u.

5. Record all voltages and currents

Note that the settings of 5.5: R = 300 // 1200 ohms = 240 ohms allows us to reach the rated voltage and current the closest of all configurations.

<table>
<tr>
<td>5.1. We wired with R = 300 ohms, I = 0.4A option on the resistor bank

</td>
<td>5.2. R = 600 ohms, I = 0.2A

</td>
</tr>
<tr>
<td>5.3. R = 1200 ohms, I = 0.1A</td>
<td>5.4. R = 300 // 600 ohms = 200 ohms</td>
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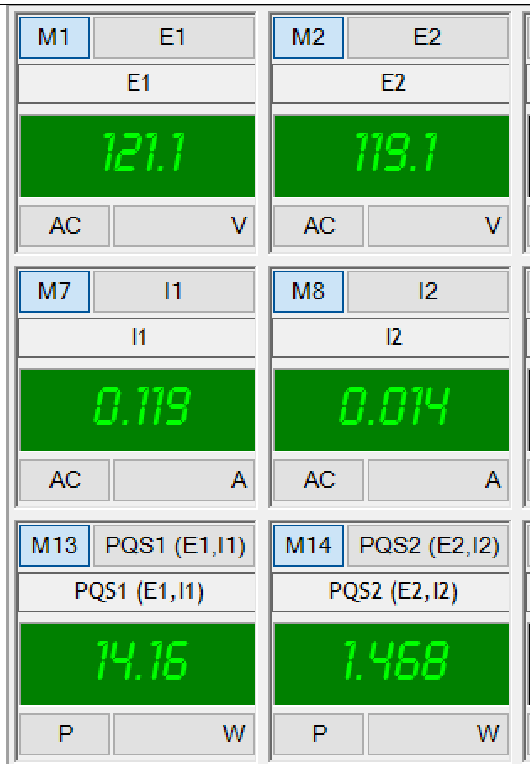
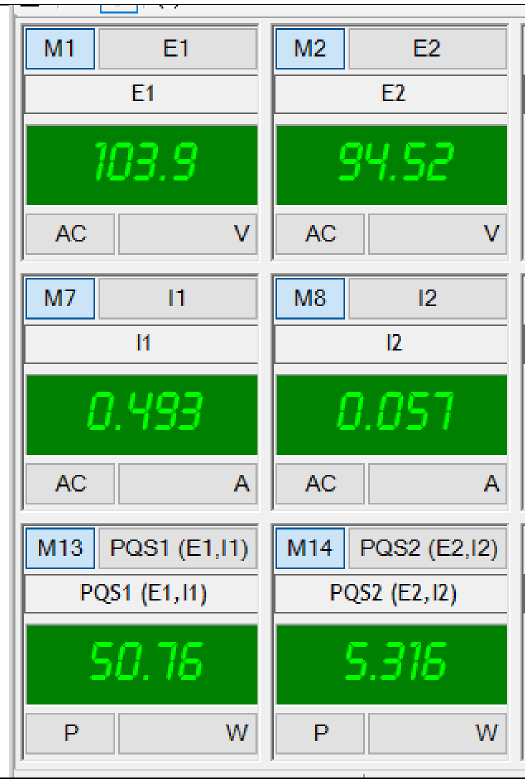
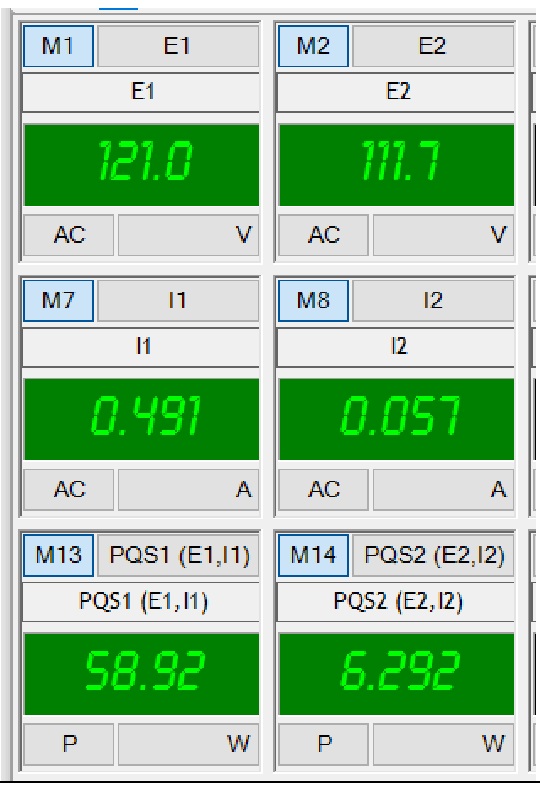
</table>

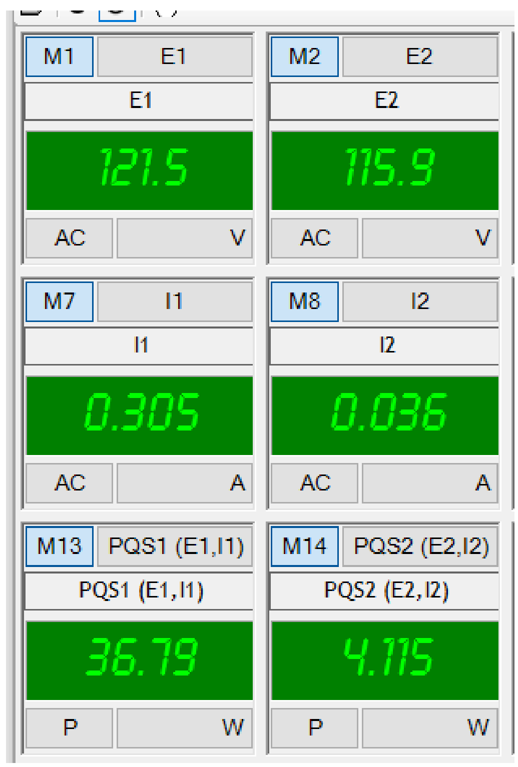




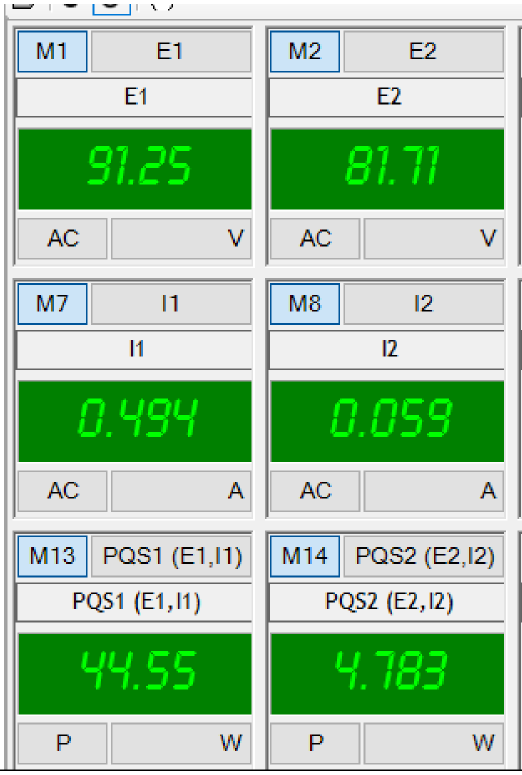
5.5. R = 300 // 1200 ohms = 240 ohms



5.6. R = 600 // 1200 ohms = ohms



5.7. R = 300 // 600 // 1200 ohms = ohms



6. Calculate the transformer voltage regulation based on measured values.

$$P = \frac{121 - 111.7}{121} \times 100 = 7.69\%$$

7. Using the transformer equivalent circuit, calculate the theoretical voltage regulation of the transformer. Compare with the one found experimentally.

$$P = \frac{120 - 0.5(240)}{120} = 0\%$$

The measured one is slightly larger than theoretical.

1.4. Supplementary questions

1. The result for shunt impedance makes sense as Rc << X_m. We can improve by choosing transformers with smaller voltage ratings.

2. We need to modify the number of turns on the winding since it is related to magnetic core of transformer.

3. It is related to the flux linkage. Therefore, to change the series impedance, we can make changes to losses from winding.

4. It leads to a high voltage drop, which would lead to increased risk of overheating and reduced efficiency.

5. It requires lower current and improved voltage regulations.

2. Basic three-phase transformer connections

2.1. Y-Y connection

3. Measure and record all phase and line voltages for both three-phase windings. Using the phasor analyser of the data acquisition unit, demonstrate the phase relationship of the voltages across the primary and the secondary windings of the transformer.

$E_1 = 118.82\angle 0$	$E_4 = 70.14\angle -148.87$	$E_7 = 118.29\angle -120.34$	$E_{10} = 70.91\angle -148.88$
$E_2 = 117.80\angle -120$	$E_5 = 72.62\angle 30.23$	$E_8 = 120.53\angle 0$	$E_{11} = 73.25\angle 30.48$
$E_3 = 117.50\angle 120$	$E_6 = 68.31\angle 88.89$	$E_9 = 119.03\angle 120.3$	$E_{12} = 69.11\angle 88.32$

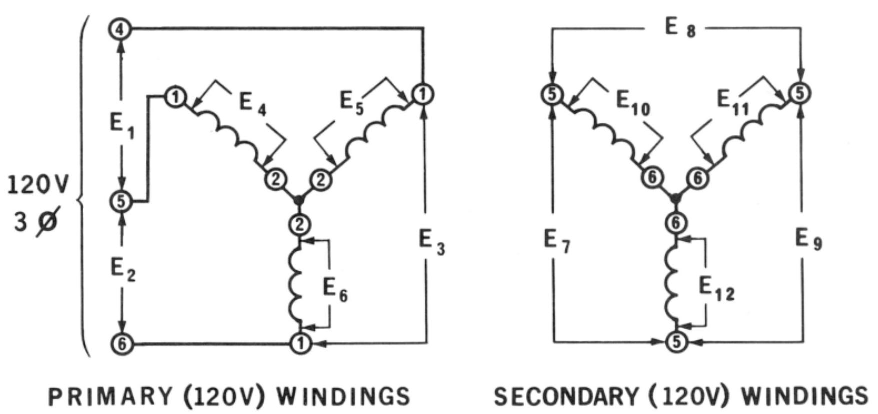
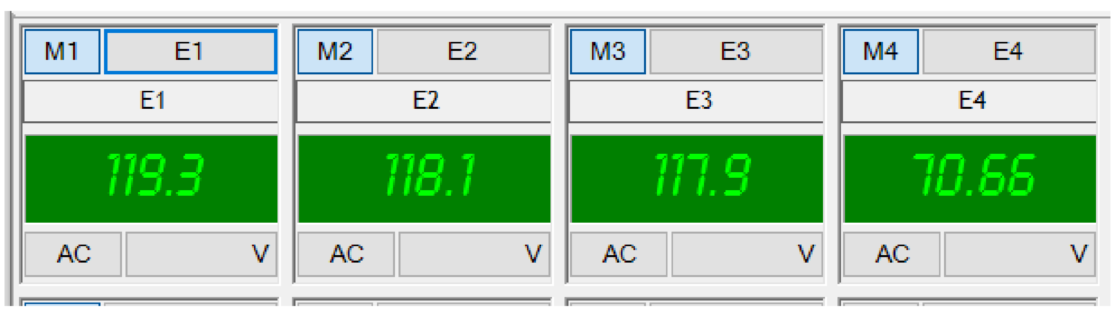
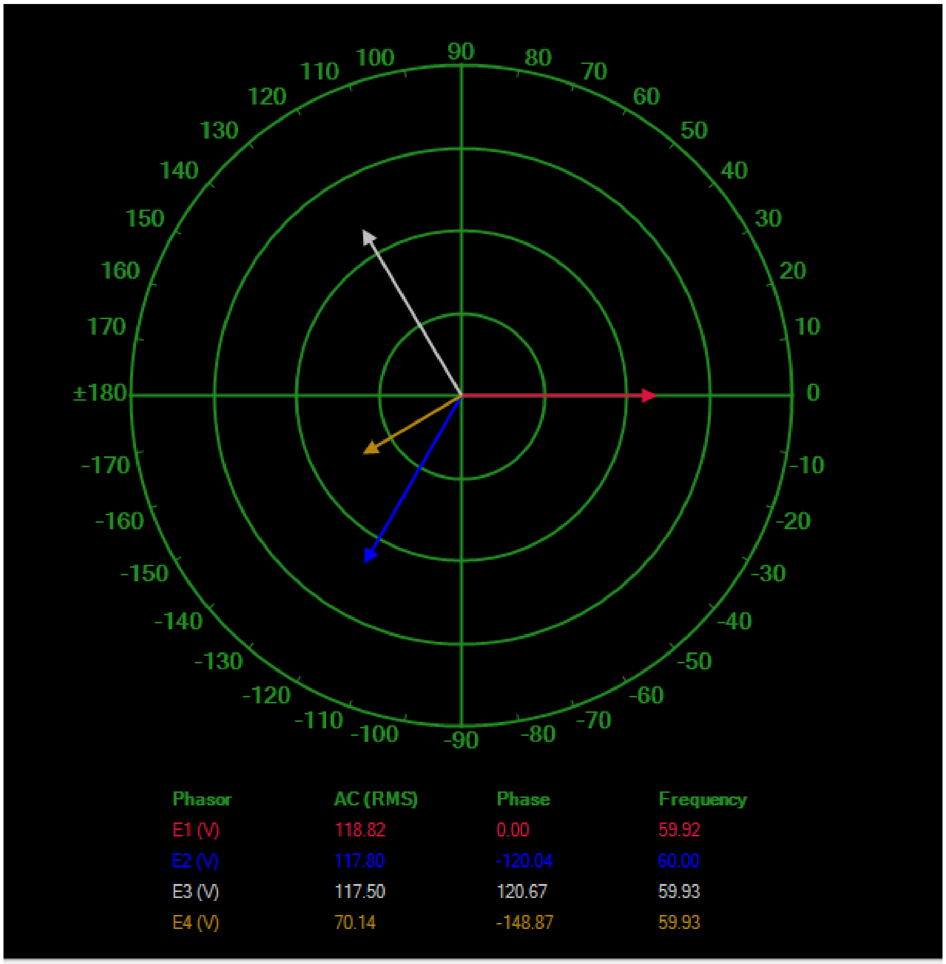


Figure 4: Y–Y transformer connection.

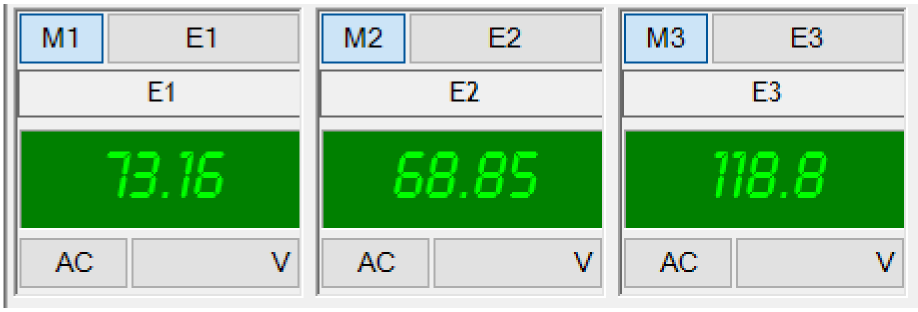
Below are the screenshots of all the measurement:

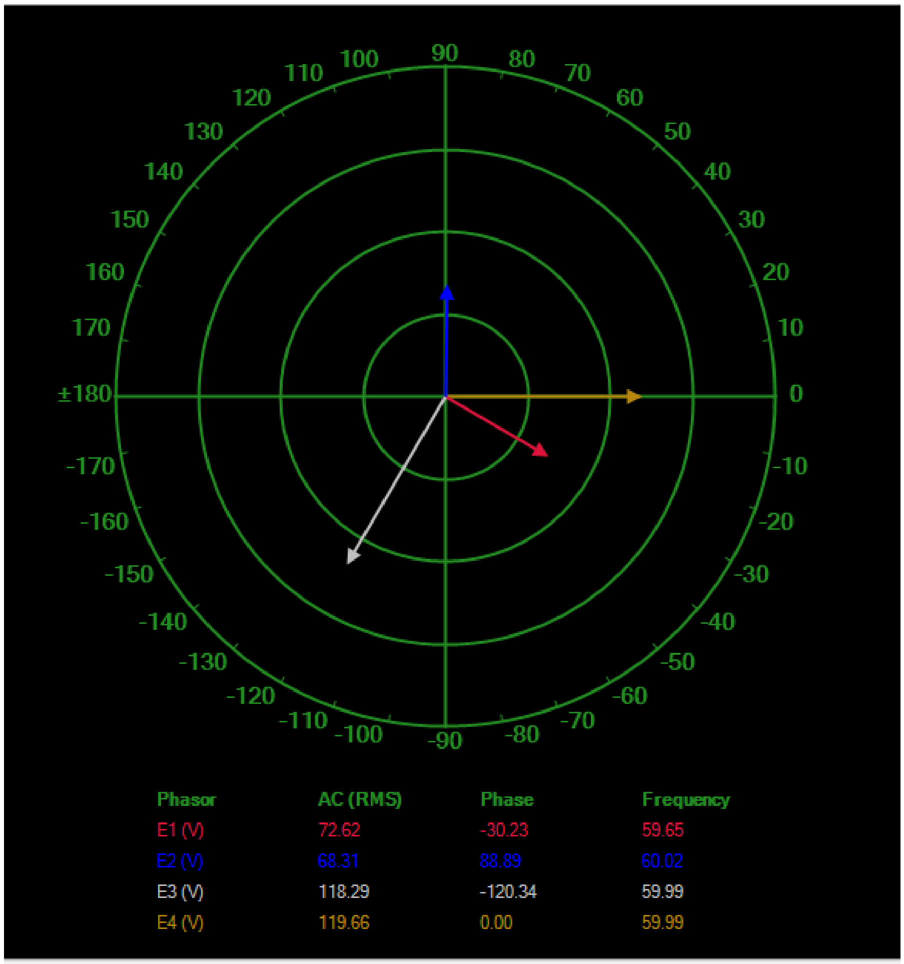
3.1. Measurements for E1, E2, E3, E4



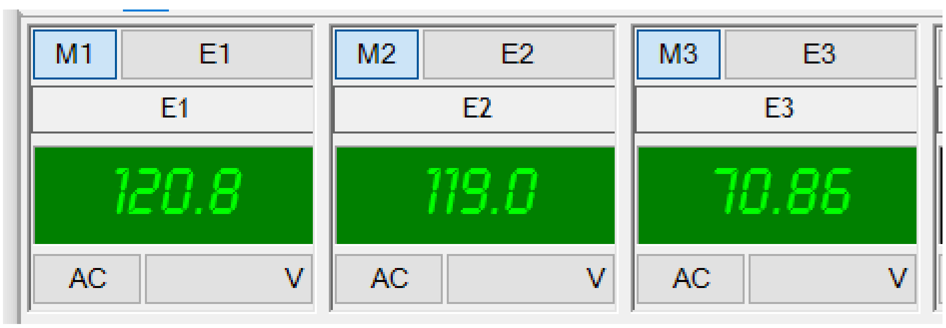


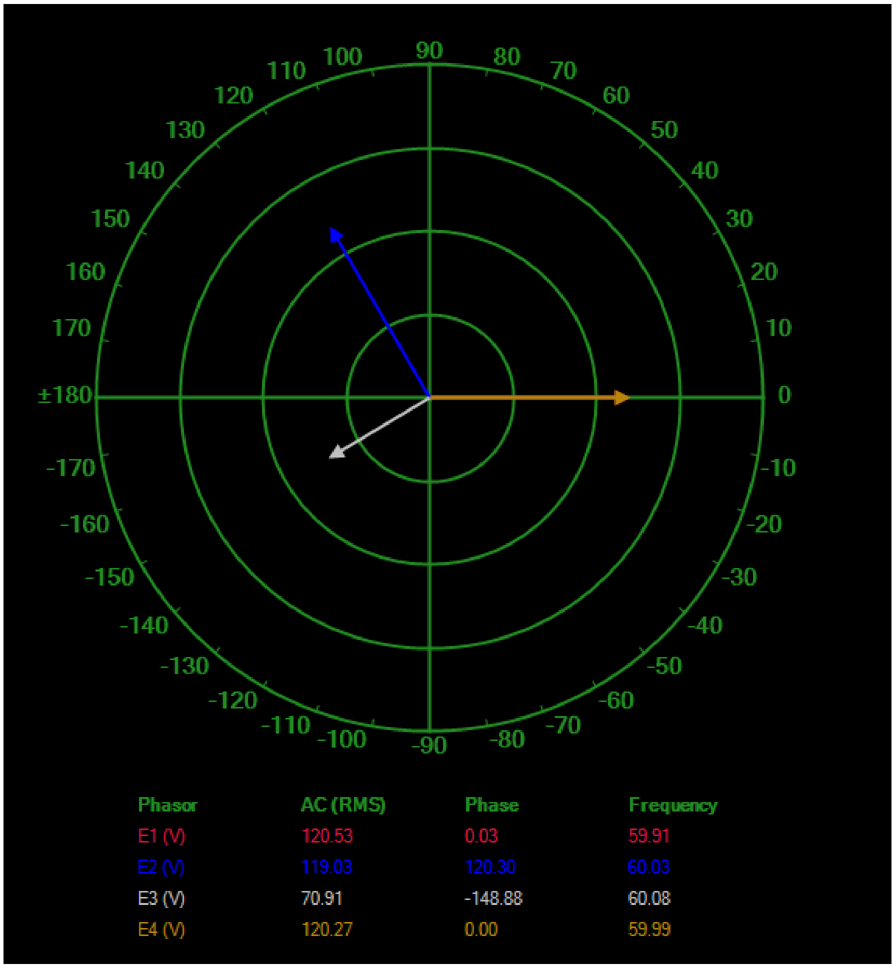
3.2. Measurements for E5, E6, E7. Note that we used *Voltmeter E4* to be E1 as the reference.



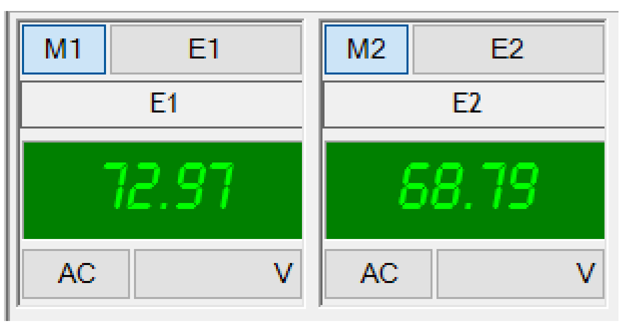


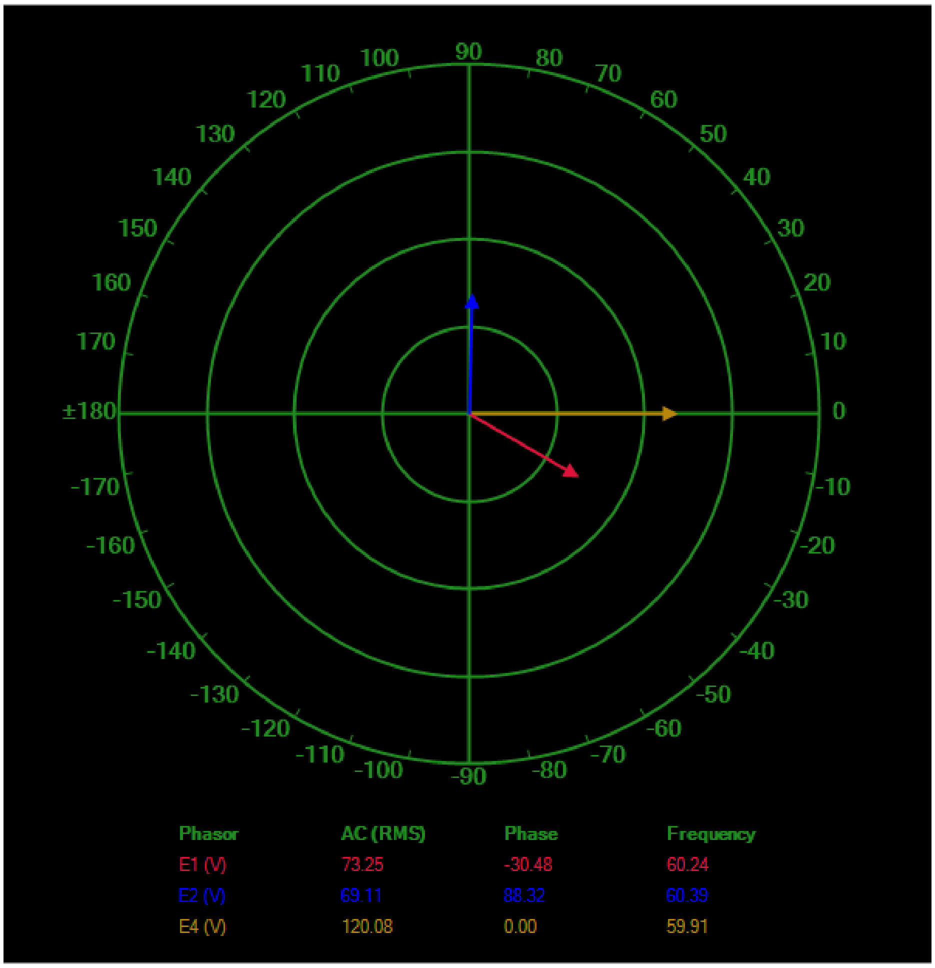
3.3. Measurements for E8, E9, E10. Note that we used *Voltmeter E4* to be E1 as the reference, and E8 has the same magnitude and phase as E1.





3.4. Measurements for E11, E12. Once again, *Voltmeter E4* is used to measure E1 as a reference.





2.2. Δ-Y connection

3. Measure and record all phase and line voltages for both three-phase windings. Using the phasor analyser of the data acquisition unit, demonstrate the phase relationship of the voltages across the primary and the secondary windings of the transformer.

$E_1 = 90.46\angle 0$	$E_4 = 153.68\angle -90.29$	$E_7 = 89.2\angle -120.49$
$E_2 = 89\angle 120.41$	$E_5 = 155.74\angle 29.37$	$E_8 = 90.70\angle -0.45$
$E_3 = 89.35\angle -120.49$	$E_6 = 154.86\angle 150.15$	$E_9 = 89.31\angle 120.16$

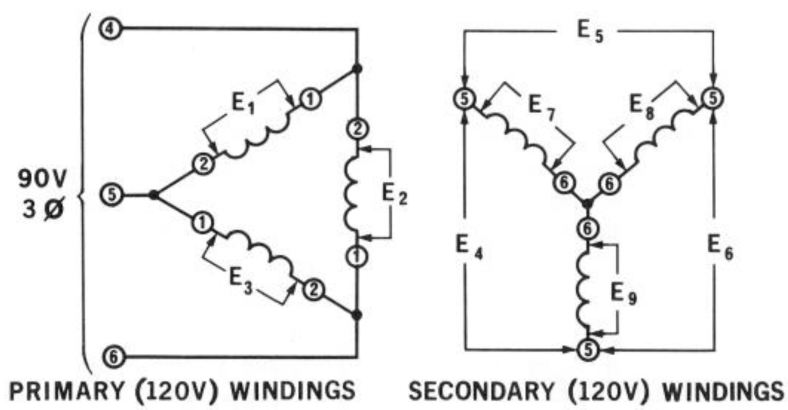
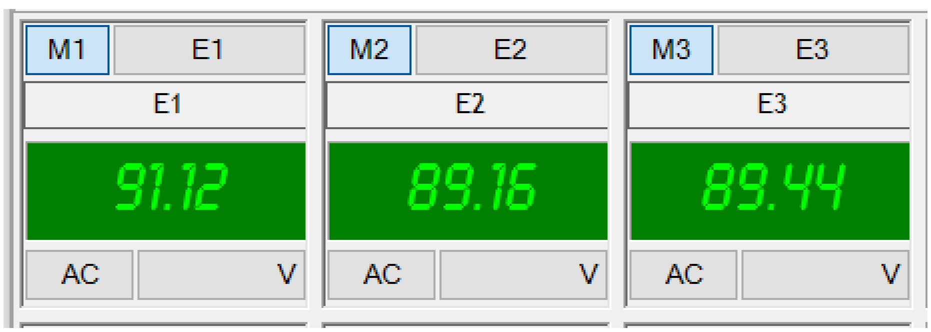
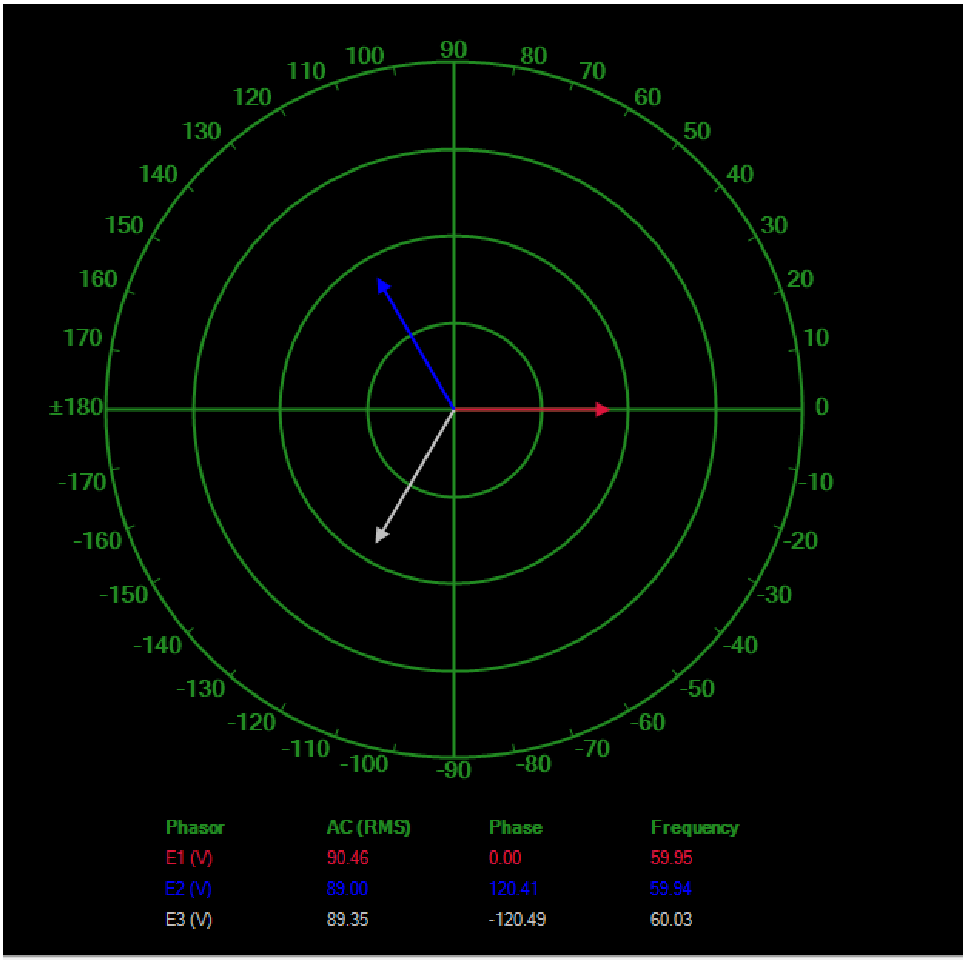


Figure 5: Δ–Y transformer connection.

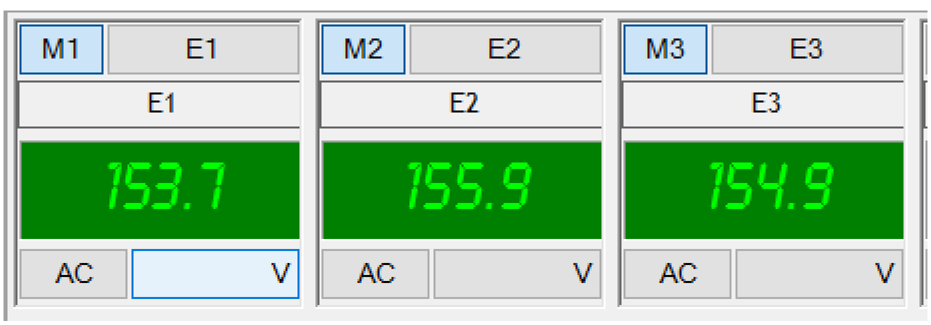
Below are the screenshots of the measurements.

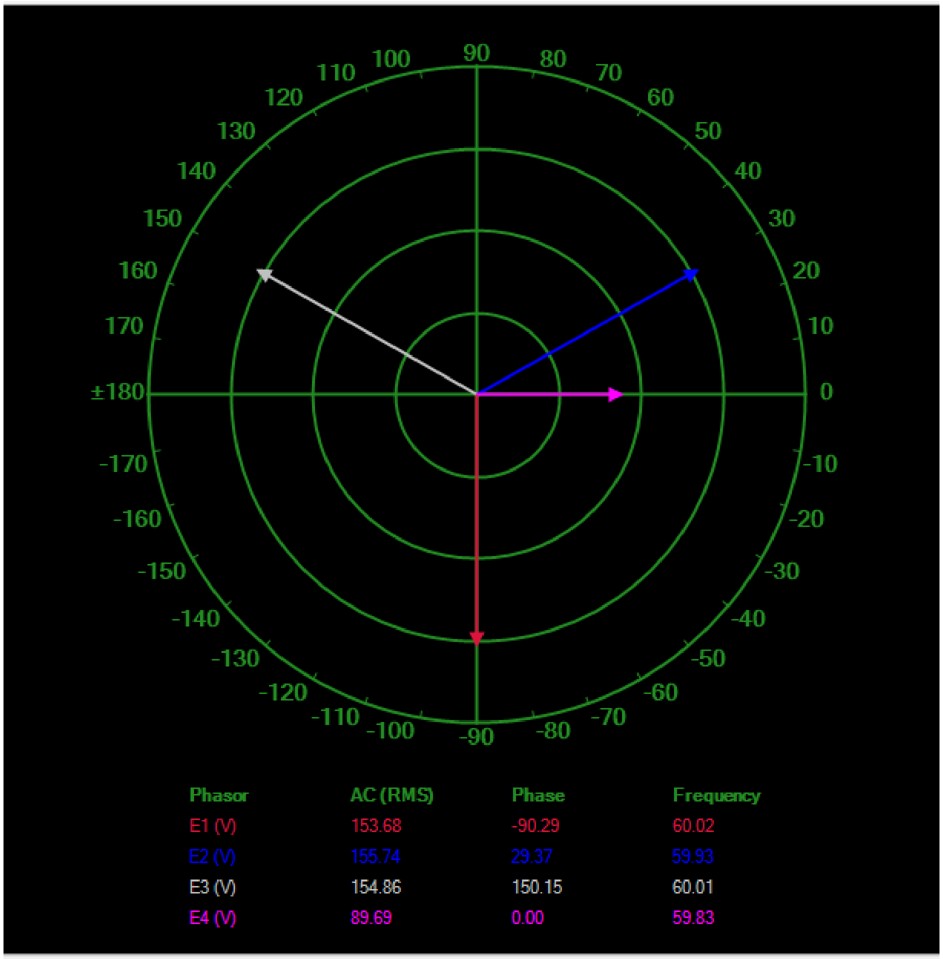
3.1. Measurements for E1, E2, E3



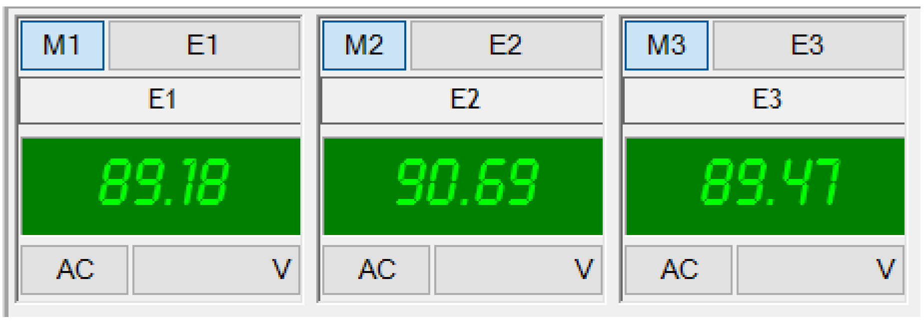


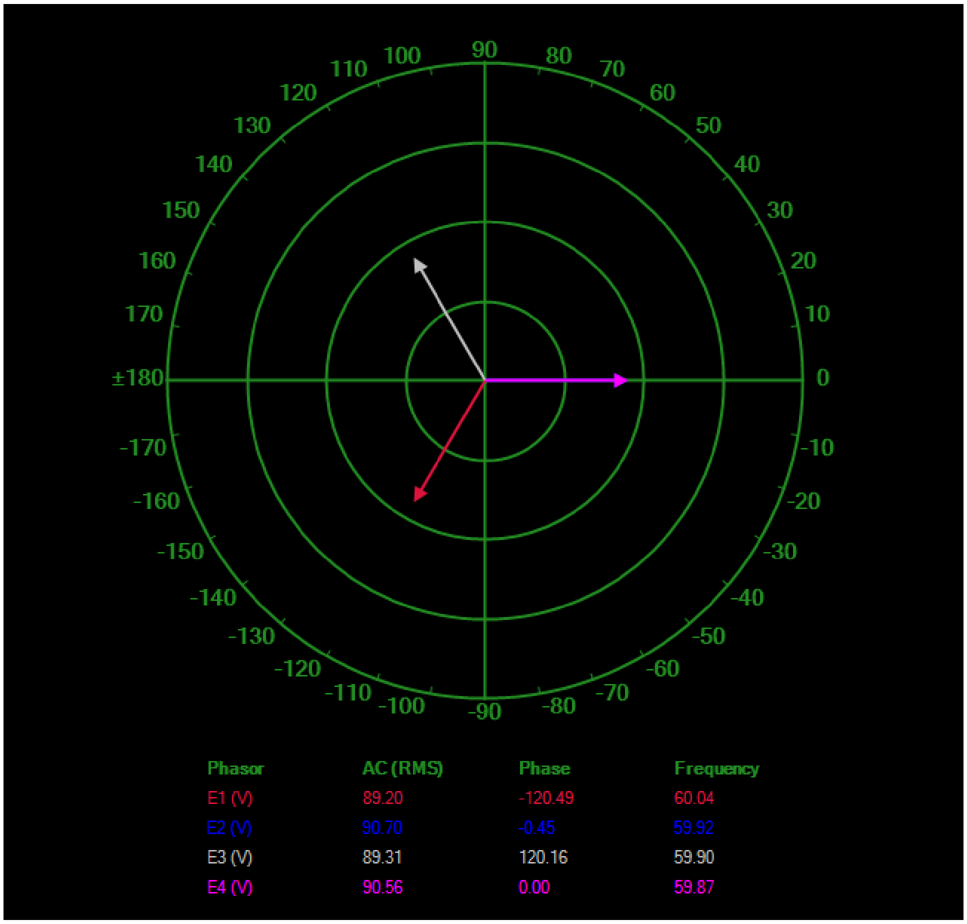
3.2. Measurements for E4, E5, E6. *Voltmeter E4* is used to measure E1 as reference (colored pink in the phasor analyser diagram).





3.3. Measurements for E7, E8, E9. *Voltmeter E4* was used to measure E1 as reference point, which has the same phase and magnitude as E8 in this scenario.




Phasor
AC (RMS)
Phase
Frequency
E1 (V) 89.20 -120.49 60.04
E2 (V) 90.70 -0.45 59.92
E3 (V) 89.31 120.16 59.90
E4 (V) 90.56 0.00 59.87

2.3. Y-Δ connection

5. Measure and record all phase and line voltages for both three-phase windings. Using the phasor analyzer of the data acquisition unit, demonstrate the phase relationships of the voltages across the primary and the secondary of the transformer. Include an appropriate screenshot in your report.

$E_1 = 121.2 \angle 0° \ V$	$E_4 = 69.29 \angle -150.50° \ V$	$E_7 = 71.76 \angle -151.44° \ V$
$E_2 = 119.7 \angle -120° \ V$	$E_5 = 69.73 \angle -30.35° \ V$	$E_8 = 69.71 \angle -29.62° \ V$
$E_3 = 119.7 \angle 120° \ V$	$E_6 = 68.63 \angle 89.45° \ V$	$E_9 = 71.15 \angle 90.81° \ V$

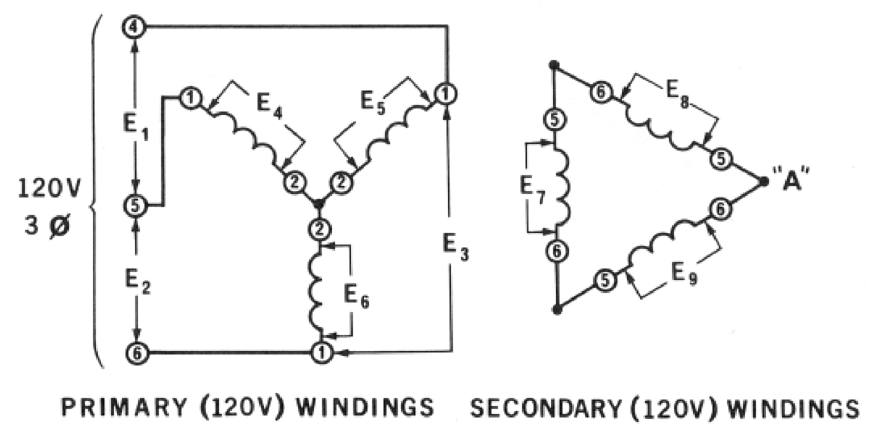
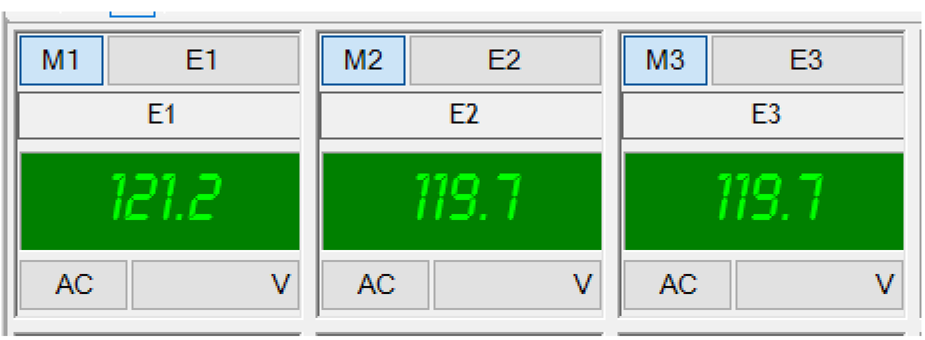
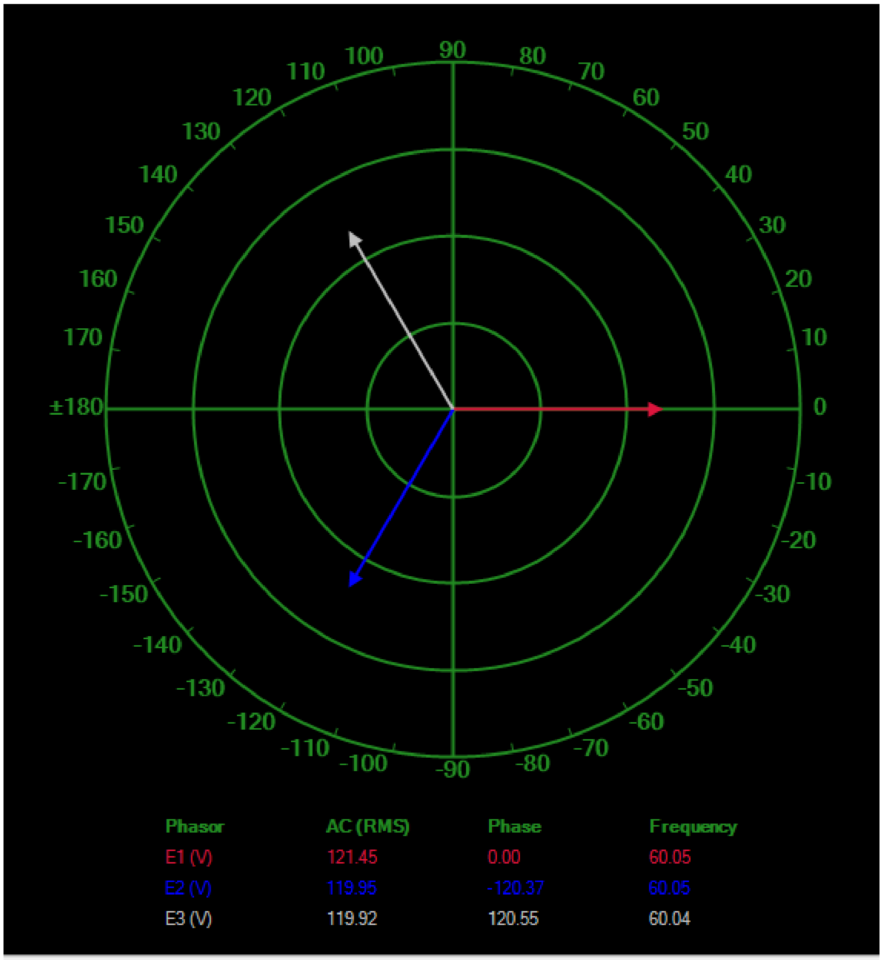


Figure 6: Y–Δ transformer connection.

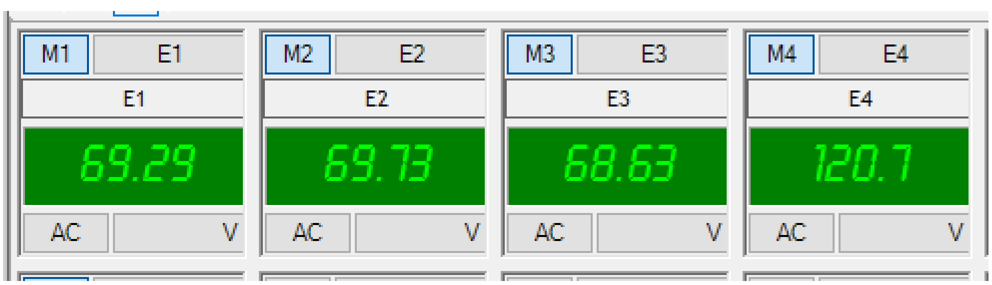
Below are the screenshots of the measurements

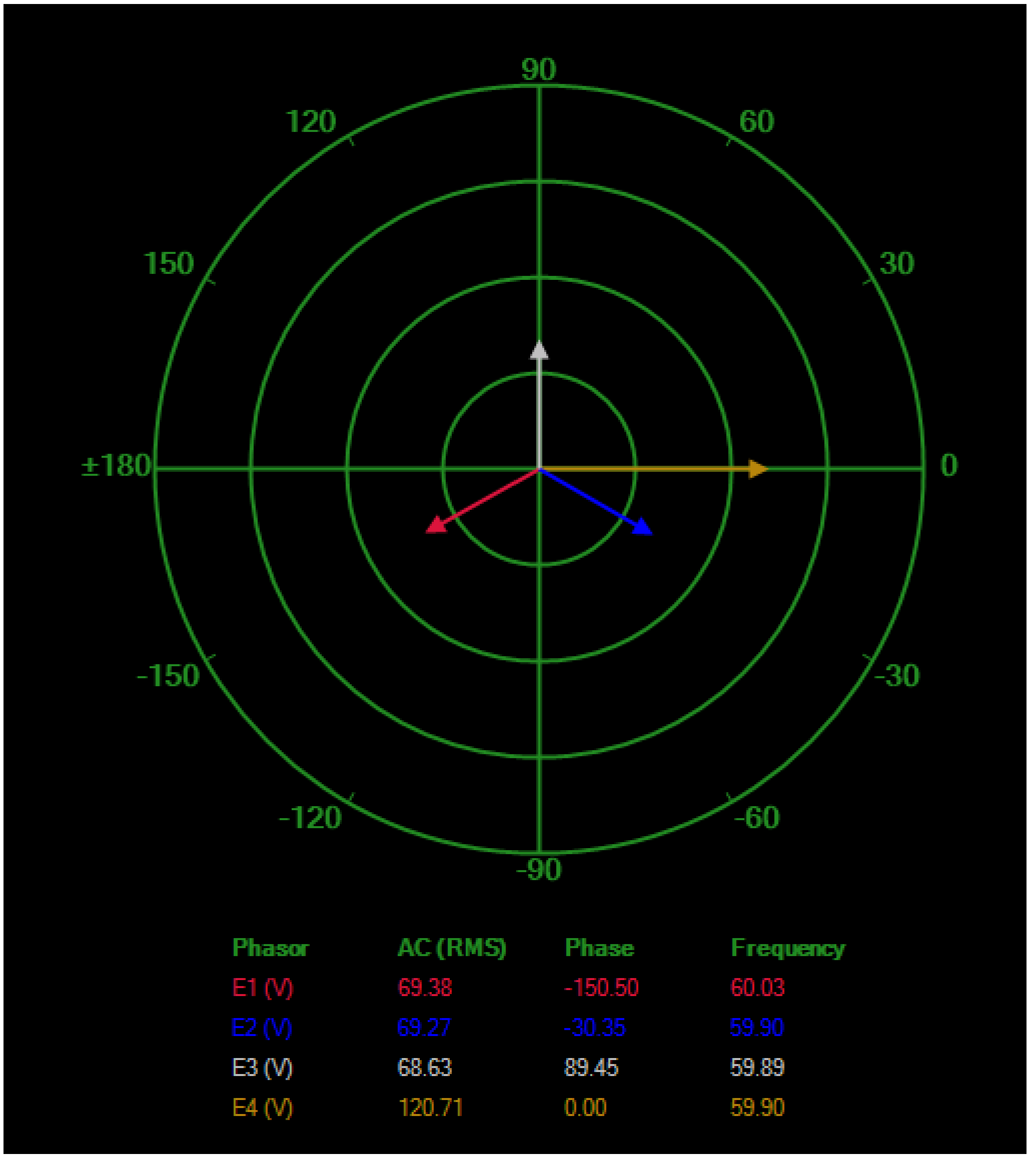
5.1. Measurements for E1, E2, E3, E4



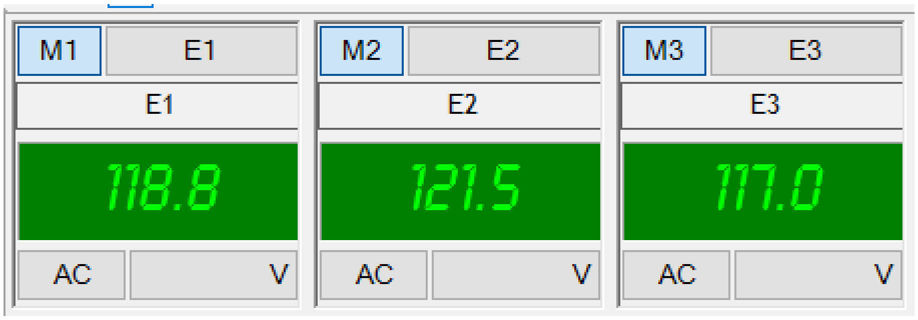


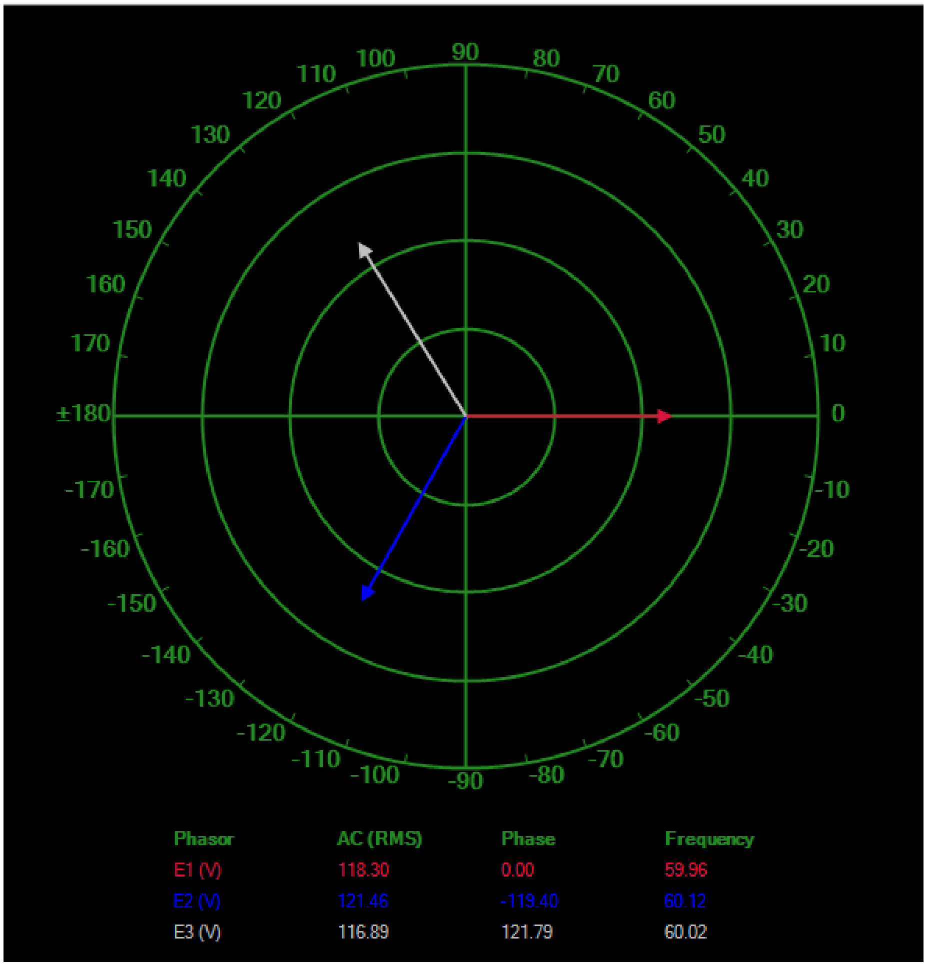
5.2. Measurements for E4, E5, E6.



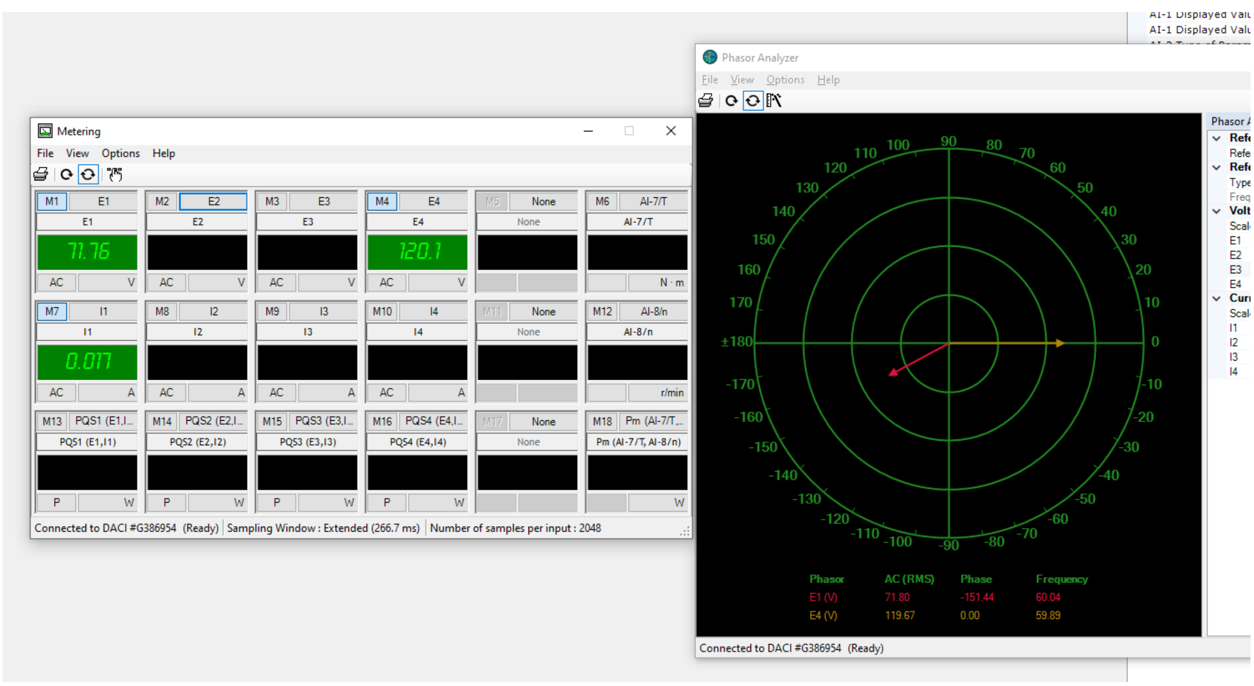


5.3. Measurements for E7, E8, E9

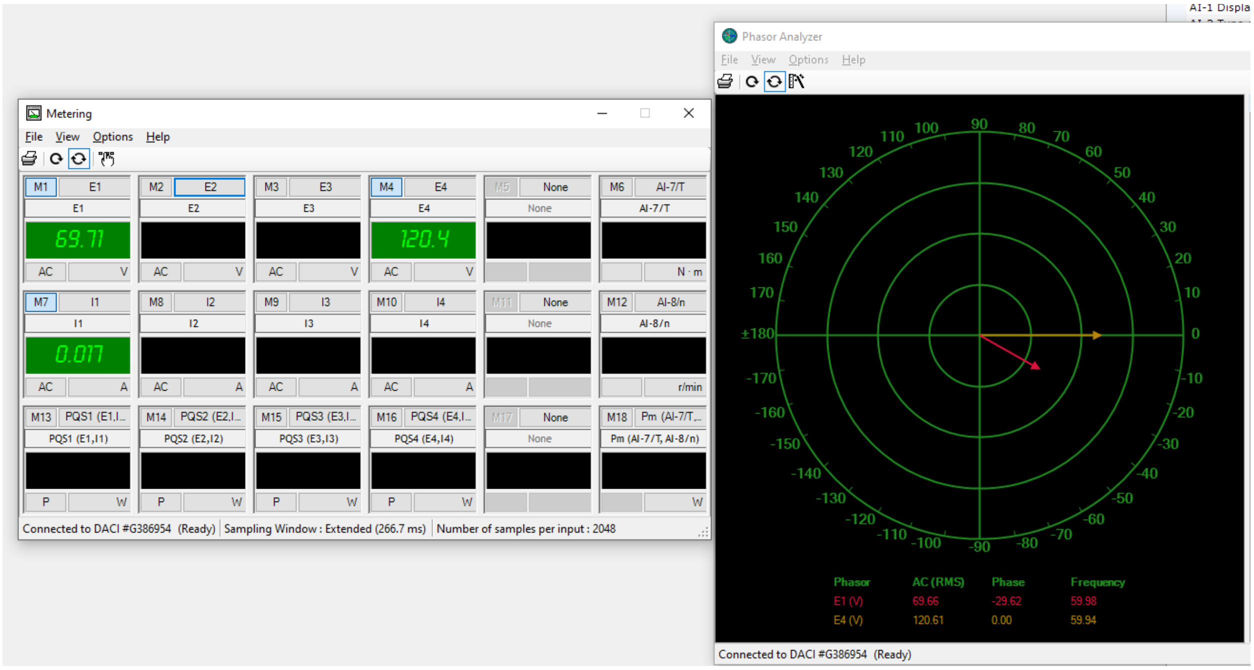



Phasor AC (RMS) Phase Frequency
E1 (V) 118.30 0.00 59.96
E2 (V) 121.46 -119.40 60.12
E3 (V) 116.89 121.79 60.02

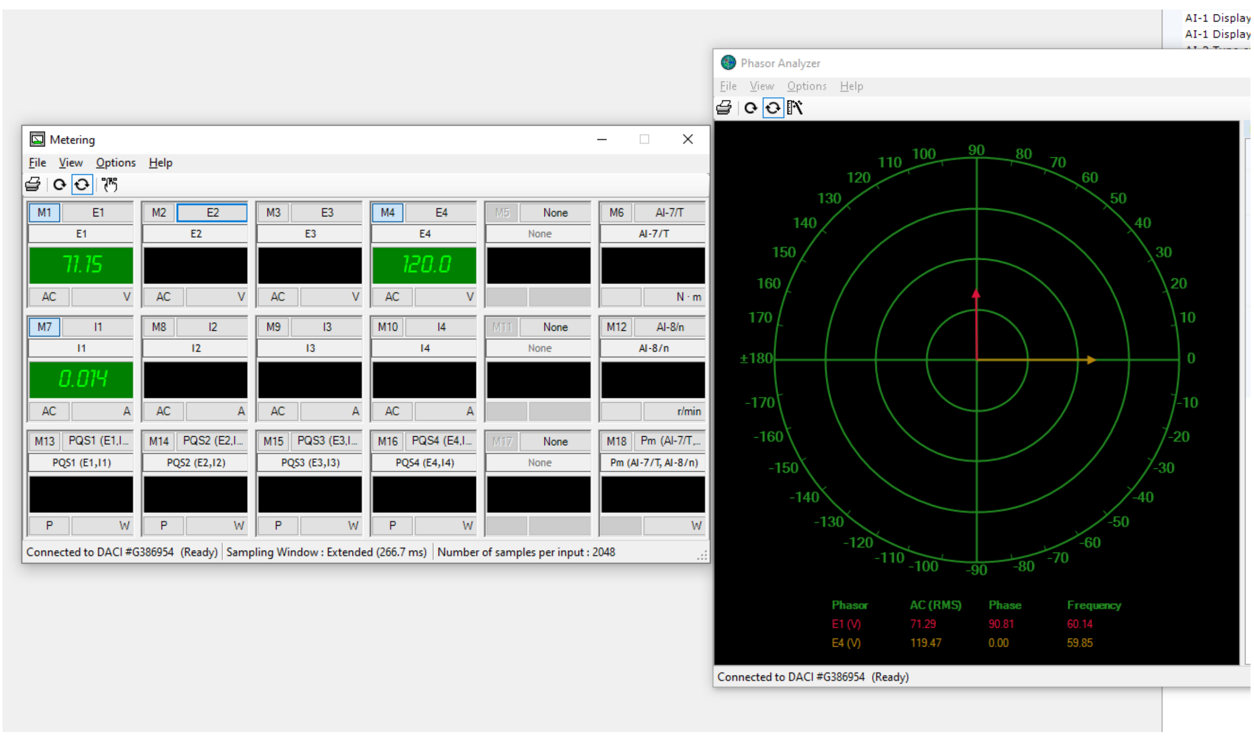
New E7:


Metering
File View Options Help
71.76
120.1
0.017
Connected to DACI #G386954 (Ready) | Sampling Window : Extended (266.7 ms) | Number of samples per input : 2048
Phasor Analyzer
File View Options Help
Phasor AC (RMS) Phase Frequency
E1 (V) 71.80 -151.44 60.04
E4 (V) 119.67 0.00 59.89
Connected to DACI #G386954 (Ready)

New E8:



New E9:



2.4. Δ-Δ connection

5. Measure and record all phase and line voltages for both three-phase windings. Using the phasor analyzer of the data acquisition unit, demonstrate the phase relationships of the voltages across the primary and the secondary of the transformer. Include an appropriate screenshot in your report.

$E_1 = 120.89 \angle 0$	$E_4 = 121.27 \angle 0$
$E_2 = 122.37 \angle 120.46$	$E_5 = 122.83 \angle 120.38$
$E_3 = 120.76 \angle -119.14$	$E_6 = 121.31 \angle -119.08$

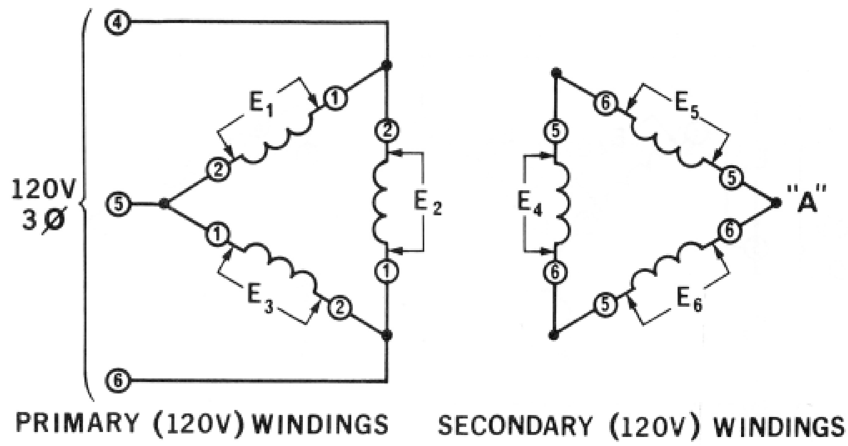
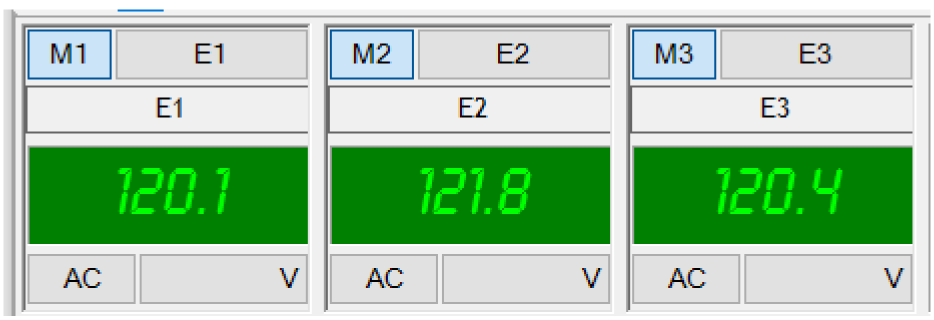
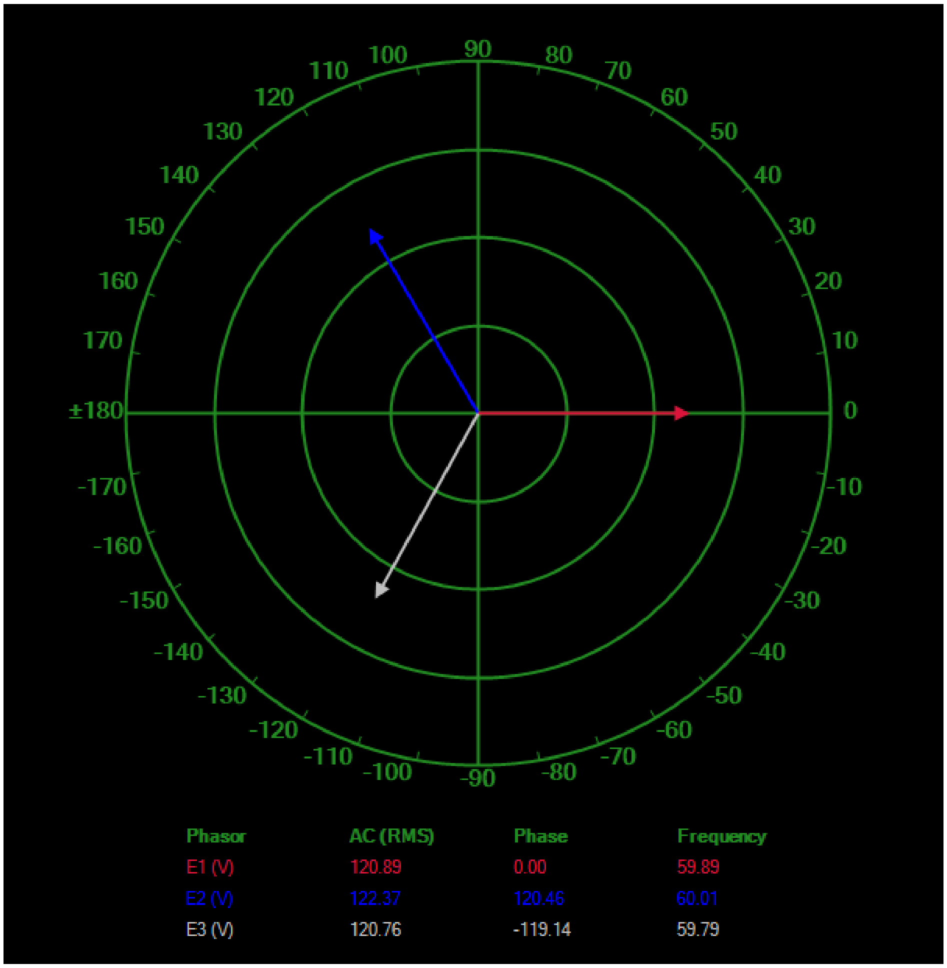


Figure 7: Δ–Δ transformer connection.

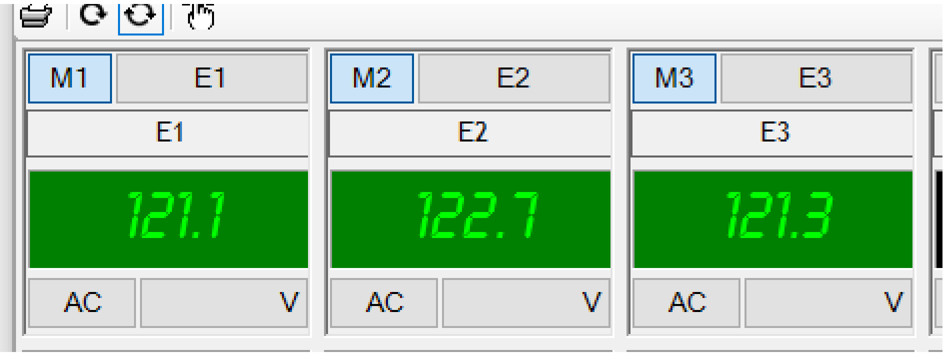
Below are the screenshots for all the measurements

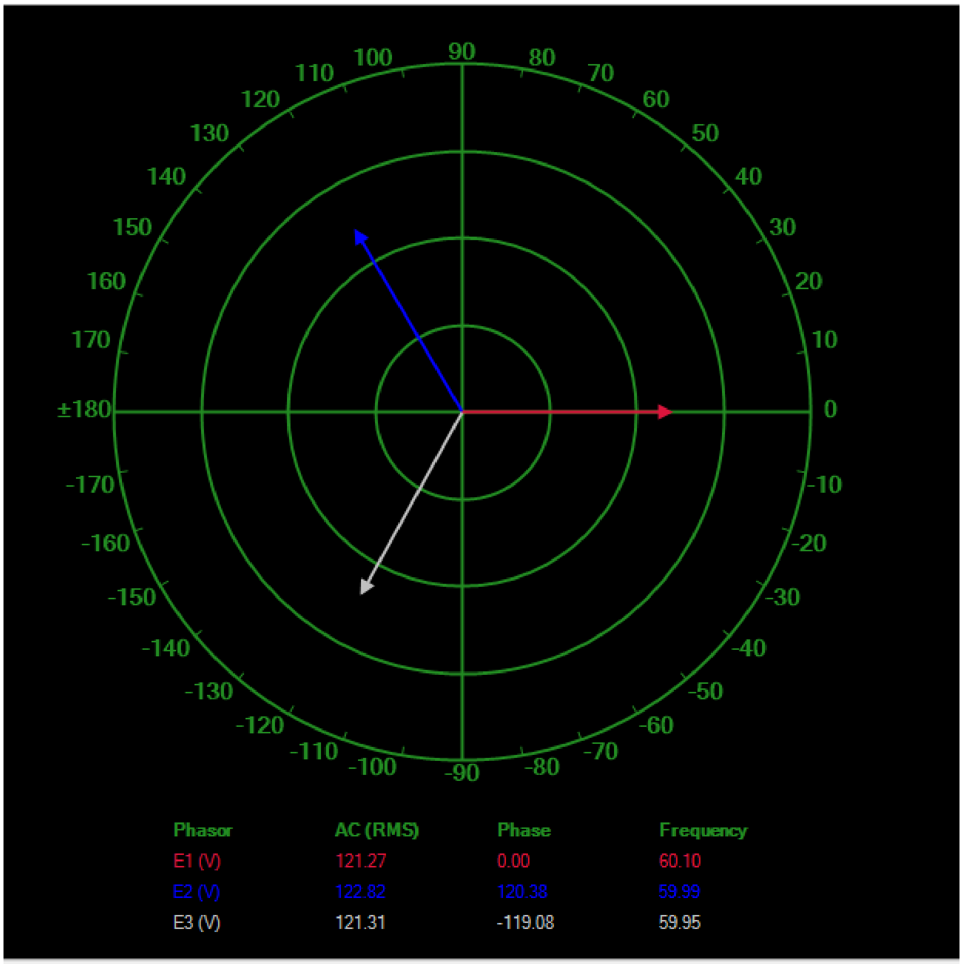
5.1. Measurements for E1, E2, E3





5.2. Measurements for E4, E5, E6




90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
±180
170
160
150
140
130
120
110
100
Phasor
AC (RMS)
Phase
Frequency
E1 (V)
121.27
0.00
60.10
E2 (V)
122.82
120.38
59.99
E3 (V)
121.31
-119.08
59.95

2.5. Supplementary Questions

1.

2.1 Y-Y Y-connection, $V_p = \frac{1}{\sqrt{3}}\angle -30\, V_L$

$E_1 = 120\angle 0$ V $\quad E_5 = 69.28\angle -30^\circ$ V $\quad E_8 = 120\angle 0^\circ$ V $\quad E_{11} = 69.28\angle -30^\circ$ V

$E_2 = 120\angle -120$ V $\quad E_4 = 69.28\angle -150^\circ$ V $\quad E_7 = 120\angle -120^\circ$ V $\quad E_{10} = 69.28\angle -150^\circ$ V

$E_3 = 120\angle 120$ V $\quad E_6 = 69.28\angle 90^\circ$ V $\quad E_9 = 120\angle 120^\circ$ V $\quad E_{12} = 69.28\angle 90^\circ$ V

2.2 Δ-Y Δ connection $V_p = V_L$ $\quad$ Y: $V_L = \sqrt{3}\angle 30\, V_p$

$E_1 = 90\angle 0$ V $\quad E_5 = 156\angle 30$ V $\quad E_8 = 90\angle 0$

$E_2 = 90\angle -120$ V $\quad E_4 = 156\angle -90$ V $\quad E_7 = 90\angle -120$

$E_3 = 90\angle 120$ V $\quad E_6 = 156\angle 150$ V $\quad E_9 = 90\angle 150$

2.3 Y-Δ

$E_1 = 120\angle 0$ V $\quad E_5 = 69.28\angle -30$ V $\quad E_7 = 120\angle 0$ V

$E_2 = 120\angle -120$ V $\quad E_4 = 69.28\angle -150$ V $\quad E_8 = 120\angle -120$ V

$E_3 = 120\angle 120$ V $\quad E_6 = 69.28\angle 90$ V $\quad E_9 = 120\angle 120$ V

2.4 Δ-Δ

$E_1 = 120\angle 0$ $\quad E_4 = 120\angle 0$

$E_3 = 120\angle -120$ $\quad E_6 = 120\angle -120$

$E_2 = 120\angle 120$ $\quad E_5 = 120\angle 120$

Between primary and secondary voltages

Y-Y connection no shift

Δ-Y connection phase voltage equal, line voltage on primary side is $\sqrt{3}\angle 30$ of secondary side

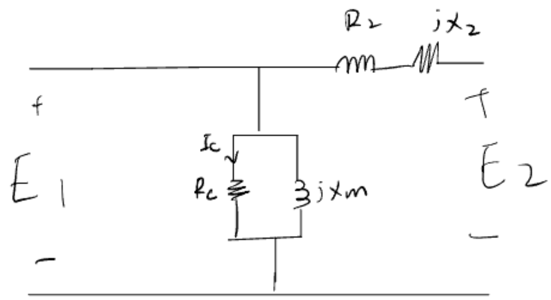
Y-Δ connection line voltage equal, phase voltage on primary side is $\frac{1}{\sqrt{3}}\angle -30$ of secondary side

Δ-Δ connection no shift

2. $S_{max} = 100 \times 3 = 300\ KVA$

3. Based on the equivalent circuit of the single-phase transformer found in Section 1.3, calculate the single line equivalent circuit parameters for each three-phase connection in ohms on the high and on the low voltage side and in per unit. Use as base quantities the rated line voltages and the three-phase rated power of the transformer.

From Section 1.3, we have the equivalent circuit:



We have the three-phase transformer voltage ratings are 208 V/120V, where 208 V is the rating for phase-to-phase connection (Y-connection line voltage) and 120 V is the rating for phase-to-neutral (Δ-connection line voltage). The rated power is 180 VA. Hence, we have the base quantities:

$$V_{base-Y} = 208\ V \mid V_{base-\Delta} = 120\ V$$

$$S_{base} = 180\ VA$$

3.1. Y-Y circuit

We have the base impedance: $Z_{base} = \frac{208^2}{180} = 240\ \Omega$, and it is the same for both side of the transformer. Assume the current is set up similar to the open-circuit and short-circuit test from Part 1, we can obtain the shunt and series impedances, respectively:

- Shunt impedance:

$$Z_{shunt} = \mathbf{4888\ \Omega} = \frac{4888\Omega}{240\Omega} = \mathbf{20.37\ (p.u.)}$$

- Series impedance:

$$Z_{series} = \mathbf{29.05\ \Omega} = \frac{29.05\Omega}{240\Omega} = \mathbf{0.12\ (p.u.)}$$

3.2. Δ-Y circuit

Per unit parameters remains the same regardless of connection types. Those are shunt impedance: $Z_{shunt} = 20.37\ p.u.$ and $Z_{series} = 0.12\ p.u.$

- On the primary (Δ) side: $V_{b1} = 120V$ instead of 208V due to the Δ-connection making the voltage to be phase-to-neutral. Hence,

$$Z_{shunt-1} = 20.37\ \times \frac{120^2}{250} = \mathbf{1173.31\ \Omega}$$

$$Z_{series-1} = 0.12 \times \frac{120^2}{250} = \mathbf{6.91\ \Omega}$$

- On the secondary (Y) side: $V_{b2} = 208V$

$$Z_{shunt-2} = 20.37 \times \frac{208^2}{250} = \mathbf{4888\ \ \Omega}$$

$$Z_{series-2} = 0.12 \times \frac{208^2}{250} = \mathbf{29.05\ \Omega}$$

3.3. Y-Δ circuit

- On the primary (Y) side: $V_{b1} = 208V$

$$Z_{shunt-1} = 20.37 \times \frac{208^2}{250} = \mathbf{4888\ \ \Omega}$$

$$Z_{series-1} = 0.12 \times \frac{208^2}{250} = \mathbf{29.05\ \Omega}$$

- On the secondary (Δ) side: $V_{b2} = 120V$

$$Z_{shunt-2} = 20.37 \times \frac{120^2}{250} = \mathbf{1173.31\ \Omega}$$

$$Z_{series-2} = 0.12 \times \frac{120^2}{250} = \mathbf{6.91\ \Omega}$$

3.3. Δ-Δ circuit

- On the primary (Δ) side: $V_{b1} = 120V$

$$Z_{shunt-1} = 20.37 \times \frac{120^2}{250} = \mathbf{1173.31\ \Omega}$$

$$Z_{series-1} = 0.12 \times \frac{120^2}{250} = \mathbf{6.91\ \Omega}$$

- On the secondary (Δ) side: $V_{b2} = 120V$

$$Z_{shunt-2} = 20.37 \times \frac{120^2}{250} = \mathbf{1173.31\ \Omega}$$

$$Z_{series-2} = 0.12 \times \frac{120^2}{250} = \mathbf{6.91\ \Omega}$$

4. (a) No	(b) No	(c) No	(d) Yes
5. (a) No	(b) Yes	(c) No	(d) Yes

3. Special Transformer Connections

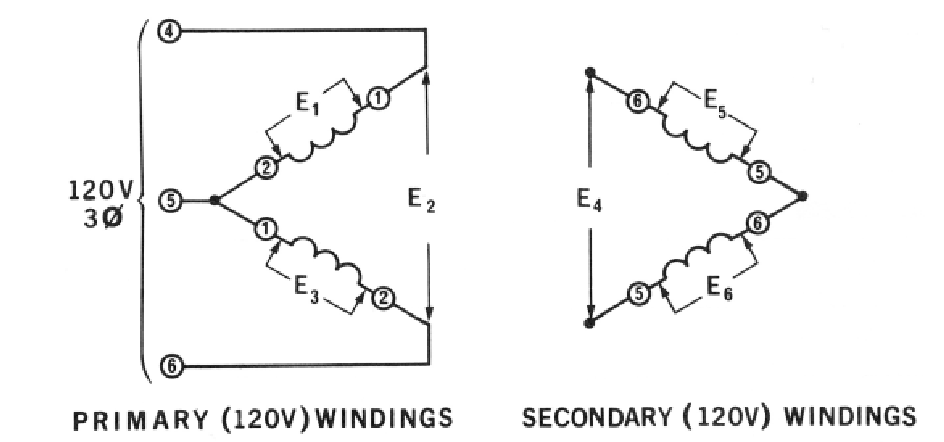


Figure 8: Open-Δ transformer connection.

3.1. The open-Δ connection

1.

$E_1 = 120\angle 0$

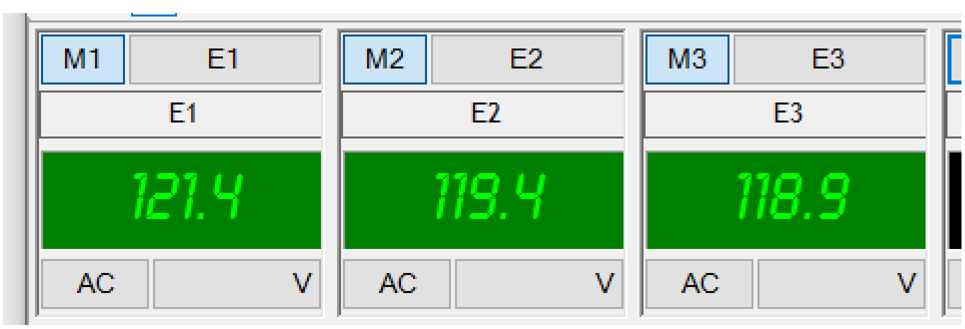
$E_2 = 120\angle 120$

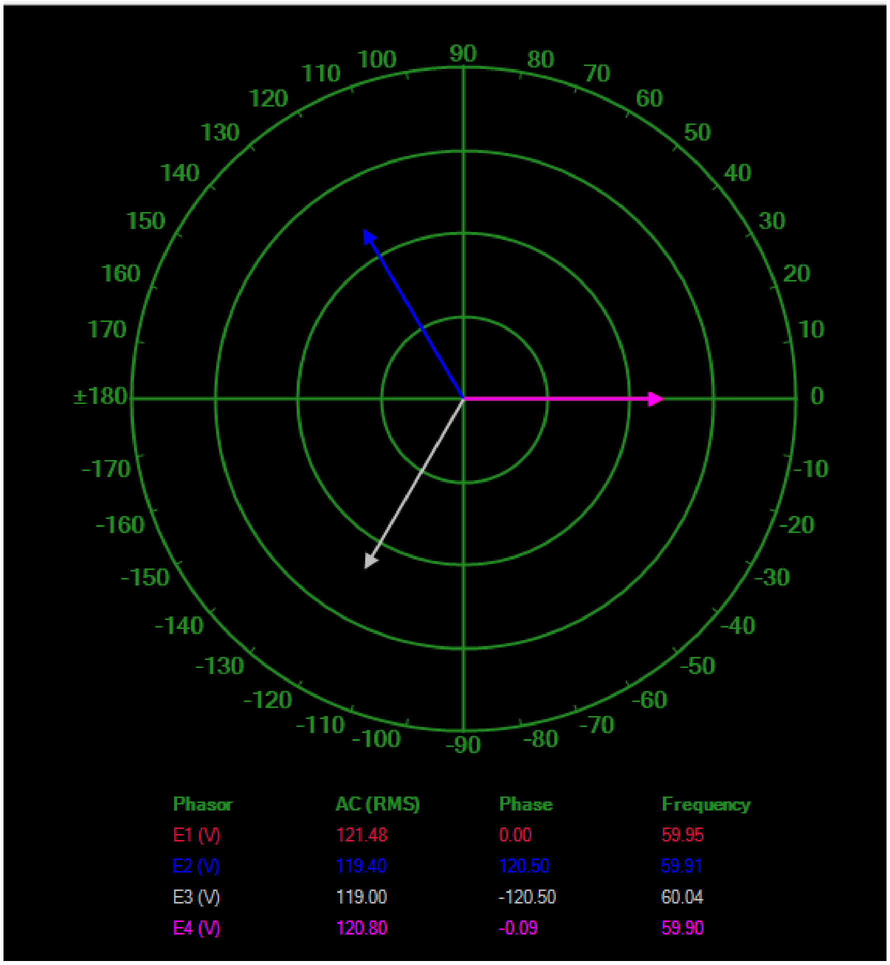
$E_3 = 120\angle -120$

$E_5 = 120\angle 0$

$E_4 = 120\angle 120$

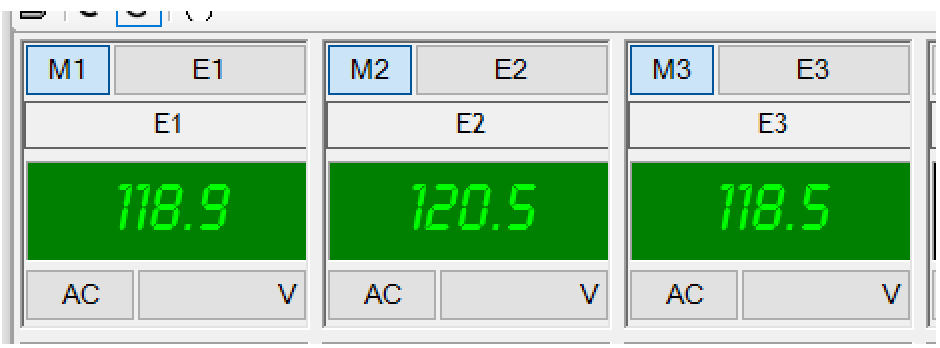
$E_6 = 120\angle -120$

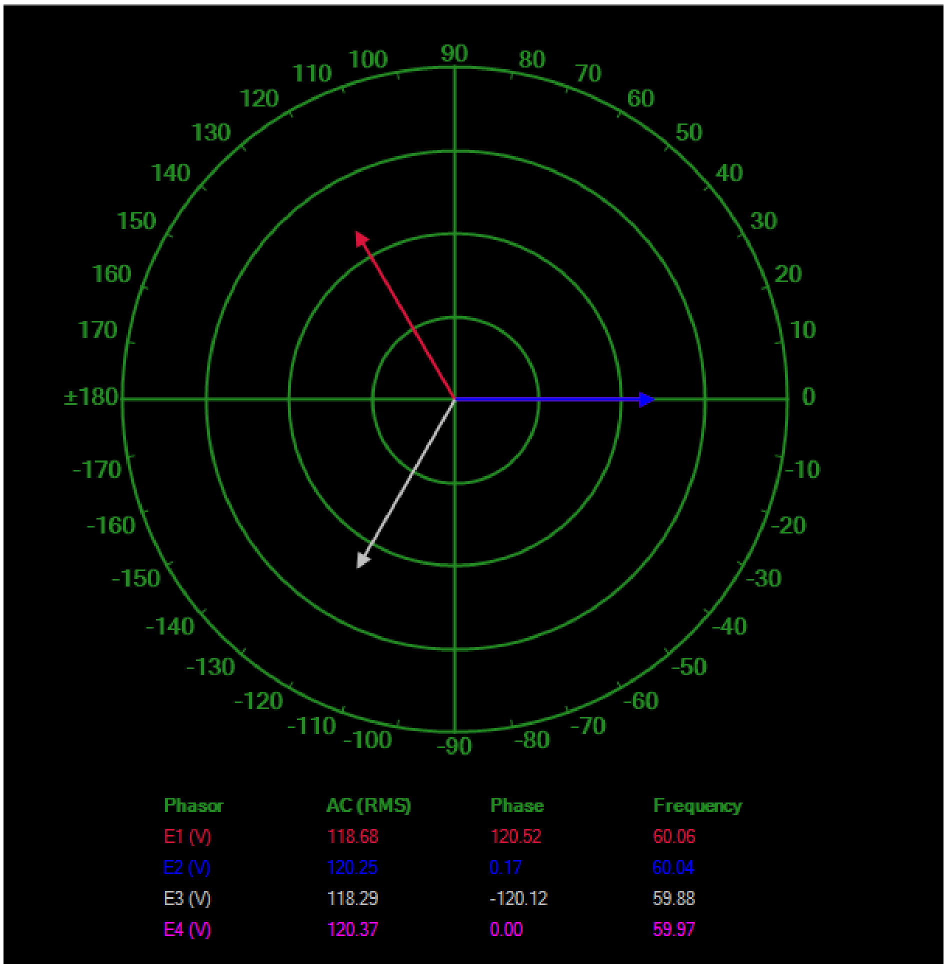




Voltmeter E4 is measuring the source voltage (between node 4 and 5) here

3.2. Measurements for E4, E5, E6. *Voltmeter E4* is measuring the source voltage (between node 4 and 5).





3.2. Supplementary questions

Comparing the results of Sections 2.4 and 3.1:

(a) There is no difference.

(b) Open delta connection, line current is equal to phase current. $voltamp\ rating = \sqrt{3}VI^*$, delta delta connection, line current is equal to $\sqrt{3}$ phase current $voltamp\ rating = 3VI^*$

(c) With the current increase, the open delta connection can work like delta-delta connection. When current increases, the power rating of each winding increases. Therefore, it can have the same power rating as the delta-delta connection for a certain increase of the current rating.