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by Alex Williams

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TIME SUBMITTED	18-MAY-2020 10:12AM (UTC+0100)	WORD COUNT	3598
SUBMISSION ID	128030808	CHARACTER COUNT	21088

Course:	HNC Electrical and Electronic Engineering
Module:	SGEE4000 – Electrical and Electronic Principles
Assignment Title:	Three Phase Circuits
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University Number:	1909751
Date Submitted:	18/05/20
Word Count:	2342

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1.0 Introduction and Background Theory

The following report looks at three phase systems and its circuits. In a three-phase system, there are three voltages at the same frequency, having the same amplitude, but with a phase displacement of 120° between each phase. The voltage in a three-phase supply is 415 volts compared with single-phase which is 230 volts. In a three-phase system, the power is supplied through three wires, but some contain four wires if neutral is included. The two types of circuit configurations are known as Star and Delta. There is no neutral wire in Delta configuration which is the configuration used in all high voltage systems.

This report uses research to explain why electricity is distributed on three-phase systems in the UK and throughout the developed world and describes what is meant by the term power factor and its importance in electrical engineering systems. It also describes the four possible connection arrangements of Star and Delta which are Star-Star, Star-Delta, Delta-Delta and Delta-Star and gives examples of where these arrangements can be used.

It then goes onto calculate and analyse different components of a three-phase system such as its line current and voltage, phase current and voltage as well as its phase angle and power factor. The circuits include a balanced Star and Delta circuit and an unbalanced star circuit. The circuits are also simulated to prove theoretical calculations and account for any discrepancies.

2.0 Research

2.1 Three phased systems

Most of today's electricity is transmitted utilising the form of AC (alternating current) voltage. AC power can either be delivered in a single or three-phase system. The main way of distributing electrical power throughout the UK and developed world is via the use of three-phase circuits. Bird states that this is an electrical distribution method utilising "three alternating currents to supply power" and goes onto say "this type of power distribution is the most widely used in the world for transferring power from generating systems to electrical supply grids" (2017, p. 336). There are a variety of reasons why electricity is transmitted on a three-phase basis, the main ones being is that it is more economical and efficient than a single-phase power supply, as explained below.

In a three-phase supply, there are three voltages at the same frequency (usually 50 hertz), having the same amplitude, but with a phase displacement of 120° between each phase as shown in Figure 1. This means that the output would never fall to zero, due to having the three phases and does not experience such a wide variation in voltage when compared to a single-phase supply where the supply would be at zero three times each cycle as shown in Figure 2 (Ravi, 2019). Therefore, three-phase is used since the supply is constant, and as acknowledged by Bird, this makes it a 'very efficient form of electrical power distribution'. (2017, p. 336)

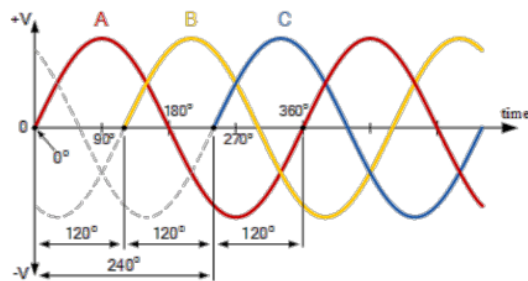


Figure 1: Three phase sine wave

(ElectronicsTutorials, 2018)

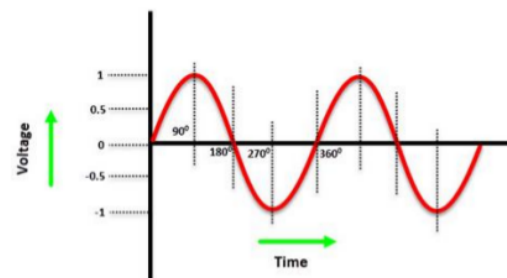


Figure 2: Single phase sine wave

(Ravi, 2019)

Bird advises that in a three-phase power supply, the power is carried by three conductors called lines, which Tyler in his 'Electrical Applications' book (1987) acknowledges are coloured red, yellow and blue. Although, from 1st April 2004, this was changed to grey, black and brown to harmonise with the colours being used by most of Europe- see Figure 3) (NewFound Energy Ltd, 2017).

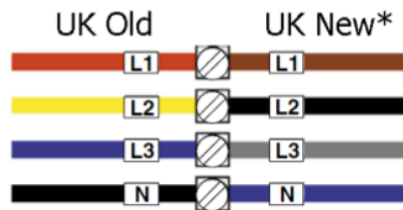


Figure 3: Colours for electrical three-phase wiring

(NewFound Energy Ltd, 2017)

The other properties making a three-phase system preferable for use in electrical distribution systems are:

1. As all the phase conductors carry the same current, they can be the same size, making it easier to deliver a balanced load which is not possible with a single-phase system. This subsequently helps to reduce generator and motor vibrations. In addition, Rao (2019) advises that the *'phase currents tend to cancel each other out, summing to zero where there is a linear balanced load'*. Therefore, there is no need for a neutral conductor if the loads are balanced
2. A three-phase system allows for higher transmission at lower amperage. Therefore, for transmission of electrical power, three phase supply requires less/thinner copper wiring than a single-phase system. This makes it more efficient and economical since it uses less conductor material to transmit the same power, has a better power transfer capability and significantly reduces material and labour costs (Rahi Systems, 2020).
3. Large AC power voltages can be economically stepped up or stepped down in three-phase compared with single-phase.
4. A magnetic field can be produced, which rotates in a specific direction (K.R, 2019). This simplifies the design of electric motors, making it possible for a three-phase machine to be self-starting. Bird (2017) advises that a three-phase electric motor uses less electricity and lasts longer than a single-phase electric motor of the same voltage and rating.
5. If a high voltage is required, a three-phase system can be considered safer than single-phase as it is possible to have smaller voltages in each conductor. This is due to the fact that when going across phases, the required higher voltage can be reached compared to running a higher voltage in a single phase.
6. Single phase system can be obtained from a three-phase supply system. However, it is not possible vice-versa.

2.2 Power Factor

Power factor is a way of calculating energy efficiency. Fluke® say that "Power factor (PF) is the ratio of working power, measured in kilowatts (kW), to apparent power, measured in kilovolt amperes (kVA)." (2019) . Fluke go on to use a beer analogy for power factor as shown in Figure 4.



Figure 4: Power factor analogy

The beer is the all of the power that is useful to the device that is being powered. It is the required power that is doing the work and not wasted. The foam is reactive power. This is all of the wasted energy. This is power that is lost as heat so it is not doing any work for the device. The mug that everything is in is the apparent power. This is all the power that is being delivered by the supply. (Fluke®, 2019)

Power factor can be calculated from the formula. $p.f = \frac{\text{true power (P)}}{\text{apparent power (S)}}$. The closer the number is to one the more efficient the circuit is. Circuits having a low power factor can still make the circuit more efficient by using power factor correction. This involves the use of a capacitor to balance any phases that were previously unbalanced. The result of power factor correction when a capacitor is placed in parallel across an inductive load is the apparent power decreasing, thereby decreasing the current which in turn makes the power distribution more effective. (Bird, 2017)

The size of the capacitor depends on the situation of the circuit. The value of the capacitance reactance needs to be known or calculated by using Equation 1.

$$X_C = \frac{V}{I_C}$$

Equation 1: Capacitive reactance

Once X_C is known, the formula of $X_C = \frac{1}{2\pi fC}$ can be rearranged to $C = \frac{1}{2\pi fX_C}$ to calculate the size of the capacitor required.

2.3 Star-Delta Configurations in Transformer Applications

There are four possible different connection arrangements of star and delta when being applied to transformers. They are:

- Star-Star (Figure 5)
- Star-Delta (Figure 6)
- Delta-Star Figure 7)
- Delta-Delta (Figure 8)

Star-star configuration as shown in Figure 5, will typically be used in applications that require a single-phase supply. Using one of the phases will give the required 240v supply.

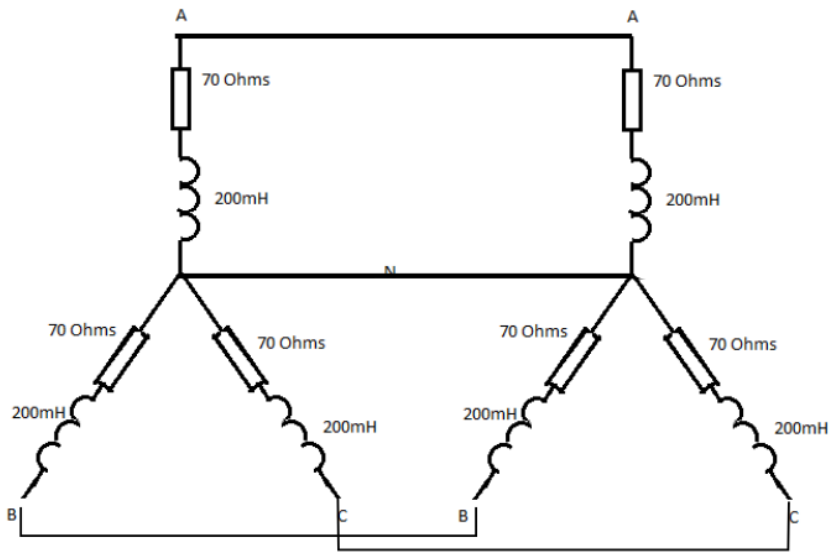


Figure 5: Star-Star connection

Star delta configuration (Figure 6), is good for when motors start up. This is because it will allow the start-up of the motor to be in star which can draw more current before changing over into delta.

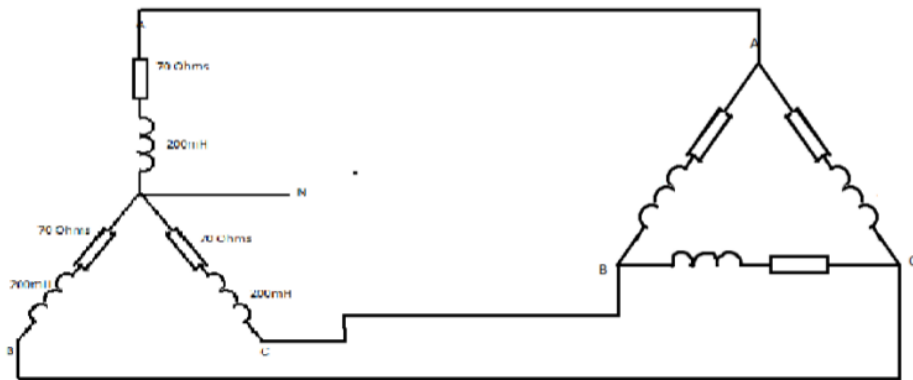


Figure 6: Star-Delta configuration

Delta-star (Figure 7), is different as it deals better with unbalanced loads between the two sides. This a strong reason why this configuration is used for step up in transformers.

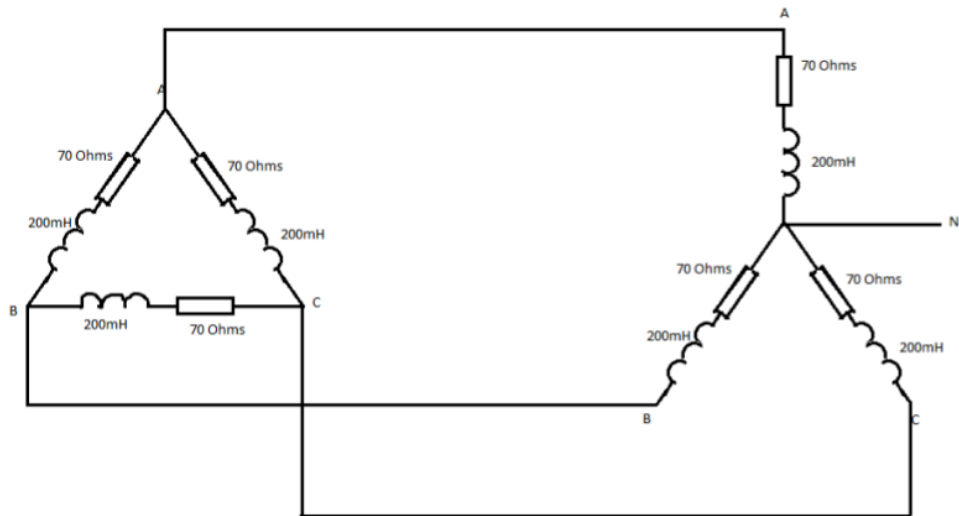


Figure 7: Delta-Star configuration

The final configuration is delta-delta shown in Figure 8. This positive of this configuration is that it has no phase shift so it is good for low voltage transformers.

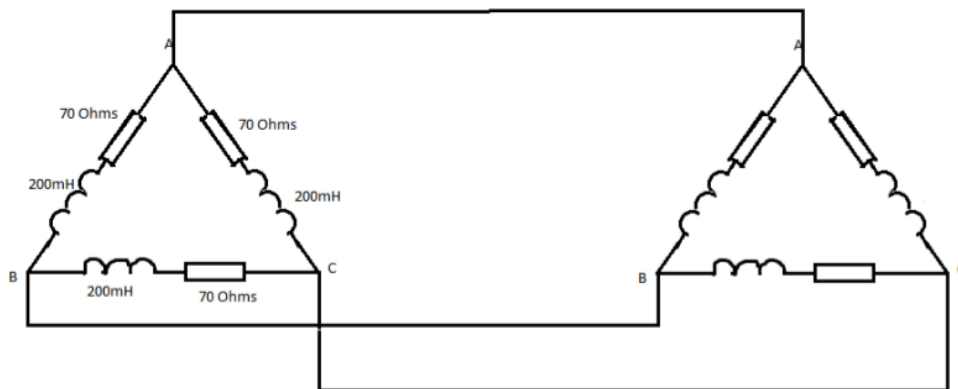


Figure 8: Delta-Delta configuration

3.0 Experimental Procedures and Results

3.1 Star Balanced R-L Circuit

Circuit one shown in Figure 9 is a star balanced R-L circuit.



Figure 9: Balanced Star R-L Circuit

The circuit had a 210v, 50Hz supply connected to resistors of 70Ω and with an inductance of 200mH. The circuit was analysed by calculating impedance, current, power, phase angle and power factor.

Phase voltage

$$V_P = \frac{V_L}{\sqrt{3}} = \frac{210}{\sqrt{3}} = 121.24V$$

Inductive reactance

$$X_L = 2\pi fL$$

$$X_L = 2 \times \pi \times 50 \times (200 \times 10^{-3}) = 62.83\Omega$$

Impedance of each phase

$$Z_P = \sqrt{R^2 + X_L^2}$$

$$Z_P = \sqrt{70^2 + 62.83^2} = 94.06\Omega$$

Power factor

$$\text{Power factor} = \cos \phi = \frac{R}{Z} = \frac{70}{94.06} = 0.744$$

Phase angle

$$\phi = \cos^{-1} 0.744 = 41.9^\circ$$

The circuit is inductive so current lags voltage by 41.9°

Currents

$$I_L = I_P = \frac{V_P}{Z_P} = \frac{121.24}{94.06} = 1.289A$$

$$I_R = I_Y = I_B$$



$$I_R = 1.289\angle -41.9^\circ A = (0.959 - j0.86)A$$

$$I_Y = 1.289\angle -41.9^\circ - 120^\circ$$

$$I_Y = 1.289\angle -161.9^\circ A = (-1.225 - j0.4)A$$

$$I_B = 1.289\angle -41.9^\circ + 120^\circ$$

$$I_B = 1.289\angle 78.1^\circ A = (0.066 + j1.261)A$$

Power

$$\text{True power } P = \sqrt{3}VI \cos \phi = \sqrt{3} \times 210 \times 1.289 \times 0.744 = 348.82W$$

$$\text{Apparent power } s = \sqrt{3}VI = \sqrt{3} \times 210 \times 1.289 = 468.84VA$$

$$\text{Reactive power } Q = \sqrt{3}VI \sin \phi = \sqrt{3} \times 210 \times 1.289 \times 0.668 = 313.19vars$$

In appendix A, Figure 17 and Figure 18 show the power triangle and phasor diagram respectively for this circuit. The circuit was subsequently built and simulated on Multisim to prove the calculations. The simulation is shown in Figure 10 with XMM1 reading the phase current, XMM2 measuring the line current and XMM3 measuring the line voltage. Wattmeter XWM1 then measures the power factor. The results of all the Multisim results can be seen in Table 1.

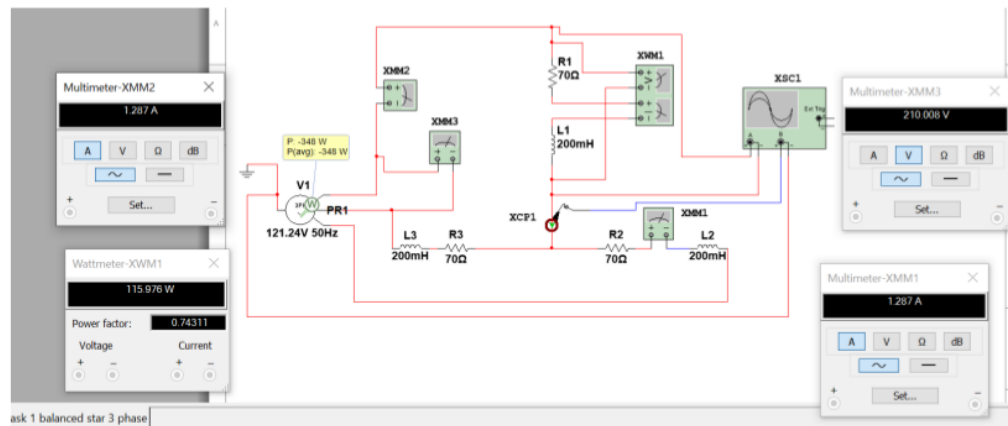


Figure 10: Balanced Star R-L Circuit Simulation

Table 1: Balanced Star R-L Circuit Simulation Results

	POWER FACTOR	PHASE ANGLE	PHASE CURRENT	LINE CURRENT	TRUE POWER
THEORY	0.744	41.9°	1.289A	1.289A	348.82W
MULTISIM	0.743	42°	1.287A	1.287A	348W



The phase angle was worked out on Multisim by using the following formula. $\phi = f \times \Delta t \times 360 \therefore \phi = 50 \times (2.334 \times 10^{-3}) \times 360 = 42.012^\circ$. The oscilloscope can be seen in Figure 11.

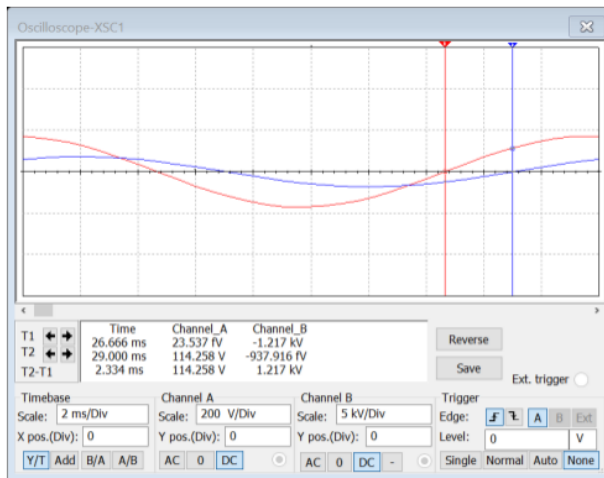


Figure 11: Balanced Star R-L Circuit Oscilloscope

3.2 Delta balanced R-L circuit

Circuit one was then reconfigured into a delta and the same calculations repeated. Circuit two diagram can be seen in Figure 12. The circuit was then also built and simulated on Multisim to prove the calculations. The results of all the Multisim results can be seen in Table 2 and the power triangle and phasor diagram in appendix B, Figure 19 and Figure 20.

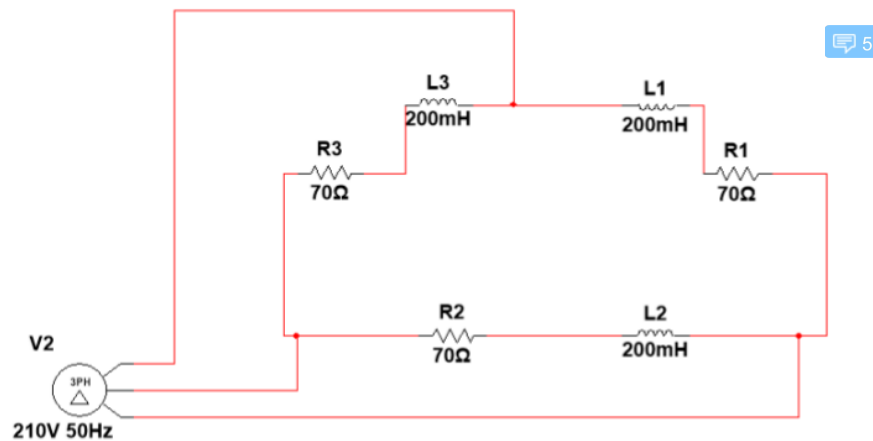


Figure 12: Balanced Delta R-L Circuit

Phase voltage

$$\text{Delta connection } V_p = V_L = 210V$$

Inductive reactance

$$X_L = 2\pi fL$$

$$X_L = 2 \times \pi \times 50 \times (200 \times 10^{-3}) = 62.83\Omega$$

Impedance of each phase

$$Z_P = \sqrt{R^2 + X_L^2}$$

$$Z_P = \sqrt{70^2 + 62.83^2} = 94.06\Omega$$

Power factor

$$\text{Power factor} = \cos \phi = \frac{R}{Z} = \frac{70}{94.06} = 0.744$$

Phase angle

$$\phi = \cos^{-1} 0.744 = 41.93^\circ$$

The circuit is inductive so current lags voltage by 41.93°

Currents

$$I_P = \frac{V_P}{Z_P} = \frac{V_L}{Z_P} = \frac{210}{94.06} = 2.23A$$

$$I_L = \sqrt{3}I_P = \sqrt{3} \times 2.23 = 3.86A$$

Using RY as reference 0°

$$I_{RY} = 2.23\angle -41.93^\circ A = (1.659 - j1.49)A$$

$$I_{YB} = 2.23\angle -41.93^\circ - 120^\circ$$

$$I_{YB} = 2.23\angle -161.9^\circ A = (-2.12 - j0.69)A$$

$$I_{BR} = 2.23\angle -41.9^\circ + 120^\circ$$

$$I_{BR} = 2.23\angle 78.07^\circ A = (0.46 + j2.18)A$$

$$I_R = I_{RY} - I_{BR}$$

$$I_R = [(1.659 - j1.49) - (0.46 + j2.18)]$$

$$I_R = (1.99 - j3.67)$$

$$I_R = 3.86\angle -71.90^\circ A$$

$$I_B = I_{BR} - I_{YB}$$

$$I_B = [(0.46 + j2.18) - (-2.12 - j0.69)]$$

$$I_B = (2.58 + j2.87)$$

$$I_B = 3.86\angle 48.05^\circ A$$

$$I_Y = I_{YB} - I_{RY}$$

$$I_Y = [(-2.12 - j0.69) - (1.659 - j1.49)]$$

$$I_Y = (-3.779 + j0.8)$$

$$I_Y = 3.86 \angle 168.05^\circ \text{ A}$$

Power

$$\text{True power } P = \sqrt{3}VI \cos \phi = \sqrt{3} \times 210 \times 3.86 \times 0.744 = 1.045 \text{ KW}$$

$$\text{Apparent power } s = \sqrt{3}VI = \sqrt{3} \times 210 \times 3.86 = 1.404 \text{ KVA}$$

$$\text{Reactive power } Q = \sqrt{3}VI \sin \phi = \sqrt{3} \times 210 \times 3.86 \times 0.668 = 397.87 \text{ vars}$$

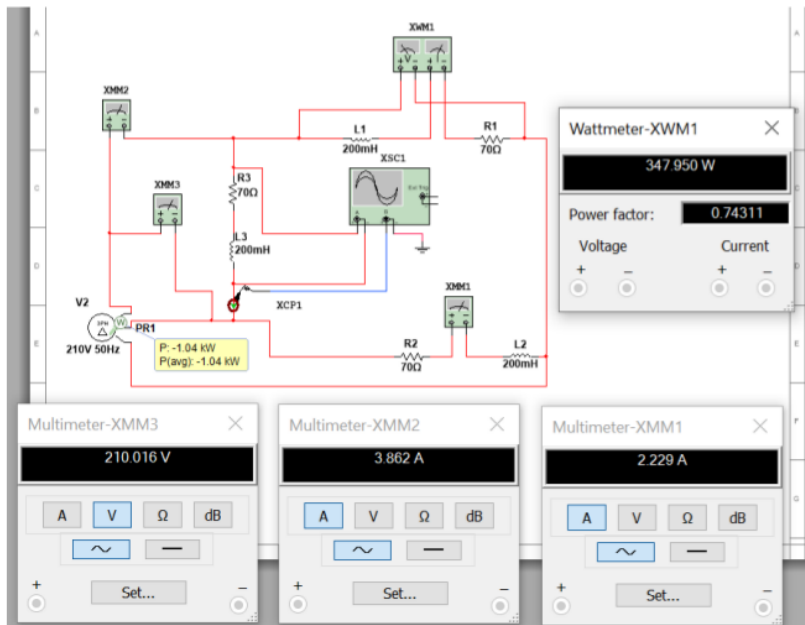


Figure 13: Balanced Delta R-L Circuit simulation

Table 2: Delta balanced R-L circuit simulation results

	POWER FACTOR	PHASE ANGLE	PHASE CURRENT	LINE CURRENT	TRUE POWER
THEORY	0.744	41.9°	2.23A	3.86A	1.045KW
MULTISIM	0.743	41.994°	2.229A	3.862A	1.04KW

The phase angle was worked out on Multisim by using the following formula $\Phi = f \times \Delta t \times 360 \therefore \Phi = 50 \times (2.333 \times 10^{-3}) \times 360 = 41.994^\circ$. The oscilloscope can be seen in Figure 14.

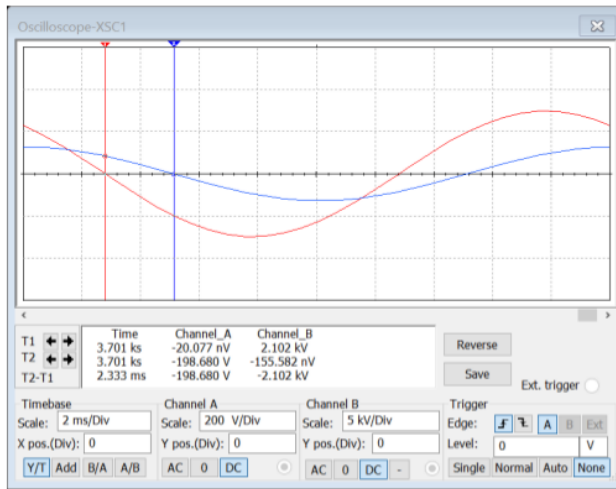


Figure 14: Delta balanced R-L circuit simulation results

3.3 Unbalanced Star Circuit

Circuit three shown in Figure 15 is an unbalanced star circuit.

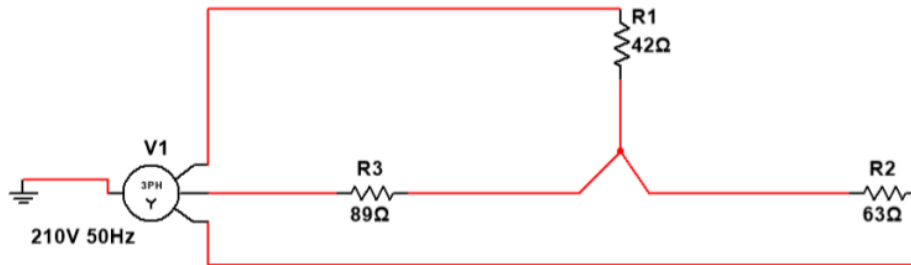


Figure 15: Unbalanced star purely resistive circuit

The circuit had a 210v, 50Hz supply connected to resistors of 42Ω, 63Ω and 89Ω with the circuit being purely resistive. The circuit was simulated in Figure 16 with the results shown in Table 3. This circuit is looking at the line current while calculating the current in the natural line. The phasor diagram is shown in Figure 21 in appendix C.

Phase voltage

$$V_P = \frac{V_L}{\sqrt{3}} = \frac{210}{\sqrt{3}} = 121.24V$$

Currents

$$I_R = \frac{V_P}{R_R} = \frac{121.24}{42} = 2.886A$$

$$I_Y = \frac{V_P}{R_Y} = \frac{121.24}{63} = 1.92A$$

$$I_B = \frac{V_P}{R_B} = \frac{121.24}{89} = 1.36A$$

$$I_{NHorizontal} = 2.86 \times \cos 90^\circ + 1.92 \times \cos 330^\circ + 1.36 \times \cos 210^\circ = 0.485A$$

$$I_{NVertical} = 2.886 \times \sin 90^\circ + 1.92 \times \sin 330^\circ + 1.36 \times \sin 210^\circ = 1.246A$$

$$I_N = \sqrt{(\sum Verticals)^2 + (\sum Horizontal)^2}$$

$$I_N = \sqrt{0.485^2 + 1.246^2} = 1.337 A$$

10

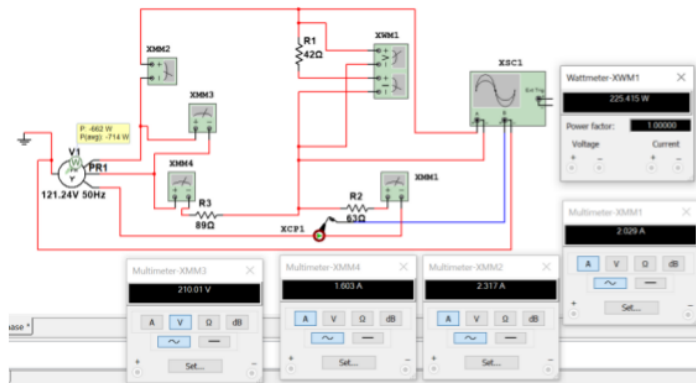


Figure 16: Unbalanced Star Circuit simulation

Table 3: Unbalanced Star Circuit simulation results

	I_R	I_Y	I_B	I_N
THEORY	2.886	1.92	21.36A	1.337A
MULTISIM	0.743	41.994°	2.229A	3.862A

4.0 Discussion of Results

Circuits one and two are the same circuit apart from the configuration of one being in star and the other in delta. Both circuits have results calculated theoretically and then simulated. The results that were displayed in the tables for circuits one and two had very little discrepancies between them. This supports the calculations in showing the theory is correct.

The power factor and phase angle were the same in both circuits. This is because they are both balanced circuits with the same inductance and resistive values. This also shows that the impedance per phase is also the same. However, in star, the line and phase voltage are different where in delta line voltage is equal to the phase voltage meaning in delta there is a higher voltage per phase. Current is also higher in delta. The line and phase currents in star are the same where as they are not in delta. In delta the line current drawn is three times higher than if it was connected in star. This can be proven by multiplying the line current from circuit one (1.289A) by three, $1.289 \times 3 = 3.86A$. 

The power in the delta circuit is much higher than compared to star. This is the case for all true, apparent and reactive power. In both circuits one and circuit two the current in the neutral line is equal to zero. This is because $I_N = 0$ in a balanced system.

In circuit three the phase voltage for a balanced and unbalanced star load is the same, this is because the load is not taken into account just the line voltage. In a balanced star the current in both the line and phase current are equal as shown. $I_R = I_Y = I_B$, compared to an unbalanced circuit where each phase current is different. As the phase voltage is the same across all three phases, the smaller resistance in each phase, the larger the current. Circuit three also looks at neutral current with this being smaller than the other line currents in the circuit.

5.0 Conclusions

Electricity in the UK and developed world is transmitted on a three-phase basis. This is primarily due to it being significantly more efficient and more economical than single-phase systems. Following analysis and evaluation of why this is the case, it can be concluded that this is primarily due to the following reasons:

- The power supply is constant as the output never falls to zero volts due to there being three phases and is easier to deliver balanced and larger loads
- It can transmit three times more power than a single-phase system
- It allows for higher transmission at a lower amperage, so it uses less conductor material to transmit the same power

There are two types of circuit configurations in a three-phase power supply, namely Star and Delta. In a balanced circuit, the power factor is the same when in star or delta configuration providing it is the same circuit just reconfigured from star into delta or vice versa. In a balanced star circuit, both the line current and phase current are equal to each other but the line voltage is different to the phase voltage. This is not the case when compared to a balanced delta circuit as the line and phase current are different to each other but the line voltage is equal to the phase voltage. In both configurations for a balanced circuit, the phase current for each phase is equal to each other shown by the equation. $I_P = I_R = I_Y = I_B$. Unbalanced systems are different again compared to balanced systems. In an unbalanced circuit, all the phase currents are different as proven in the following equation. $I_R \neq I_Y \neq I_B$.

Power factor measures the efficiency of the circuits and is the ratio of true and apparent power. The closer the power factor score is to one, the more effect the circuit is, with less energy being wasted. Power factor correction is what can increase power correction score. This involves the use of capacitors to balance out a load on a phase. Circuits that run more efficient are cheaper to run as less energy is wasted.

Having the four different configurations of star delta is a huge advantage to design engineers as they can arrange the load in a way that is best suited to its application to make it cheaper to run or to perform better and more efficient.

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7.0 Appendix

Appendix A

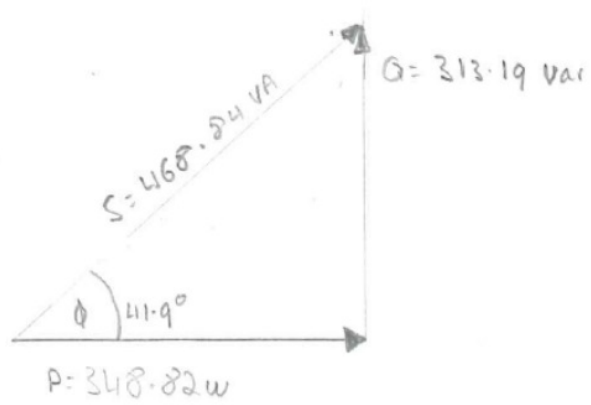


Figure 17: Star Balanced R-L Circuit power triangle

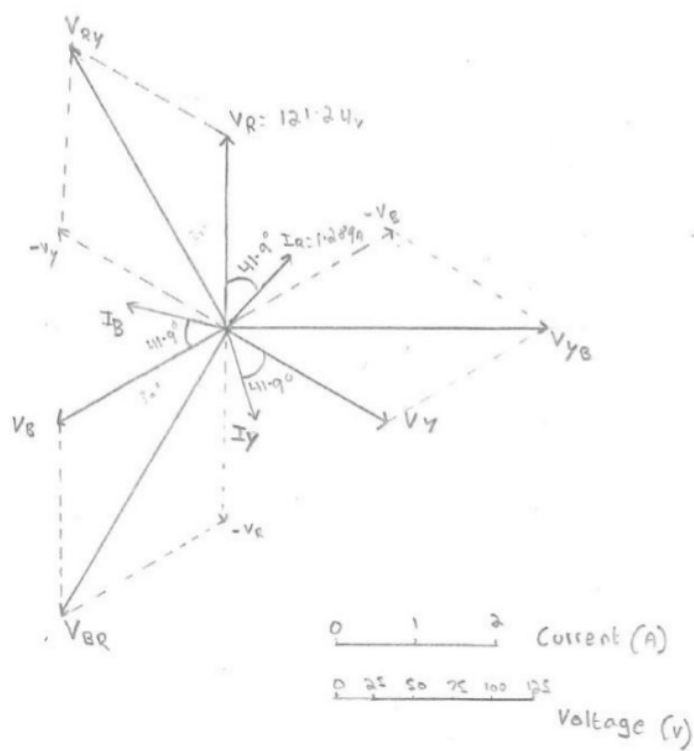


Figure 18: Star Balanced R-L Circuit phasor diagram

Appendix B

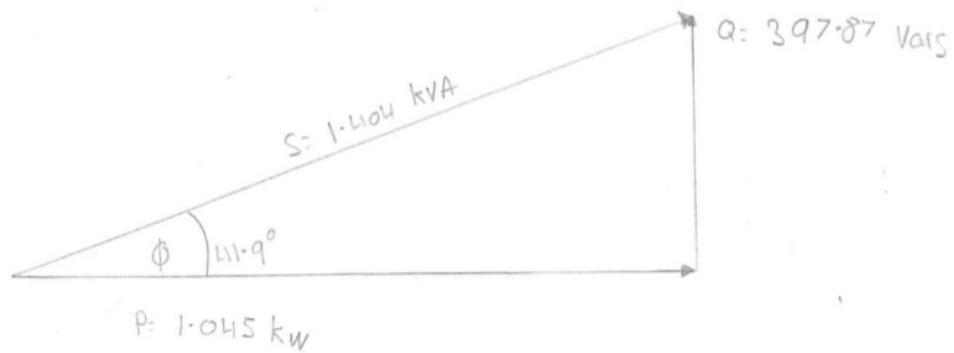


Figure 19: Delta balanced R-L circuit power triangle

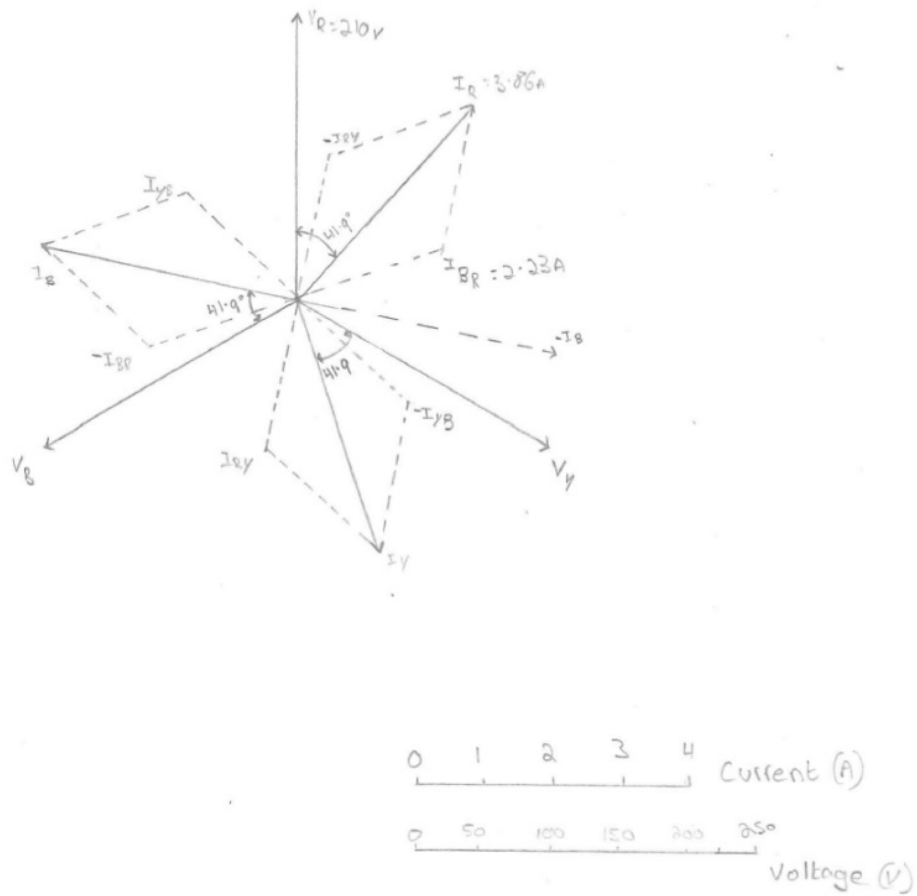
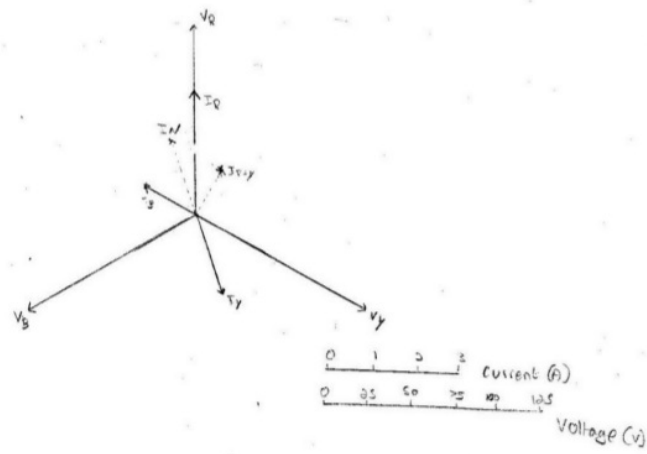


Figure 20: Delta balanced R-L circuit Phasor Diagram

Appendix C



13

Figure 21: Unbalanced Star Circuit phasor diagram

FINAL GRADE

GENERAL COMMENTS

Instructor

85/100

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Comment 1

Stick to transformer applications

PAGE 8

PAGE 9



Comment 2

Clear and correct calculations

PAGE 10



Comment 3

Good use of results table for comparison

PAGE 11



Comment 4

Good use of CRO



Comment 5

Clear circuits shown

PAGE 12



Comment 6

Correct procedures for current calculations

PAGE 13



Comment 7

check Q value



Comment 8

Good use of table for comparing results

PAGE 14



Comment 9

Good use of CRO

PAGE 15



Comment 10

Your calculations are correct, your multisim needs a neutral return, this makes the msim values incorrect.

PAGE 16



Comment 11

Excellent observation



Comment 12

A shame the multisim was not quite correct here



Comment 13

Good attempt, not quite correct

GRADING FORM: NEW CSG-RUBRIC

ALEX
WILLIAMS

85

1. ENGAGEMENT WITH LITERATURE



Very good introduction of theme, clear objectives set, the reader is led into the work in a clear and concise way. Research is detailed and mostly accurate, extensive reading evident. 8/10

8

2. KNOWLEDGE AND UNDERSTANDING



Competent knowledge and very good understanding shown, calculations and results excellent for balanced systems, error in msim for unbalanced however calculations correct. 15/20

15

3. COGNITIVE AND INTELLECTUAL



Excellent evaluation provided in the form of comparison tables, results are analysed and appropriate conclusions made in most cases. 30/40

30

4. PRACTICAL APPLICATION



An advanced application of practical skills including msim results using instruments correctly and good quality results including phasor diagrams, few small errors. 15/20

15

5. TRANSFERABLE SKILLS



Fluent coherent work structure and communication are excellent. Occasional minor weaknesses in accuracy. 17/20

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