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by Benjamin Brickle

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1) Introduction and Background Theory

Three separate experiments were performed, analysing three different combinations of three-phase power supply, monitoring and analysis differences between configurations. Research was performed to provide a good understanding of the topic, stating the differences between configurations and reasons why they may differ. The research instilled expectations regarding the circuit behaviour and how it would change with variables changing.

Each experiment was performed using calculations and Multisim, with discrepancies noted and analysed. Each circuit was analysed, noting possible reasons for behaviour.

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2) Research

Three Phase Power Systems

Three phase power systems are used worldwide to distribute electrical power from generation plants to supply grids. Three phase systems rely on three supplies, each 120° apart, creating a 360° between the three. The three phases together create a balanced load. Therefore, systems using three phase experience far less voltage differences through the cycle and will sustain a far more stable voltage. (Bird, 323)

Multiphase systems are considered to be a far more efficient method of power transmission than single phase. They can be connected in two different formats, dependent upon circuit requirements, as a star or Delta layout. With a Star layout, the phase and line currents are the same, whereas the phase and line voltages are the same within a Delta layout. (Hughes, n.d.)

With regards to efficiency, several factors should be considered. Electricity can be transferred with a lower current, as the current is shared amongst three wires, allowing wires to be thinner and therefore cheaper to manufacture and install. The three-phase system makes it far easier to balance loads, reducing the significance of harmonics within generation also. (Rahi Systems, n.d.)

The three phase systems will provide a constant power, whereas single phase will show power surges and dips. This model will ensure that power will remain far more stable, especially important for large motors or industrial electrical components. As shown in fig. 1, the output will never be 0. When R is approaching 0, Y is approaching its maximum value.

Three phase induction motors do not require an auxiliary start up motor and will start itself. These motors also have a far higher power factor than single phase motors. (Anon., 2018)

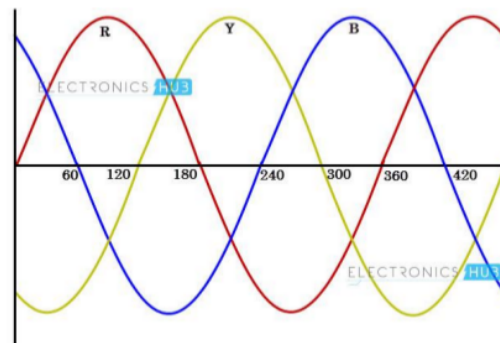


Figure 1-Three phase system (Anon, 2015)

Power Factor

Power factor is a way of determining the ratio of useful power to wasted power, or ratio of working power to apparent power. The power factor is commonly described using the power triangle. It is a useful method of determining system efficiency. If a circuit is perfectly efficient, the power factor would be 1. (Fluke, 2019)

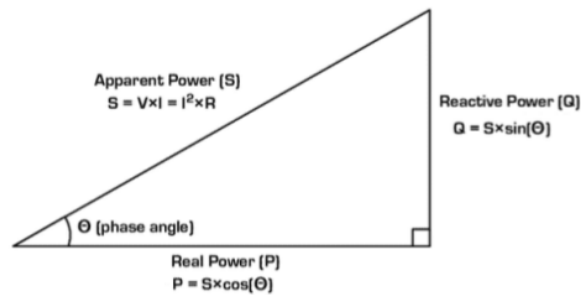


Figure 2- Power triangle (Ashrit, 2017)

Most domestic electrical systems are resistive, causing voltage and current to be in phase and therefore have a relatively high power factors. Many industrial sites have inductive loads, such as large motors for pumps. The coils within motors will store current, creating a back emf and causes a phase shift between voltage and current, creating a lagging power factor.

If a capacitive load was used, the opposite is true. The voltage will be stored, causing a leading power factor. This will mean that electricity would've been paid for, but not required. (Evans, 2018)

For economic terms, it may be beneficial for industrial sites to correct their power factor, to improve the ratio of electricity paid for to electricity used. Many firms will follow IEC 61000-3-2 standard, which aims to reduce voltage distortion by using harmonic currents. (<http://powerblog.vicorpower.com/2013/02/what-does-power-factor-mean-and-why-must-we-correct-it/>, 2013)

Most electrical suppliers will implement financial penalties for firms who work under a poor power factor, based on apparent power (kVA). Power factor correction (PFC) may be investigated by firms operating under a poor power factor to avoid fines by the national grid. To combat poor power factors, sites with large inductive loads will use large capacitors as a method of storing electricity. These will provide reactive current, and therefore reduce the current draw from the grid. The sizes of these capacitors can be calculated using formulae such as:

$$\text{kVar} = \text{kVA} \times \sin(\cos^{-1}(\text{PF}))$$

(Fu Zheng, 2017)

Other methods of correction include converters to reduce harmonic currents to improve a PFC (Notohara, 2010) or using a PLC to trigger capacitors when required to improve power factor at certain times (Kulkarni, 2015)

Star and Delta Transformer Applications

These can be arranged in a Star-Star load, Delta-Delta load, Star-Delta load or a Delta-Star load.

Star-Star- When using primary winding, each phase is 120° away from the other two phases, as is the secondary winding. Each primary winding has magnetic connections to each other via a common leg, and each primary and secondary winding are connected via one neutral point. (Anon., 2012) This layout offers no phase displacement, but will offer harmonic issues if the neutrals of the primary winding and generator are not connected. (Anon., 2020) This layout is very rarely used due to issues that may arise from unbalanced loads.

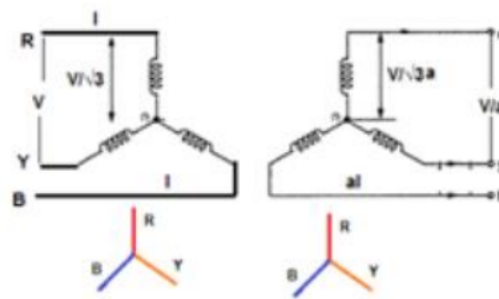


Figure 3- Star-Star (Y-Y) layout (Anon., 2012)

Delta-Delta- This arrangement has primary and secondary windings placed into a delta configuration. This configuration ensures no phase displacement between primary and secondary voltages. This layout, unlike star-star is suitable for unbalanced loads, and is relatively economical for low voltages. This layout cannot be used for 4-wire three phase systems. This configuration is suitable for low voltage transformers and although uncommon, can be used in industrial sites to reduce significance of single line to ground faults. (Parmar, 2012)

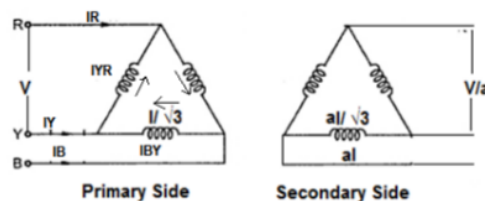


Figure 4- Delta-Delta configuration

Star-Delta – The primary is configured as a star, and the secondary is connected as a delta. The primary windings are connected in a star, and therefore requires fewer turns. This makes it suitable for high voltage step down transformers. To avoid distortion, the primary's neutral core could be earthed. As with Delta-Delta configurations, this configuration is capable of handling large unbalanced loads. This configuration creates a difference in phase between primary and secondary, and therefore cannot be connected in parallel with a Star-Star or Delta-Delta. This configuration is used for power supplies, normally at the substation. The star connection can be used as a step-down transformer. (Parmar, 2012)

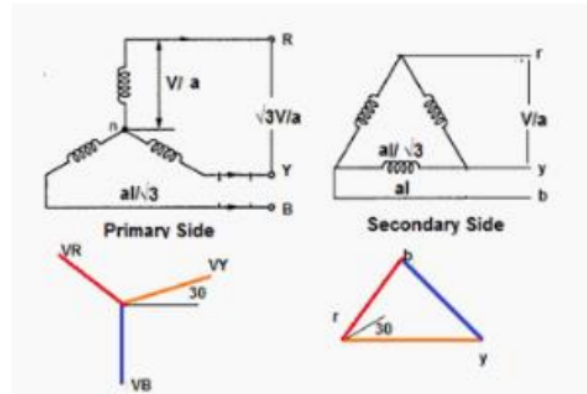


Figure 5- Star-Delta Configuration (Parmar, 2012)

Delta-Star- The primary is connected as a Delta configuration, whereas the second side is connected as a Star. This configuration can be used to reach requirements of three-phase and single-phase loads. There is a 30° difference between secondary and primary phase voltage. This configuration can be used as a four wire three-phase system. Like Delta-Delta and Star-Delta, this configuration can handle unbalanced loads. Due to the 30° phase differential, problems may arise when using in parallel. This configuration is primarily used for step up transformers or generator transformers. (Parmar, 2012)

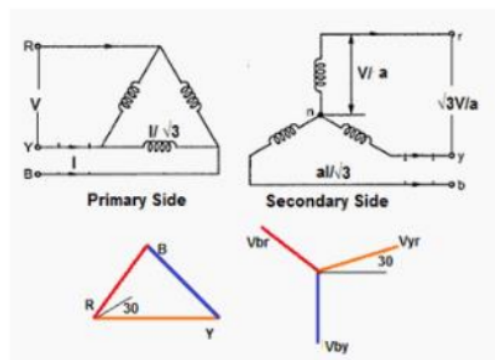


Figure 6- Delta-Star configuration (Parmar, 2012)

3) Experimental Procedures and Results

Balanced Star

Figures were calculated, using fig. 1 for reference. A resistor has been placed into each phase, with a chosen value of 65Ω .

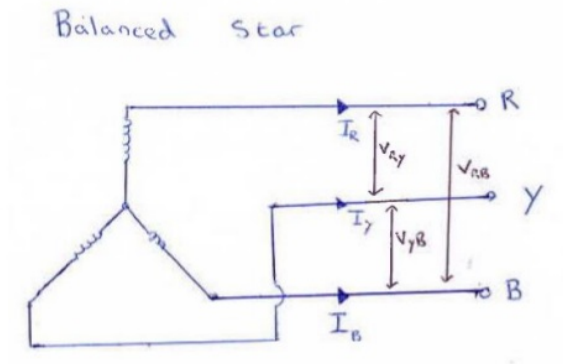


Figure 7-Star arrangement

Phase voltage of the circuit can be found, with 210V as line voltage, using:

$$V_{ph} = \frac{V_L}{\sqrt{3}}$$

The voltage in each line should be identical.

$$V_{ph} = \frac{210}{\sqrt{3}} = 121.24V$$

Phase current can be calculated using:

$$I_{ph} = \frac{V_{ph}}{Z_{ph}}$$

The impedance must be calculated before it can be applied to other equations. It can be found using:

$$X_L = 2\pi f l$$

As a result:

$$X_L = 2 \times \pi \times 50 \times 200 \times 10^{-3}$$
$$X_L = 62.832\Omega$$

With inductive reactance being calculated, impedance can be found using 200mH used for L:

$$Z_{ph} = \sqrt{R^2 + X_L^2}$$

$$Z_{ph} = \sqrt{65^2 + 62.83^2} = 90.404\Omega$$

The impedance values can be used to find the phase currents. These phase currents should be similar to each other and to the overall phase current.

$$I_{PH} = \frac{V_{ph}}{Z_{ph}}$$

$$I_{ph} = \frac{121.24}{90.404} = 1.34A$$

A phase angle must be calculated to use in the power factor formula.

$$\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$$

$$\phi = \tan^{-1}\left(\frac{62.832}{65}\right) = 44.028^\circ$$

Power factor:

$$p.f. = \cos\phi$$

$$p.f. = \cos(44.028) = 0.71$$

From this, the true, reactive and apparent power can be calculated.

$$\text{True Power, } P = \sqrt{3} \times V_L \times I_L \times \cos\phi$$

$$\text{True Power, } P = \sqrt{3} \times 121.24 \times 1.34 \times 0.71 = 199.788W$$

$$\text{Reactive Power, } Q = \sqrt{3} \times V_L \times I_L \times \sin\phi$$

$$\text{Reactive Power, } Q = \sqrt{3} \times 121.24 \times 1.34 \times \sin(44.028) = 195.57VA$$

$$\text{Apparent Power, } S = \sqrt{P^2 + Q^2}$$

$$\text{Apparent Power, } S = \sqrt{199.788^2 + 195.57^2} = 279.576VAR$$



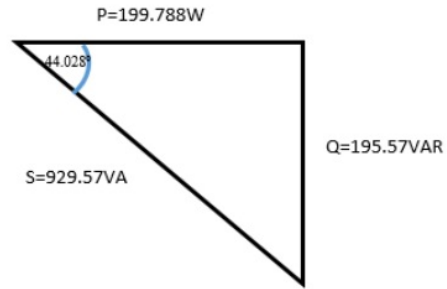


Figure 8- Star balanced power triangle

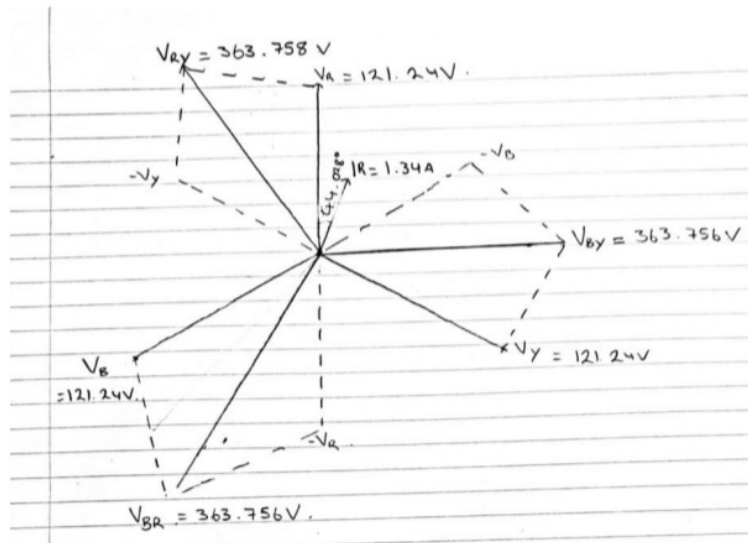


Figure 9- Star phasor diagram

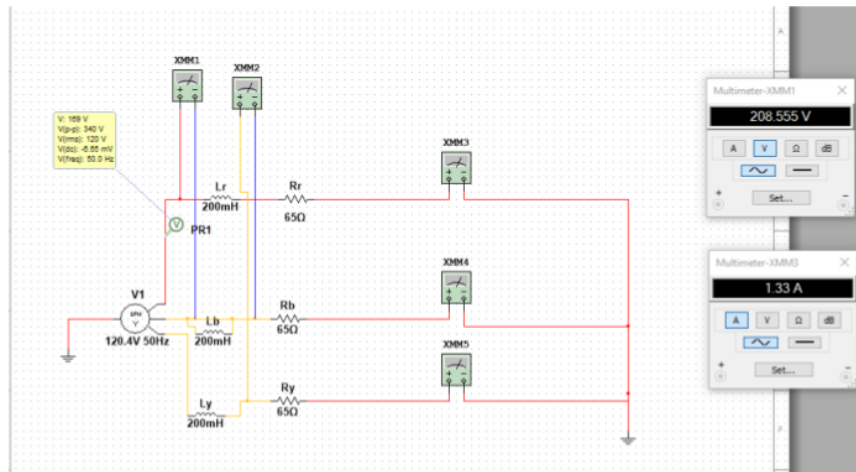


Figure 10- Showing line voltage at 120V with PR1, phase voltage at 207.862V on XMM1 and line currents at 1.33A on XMM3



Figure 11- Four channel oscilloscope showing 6.834ms between phases

Delta Balanced

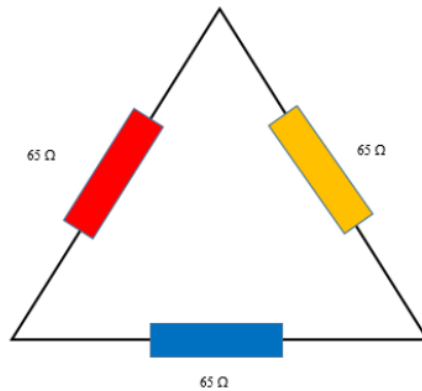


Figure 12- Delta configuration

Delta configurations have no neutral, and so: $V_{ph} = V_{line}$, therefore using 210V supply as phase and line voltage.

Load conditions are identical between star and delta, and therefore Z (impedance) is still:

$$Z_{ph} = \sqrt{65^2 + 62.83^2} = 90.404\Omega$$

Phase current can be calculated, using V and Z values provided.

$$I_{ph} = \frac{V_{ph}}{Z_{ph}}$$
$$I_{ph} = \frac{210}{94.404 \angle 44.028^\circ} = 2.224 \angle -44.028^\circ A \text{ OR } 1.599 - j1.5457A$$



In contrast to star configurations, line current is different to phase current in a Delta configuration.

$$I_{line} = \sqrt{3} \times I_{ph}$$
$$I_{line} = \sqrt{3} \times 2.224 = 3.85A$$

The phase angle between Star and Delta remain the same, therefore power factor for the Delta configuration is also 0.71.

From this, power values can be calculated.

$$\text{True Power } P = (\sqrt{3})(V_L)(I_L)(\cos \phi)$$

$$P = (\sqrt{3})(210)(3.85)(\cos 44.028) = 1.00686 \text{ kW}$$

$$\text{Reactive Power } Q = (\sqrt{3})(V_L)(I_L)(\sin \phi)$$

$$Q = (\sqrt{3})(210)(3.85)(\sin 44.028) = 699.7786 \text{ VAR}$$

$$\text{Apparent power } S = \sqrt{P^2 + Q^2}$$

$$\text{Apparent power } S = \sqrt{(1.00686 \times 10^3)^2 + 699.7786^2} = 700.498 \text{ VA}$$

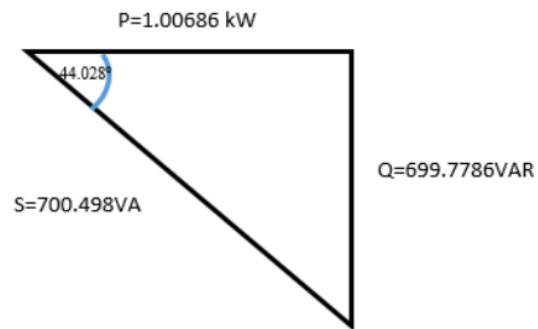


Figure 13- Delta balanced power triangle



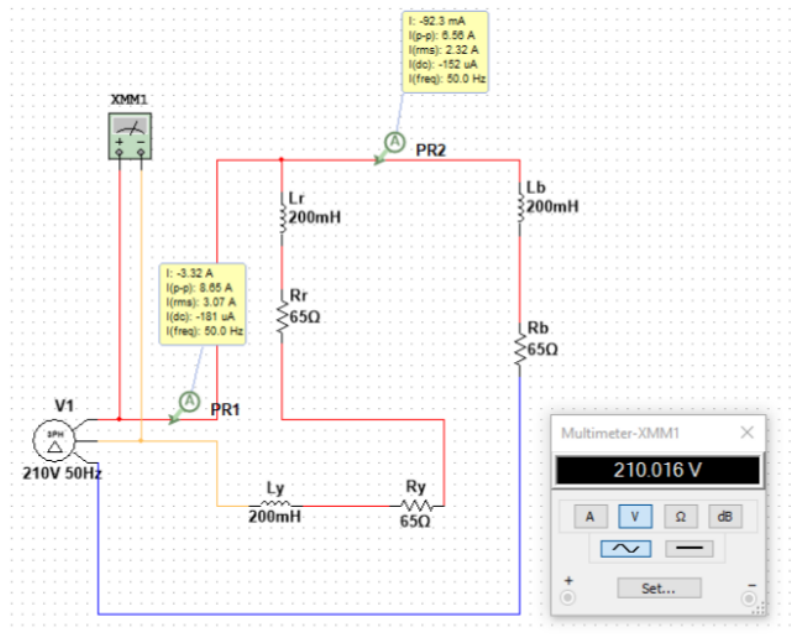


Figure 14- Delta configuration, showing 210.016V and 3.07A line current, 2.32A phase current



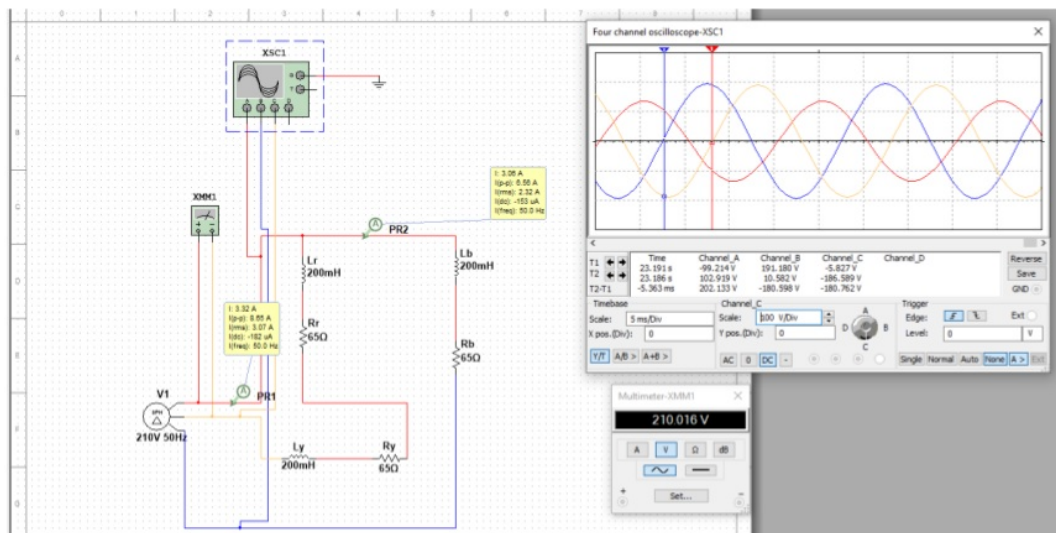


Figure 15- Showing phase difference of 5.363ms

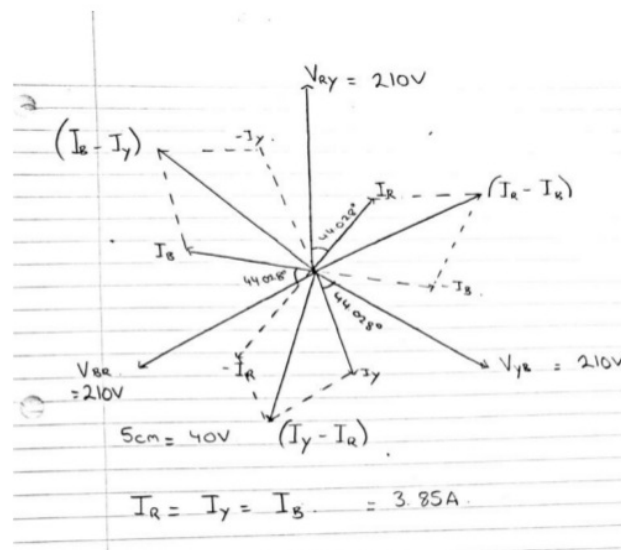


Figure 16- Delta phasor diagram

Unbalanced Delta Load

For this task, the configuration is similar to task 1, but three random resistance values have been chosen, a neutral would be attached at the meeting of all three lines.

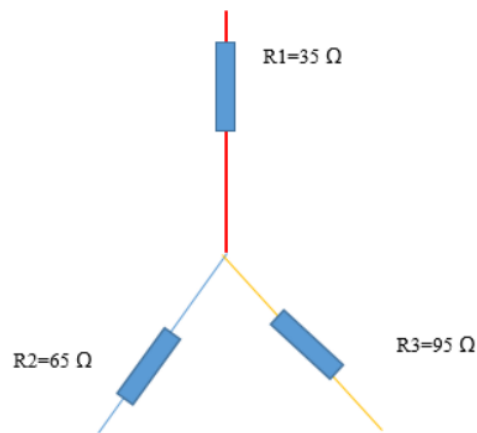
R1=35 Ω

R2=65 Ω

R3=95 Ω

Currents are labelled accordingly with resistors.

The load in this circuit is purely resistive.



$$\text{Line voltage} = 210\text{V} \quad \text{Phase voltage } V_{ph} = \frac{V_{line}}{\sqrt{3}} \quad V_{ph} = \frac{210}{\sqrt{3}} = 121.244\text{V}$$

$$I_{red} = \frac{V_{ph}}{R1} \\ I_{red} = \frac{121.244}{35} = 3.464\text{A}$$

$$I_{blue} = \frac{V_{ph}}{R2} \\ I_{blue} = \frac{121.244}{65} = 1.86\text{A}$$

$$I_{yellow} = \frac{V_{ph}}{R3} \\ I_{yellow} = \frac{121.244}{95} = 1.276\text{A}$$

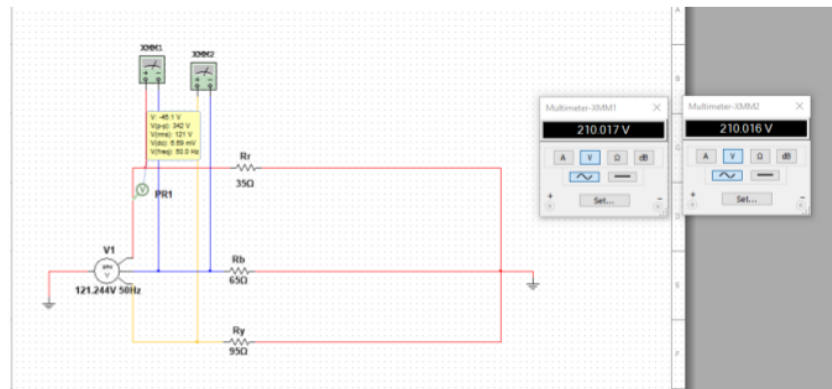


Figure 17-Line voltage showing 210V
with a phase voltage of 121V

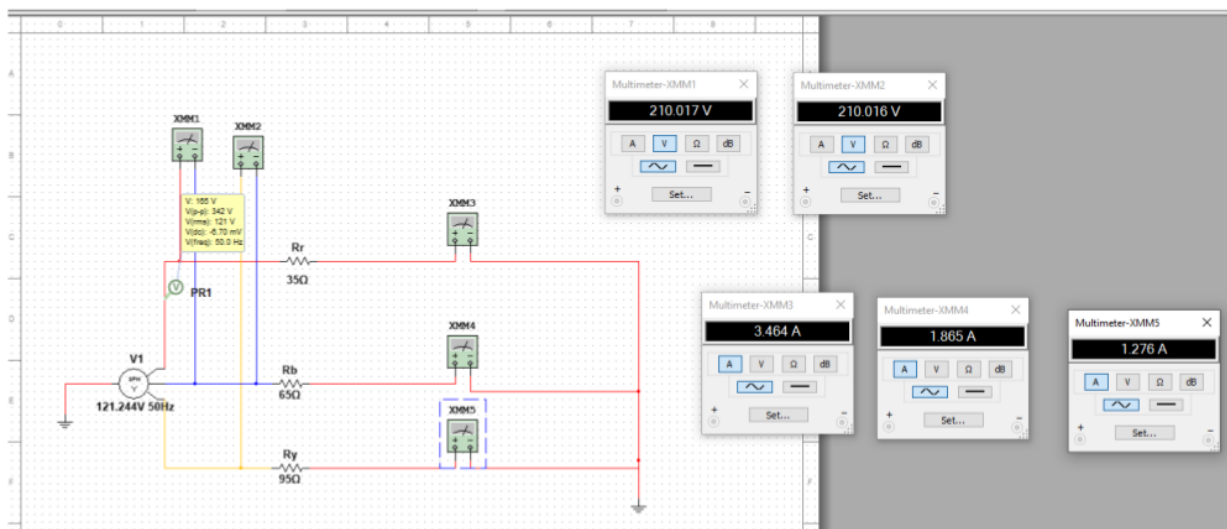


Figure 18- I_r showing 3.464A, I_b showing 1.865A, I_y showing 1.276A

	Line Voltage (V)	Phase Voltage (V)	Line Current (A)
Rr calc.	210	121.244	3.464
Rr Multism	210	121	3.464
Rb calc.	210	121.244	1.86
Rb Multism	210	121	1.865
Ry calc.	210	121.244	1.276
Ry Multism	210	121	1.276

Figure 19- Unbalanced load calculations and Multisim values

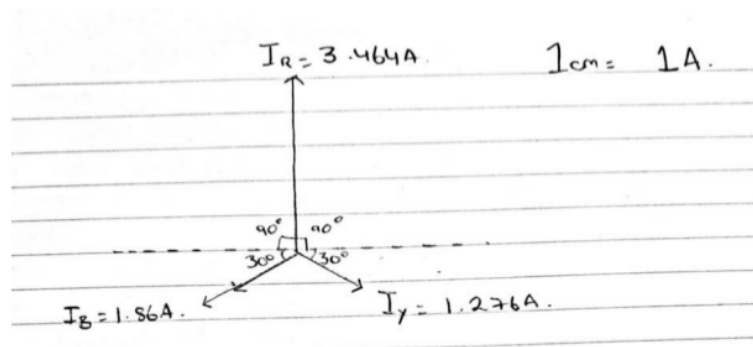


Figure 20- Current phasor diagram for unbalanced load

As I_R is vertical, there is no horizontal component and therefore not drawn in fig. 20 or 21, although the vertical component is considered when calculating total vertical value. Each current value can be written in vertical and horizontal components, to obtain a final vertical and final horizontal value. From this, a vector diagram can be drawn, using trigonometry and Pythagoras' theorem to derive the resultant vector.

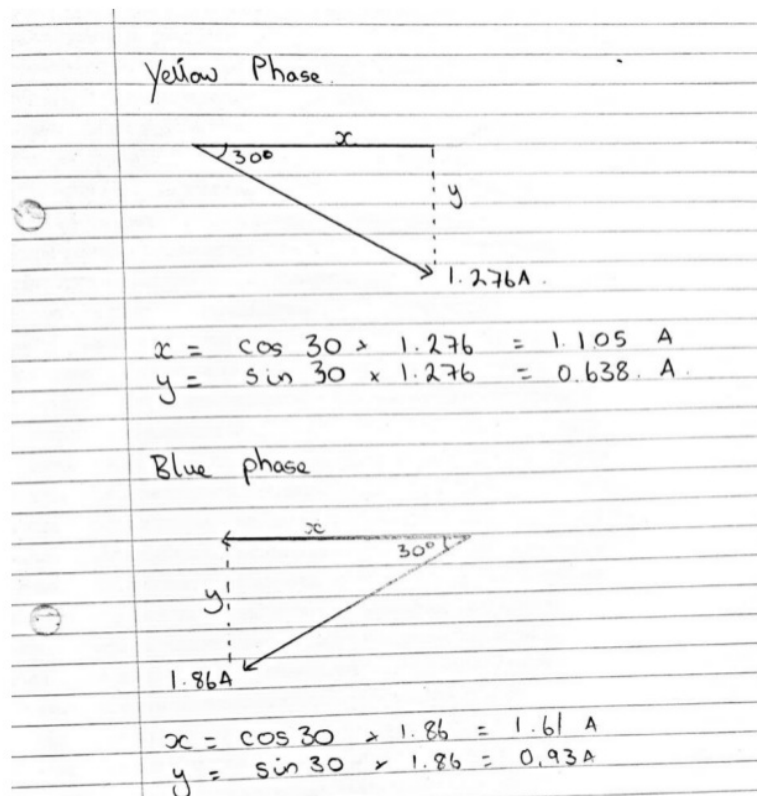


Figure 21- Vectors for yellow and blue phase

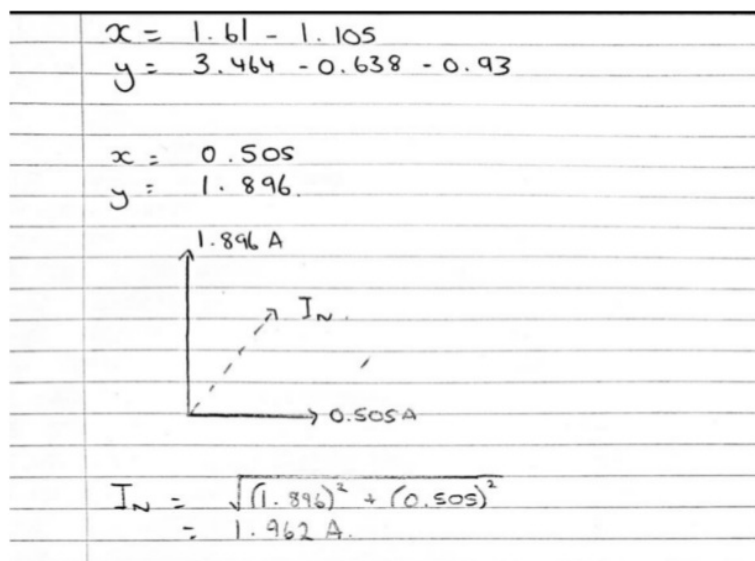


Figure 22- Calculating neutral current, at 1.962A

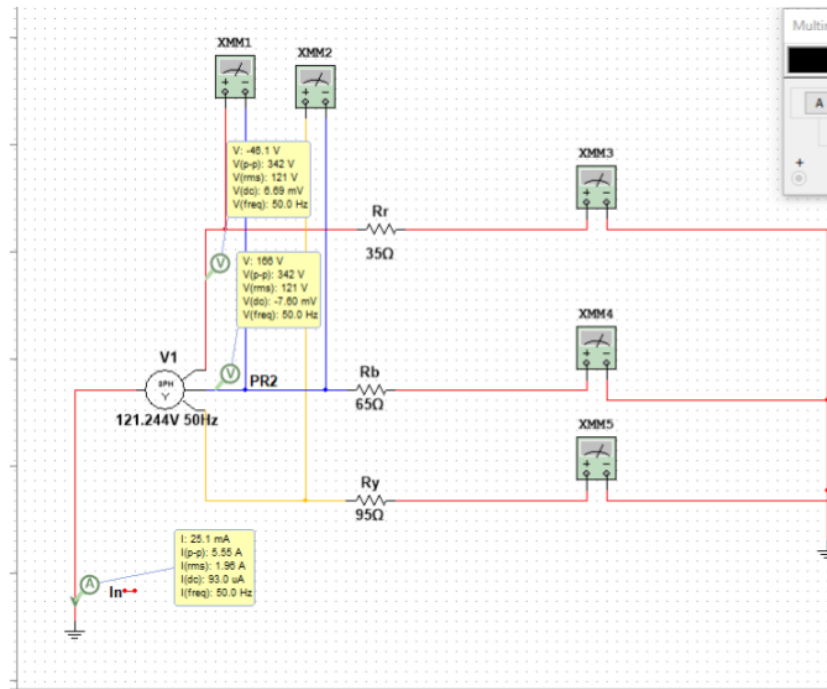


Figure 23- Current probe 'In' showing 1.96A, neutral current

4) Discussion of Results

Configuration	Line voltage (V)	Phase voltage (V)	Line Current (A)	Phase current (A)	Real Power (W)	Apparent Power (VA)	Reactive Power (VAR)
Star- Multisim	210	120.008	1.339	1.339	221.501 ($I^2 \times R$)	221.535VA	153.96 ($5 \times \sin(44.038)$)
Star-Calculatation	210	121.24	1.34	1.34	199.788	279.576	195.57
Delta-Multisim	210	210	3.07	2.32	963.46 ($I^2 \times R$)	644 (Vrms x Irms)	
Delta- Calculatation	210	210	3.85	2.224	1.00686k	700.498	699.7786

Figure 24- Results gathered from balanced Star and balanced Delta loads

From research obtained in previous sections, there were several expectations regarding the outcomes of the testing. These were:

- 1) Star- line current is equal to phase current, Delta-phase current is equal to cube root of line current.
- 2) Star- Line voltage is cube root of phase voltage, Delta- line voltage is identical to phase voltage. (Anon., 2016)

The power factor in both circuits is 0.71, which would be considered poor under industrial standards and would result in fines for a company. This power factor is partly due to the inductors within the circuit. In an industrial setting, this could be improved by using large capacitors. The unbalanced circuit is purely resistive, and therefore does not suffer from a lower power factor.

From these expectations, the Multisim and calculated values should be very similar. There are slight discrepancies between the values, where there may be rounding errors, or slight discrepancies between methods used. If this was performed practically, the values would have larger errors, due to factors such as wire resistance or component wear.

Balanced Star- Due to the configuration, each line has 120V, but 120° away from each other, as proved by Multisim values and oscilloscope. The p.d across two lines is 210V, or line voltage, whereas measuring line to ground (or neutral) shows 120V, or its phase voltage. The star configuration ensures that the current flowing between phases also flows between the lines as it is in series with the winding, and therefore: $I_{PH} = I_L$, as shown in fig. 18. A neutral has not been included in Multisim, but voltage measurements has been taken with reference to ground (0V).



Balanced Delta- Due to the configuration, there is one phase winding, or inductor between two junctions. As a result, the p.d between two lines (phase voltage) is 210V, and the p.d across a line to earth (or neutral) is also 210V. Each line will be 120° out from each other. As oppose to Star, phase current and line current in Delta are different. In Delta, the current splits at each junction, causing three separate currents, as shown by $\sqrt{3}$. Kirchhoff's law explains that the current entering and leaving a junction will be the same and can be calculated using vectors or a phasor diagram. Whilst the line currents are 120° apart from each other, the line current will be a further 30° behind the phase currents. (Anon., 2016)

$$\text{Line current} = \sqrt{3} \times \text{phase current}$$

Unbalanced Star

	Line Voltage (V)	Phase Voltage (V)	Line Current (A)
Rr calc.	210	121.244	3.464
Rr Multism	210	121	3.464
Rb calc.	210	121.244	1.86
Rb Multism	210	121	1.865
Ry calc.	210	121.244	1.276
Ry Multism	210	121	1.276

As is the case with a balanced star, the phase voltage is split through three phases, or:

$$V_{ph} = \frac{V_L}{\sqrt{3}}$$

Results throughout are consistent between Multisim values and calculations. There are very small discrepancies, likely due to rounding errors. As with the balanced loads, these discrepancies would be far more significant when performed practically, where external components and other resistances in wires for example would need to be considered.

A 120V, 50Hz supply was used, to create a line voltage of 210V, as stated in assignment brief. Whilst the voltage is similar in all three phases, as the resistors change, Ohm's law states that the currents will be different. It is also expected that as Rr has the lowest resistance value, it offers the easiest path and therefore draws the most current, the opposite is true with Ry. This is proven with calculations and Multisim simulations.

The neutral line must be considered in an unbalanced load, as it signifies the poor balance within the circuit. In the balanced circuit, one would expect the sum of all vectors to equal zero, and therefore give 0A neutral current. As this load is unbalanced, each draws a different current, creating an unbalanced circuit and therefore a neutral current is seen. The calculated value and Multisim value for this neutral current are also very similar, showing 1.96A.

Due to this circuit load being purely resistive, current and voltage are in phase with each other. Inductive or capacitive circuits cause current to lead or lag, which will alter the power factor. As this circuit has voltage and current in phase, the power factor is 1.

The values calculated and simulated for are conclusive with three phase Star-configuration theory, and therefore suggest that it was performed correctly.

The two-wattmeter method could have been utilised to measure power within each circuit, as oppose to using simulated values within formulae. This may have been more useful, although this will only measure instantaneous power, rather than reactive and apparent power.

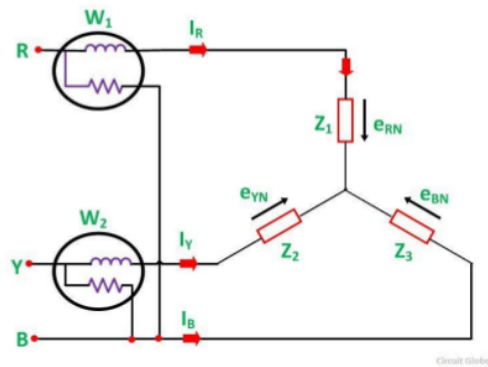


Figure 25- Two Wattmeter power measurement method, (Anon., 2016)

5) Conclusions

Research was performed which provided a good understanding of behaviour of each circuit used within the assignment. Multiple sources were used to obtain formulae and fundamental principles.

Balanced circuits were created, in a Star and Delta configuration. Results were obtained, from formulae and Multisim simulations. Throughout, values for Multisim and calculations were similar and aligned with theory obtained in the research section, so the experiment can be considered a success.

Whilst the experiment was successful, several improvements could have been made to improve the tasks. It would have been beneficial to perform the tasks practically, to offer another layer of evidence to assist with analysis to fully support the simulations and calculations. Several tests would have been beneficial to perform practically due to awkwardness performing some tasks on Multisim, such as using the two-wattmeter method to determine different power values. It may have been useful to use several different formulae's or methods to obtain values, to provide more evidence for the experiments. An example of this could be using the current values and inverse current values in the unbalanced load to calculate neutral current. The method used was relatively complexed, where other formulae could have been used such as:

$$\sqrt{(I_r^2 + I_y^2 + I_b^2) - (I_r \times I_y) - (I_y \times I_b) - (I_r \times I_b)}$$

Whilst the result would be similar or identical, it may have been useful to gather as much evidence as possible to improve the reliability and strength of experiment to support three phase theory.

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7) Appendices

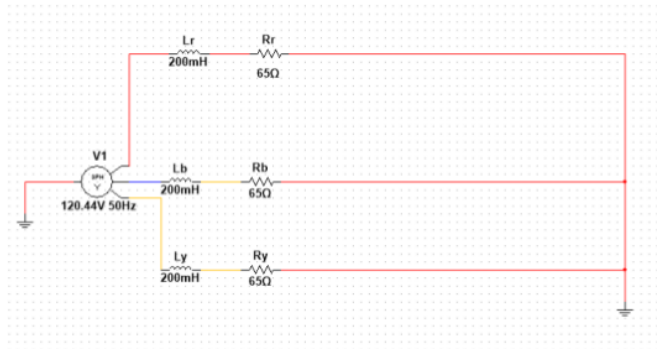


Figure 26- Balanced star

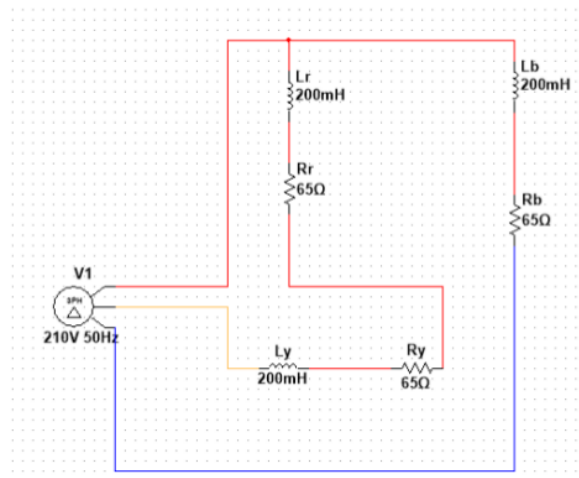


Figure 27- Balanced Delta

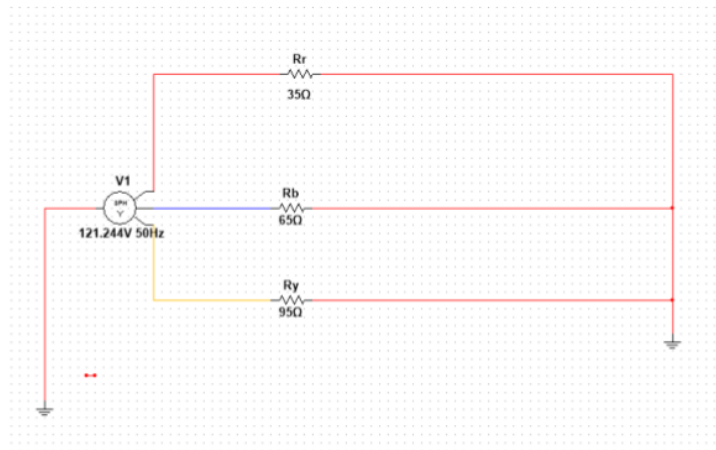


Figure 28- Unbalanced star

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GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

77 /100

Instructor

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Comment 1

Good research

PAGE 7

PAGE 8



Comment 2

msim cct would be acceptable rather than a drawing

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Comment 3

wrong voltage used

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PAGE 11

PAGE 12



Comment 4

watch decimals and values

PAGE 13



Comment 5

correct equations and method, some small errors exist

PAGE 14



Comment 6

supply should remain star

PAGE 15



Comment 7

good attempt at phasor diagram

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Comment 8

good method adopted

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PAGE 21



Comment 9

should include a neutral

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PAGE 23

PAGE 24

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**BENJAMIN
BRICKLE**

77

1. ENGAGEMENT WITH LITERATURE



Theme introduced well and a wide range of reliable sources referenced, good level of detail. 7/10

7

2. KNOWLEDGE AND UNDERSTANDING



Competent knowledge of basic principles, correct methods adopted, some errors exist with values and decimals etc. Results discussed appropriately. 15/20

14

3. COGNITIVE AND INTELLECTUAL



Evaluation of the results is sound and save for some small errors methods and discussion are good. 30/40

28

4. PRACTICAL APPLICATION



Very good application of methods, good attempt at phasor diagrams, sound methods for calculating results and results displayed appropriately. 14/20

14

5. TRANSFERABLE SKILLS



Produced coherent and professionally presented report. Work flows and communication is good. 15/20

14