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Power Electronics and Drives

ACDA6004

Assignment Power Factor Correction & Variable Frequency Drives

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Contents

Abstract	3
Introduction	4
Power Factor Correction	4
Three Phase Inverters	5
Methodology	6
Phase Angle Calculation Method	6
Current Amplitude Calculation Method	6
Results	10
Discussion	10
Fault Finding	12
Results	15
Discussion	15
Conclusion	15
Three Phase Inverter	16
Three Phase Supply	17
Overcurrent Protection	18
Results	20
Discussion	20
Conclusion	20
Single Phase Synchronous Motor	22
Results	23
Discussion & Conclusion	23
References	24
Fig 0 Insulated Gate Bipolar Transistor Circuit	5
Fig 1 Supply Phase Angle PFC	6
Fig 2 Supply Current Amplitude PFC	6
Fig 3 10 μ F shunt capacitor Phase Angle PFC	7
Fig 4 10 μ F shunt capacitor Current Amplitude PFC	7
Fig 5 20 μ F shunt capacitor Phase Angle PFC	8
Fig 6 20 μ F shunt capacitor Current Amplitude PFC	8
Fig 7 15 μ F shunt capacitor Phase Angle PFC	9
Fig 8 15 μ F shunt capacitor Current Amplitude PFC	9
Fig 9 Supply Voltage Measurement PFC	9
Fig 10 10 μ F shunt capacitor Phase Angle – Fault inserted	12
Fig 11 10 μ F shunt capacitor Current Amplitude – Fault inserted	12
Fig 12 20 μ F shunt capacitor Phase Angle – Fault inserted	13
Fig 13 20 μ F shunt capacitor Current Amplitude – Fault inserted	13
Fig 14 15 μ F shunt capacitor Phase Angle – Fault inserted	14
Fig 15 15 μ F shunt capacitor Current Amplitude – Fault inserted	14
Fig 16 Three Phase Inverter Initial Setup	16
Fig 17 Positive Half cycle	16
Fig 18 Negative Half Cycle	17
Fig 19 Overcurrent Protection Initial Current Measurement	18
Fig 20 Short Circuit Connected Across 2.2 & 2.3	18
Fig 21 Short Circuit Fault T+ 120s	19
Fig 22 Short Circuit Removed	19
Fig 23 Power Supply Off and Immediately Back On	19
Fig 24 Power Supply Off and On After 5 Min Delay	20
Fig 25 Supply Frequency	22
Fig 26 Supply Phase Angle	22
Fig 27 Supply Current Amplitude	23
Fig 28 Fault Condition	23
Table 1 Results – Power Factor Correction	10
Table 2 Results – Power Factor Correction Fault Condition	14
Table 3 Results – Power Factor Correction Comparison Table	15
Table 4 Results – Single Phase Synchronous Motor Fault	23

Annex A	Power Factor Correction Circuit Connections
Annex B	Three Phase Inverter Connections
Annex C	Overcurrent Protection Connections
Annex D	Single Phase Synchronous Motor Connections

Abstract

Power Factor Correction (PFC) is an important concept with respect to efficiency in electrical installations. It has a major effect on power consumption and by reducing such, will contribute to energy conservation. This in turn can reduce costs and also contribute to improving our climate by reducing the negative impact of CO2 emissions.

This report investigates the effect of Power Factor Correction on a single-phase synchronous AC motor by observing and recording the supply waveforms prior to introducing differing levels of Power Factor Correction. The resultant changes to the waveforms for different levels of correction are recorded and analysed and compared to ascertain the optimum level of PFC, and its effect on the output voltage, current and power. Two fault scenarios are injected and investigated to demonstrate the fault-finding process and circuit behaviour under fault conditions.

The second part of the report investigates DC to AC conversion by analysing the action of a three-phase inverter. The report looks at how the input DC supply is manipulated by the output pulses of a microcontroller and processed to produce an AC sinusoidal waveform at a voltage and frequency as dictated by the Microprocessor.

Overcurrent protection of a three-phase supply is considered, and a short circuit fault injected and analysed to ascertain the action of the protective circuits in fault condition.

Introduction

Power Factor Correction

The term POWER FACTOR (PF) refers to the ratio between the TRUE power and APPARENT power consumed by an electrical installation. It is a measure of how efficiently the electrical power is converted into useful work output. The ideal PF is unity (1) but in reality, is well below this. The lower the power factor then the more power is required to achieve the required task. This results in greater inefficiency and higher cost. Indeed, electricity suppliers will penalise operators of installations with low power factors.

Any current flow in a system suffers some losses. A load with a PF less than 1 will suffer additional losses. This "missing" power is referred to as the REACTIVE power and is lost to the magnetising forces required by motors and other inductive loads.

A poor PF can be the result of high harmonic distorted current waveform caused by an inverter, rectifier or variable speed drive. Improvement to the PF due to this equipment is expensive as it requires redesign of equipment or the addition of harmonic filtering. However, it is usually the result of a significant phase difference between the supply voltage and current. This can be the result of inductive loads such as motors, power transformers, welding equipment or ballast in luminaires. Poor PF caused by inductive loads can be easily improved by Power Factor Correction.

An inductive load creates a magnetic field in order to operate. Creation of this field causes the current (I) to be out of phase with the voltage (V), with the current lagging the voltage. If the magnitude of the phase lag can be reduced, then the PF will be improved. This is achieved by introducing sufficient capacitance across the supply to create a leading current, compensating for the current lag in the inductive load. This reduces the phase shift to a minimum and significantly improves the PF.

Three Phase Inverters

An INVERTER is a power electronic device which converts power from one form to another, for example from DC form to AC form, at the required frequency and voltage output. Inverters are classified based on their supply source, i.e. Voltage Source Inverter (VSI) and Current Source Inverter (CSI). A VSI has a smaller input impedance at the input terminals than a CSI. They are used in high power applications such as High Voltage DC transmission and variable frequency drives for motor control.

A three-phase inverter converts single phase DC input into a three phase AC output. This is achieved by employing Pulse Width Modulation (PWM) technology to control transistor pairs switching DC at a rate controlled by a 3-phase pulse width modulation circuit. The width of the switching pulse would dictate the output voltage of the AC sinewave due to the duty cycle [1], a broader pulse giving a more positive output voltage and the torque being controlled by the frequency of the clocking pulse of the microprocessor. The program for controlling the microprocessor is stored in the EEPROM.

Such a device is an Insulated Gate Bipolar Transistor (IGBT) (Fig 0). An IGBT is a semiconductor switching device capable of handling large voltages and currents at high switching speeds, at low control voltages.

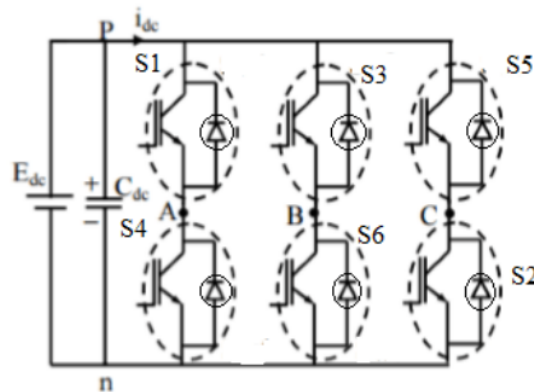


Fig 0 Insulated Gate Bipolar Transistor Circuit

Citation Needed

Phase Angle Calculation Method

The phase angle (ϕ) was calculated using the following method:

$$\phi = \frac{\Delta t}{T} \times 360$$

Caption required

Where: Δt is the difference between t_1 and t_2 for each waveform

And: T is the period of the supply frequency calculated as:

$$T = \frac{1}{f} = \frac{1}{70.85\text{Hz}} = 14.114\text{ms}$$

Caption required

Current Amplitude Calculation Method

Supply Current amplitude (mA p-p) was calculated using the following method:

$$\frac{2 \times \text{peak} \times 1000}{10}$$

Caption required

A $10\mu\text{F}$ shunt capacitor was connected in parallel to the supply and the following was observed. The measurements were repeated and recorded in table 1.

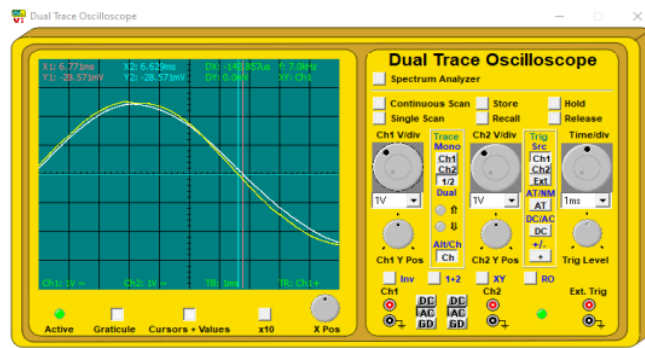


Fig 3 $10\mu\text{F}$ shunt capacitor phase angle measurement

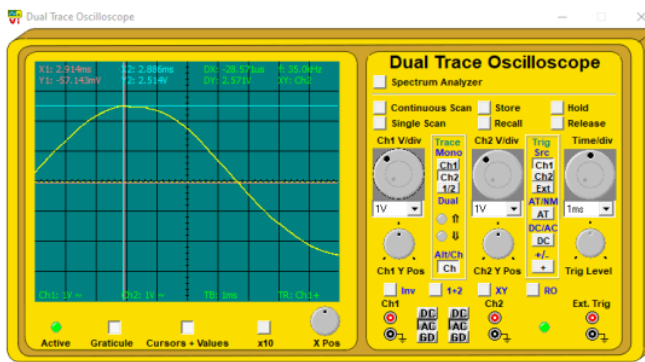


Fig 4 $10\mu\text{F}$ shunt capacitor current amplitude measurement

A $20\mu\text{F}$ shunt capacitor was connected in parallel to the supply and the following was observed. The measurements were repeated and recorded in table 1.

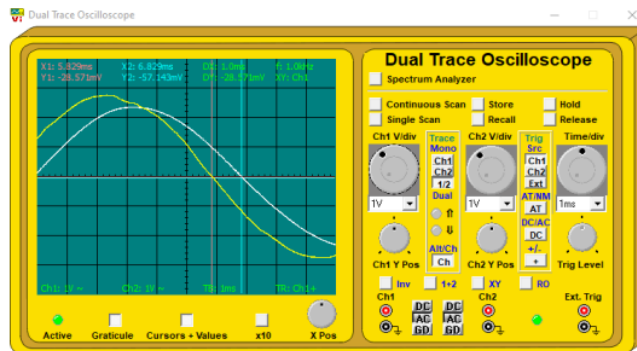


Fig 5 $20\mu\text{F}$ shunt capacitor phase angle measurement

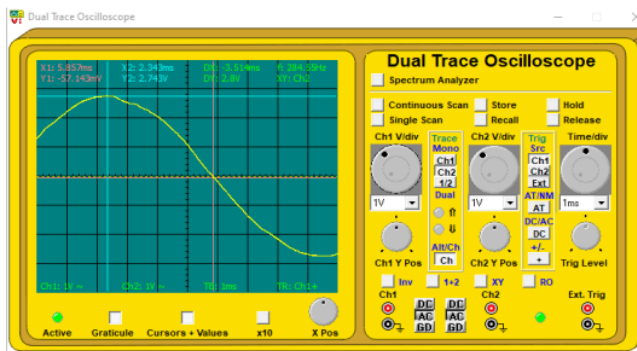


Fig 6 $20\mu\text{F}$ shunt capacitor current amplitude measurement

A 15 μ F shunt capacitor was connected in parallel to the supply and the following was observed. The measurements were repeated and recorded in table 1.

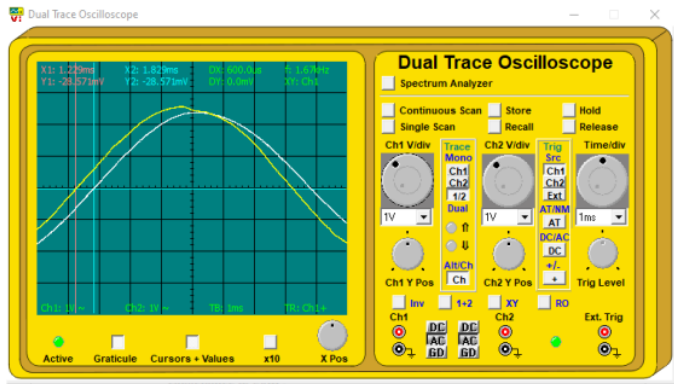


Fig 7 15 μ F shunt capacitor phase angle measurement

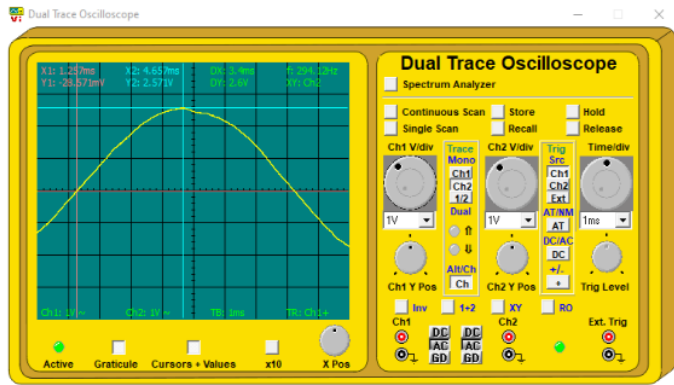


Fig 8 15 μ F shunt capacitor current amplitude measurement

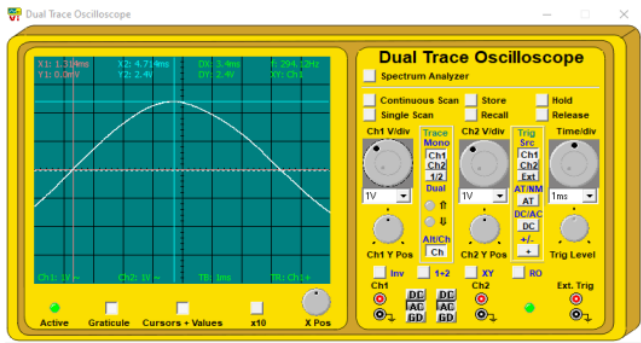


Fig 9 Supply Voltage Measurement

Results

Correction Capacitor	None	C2 - 10 μ F	C2 + C3 20 μ F	C2 + C4 15 μ F
Phase Angle (Lead/Lag)	22.59° Lag	3.64° Lead	25.5° Lead	15.3° Lead
Current Amplitude	491.4mA	514.2mA	560mA	520mA

Table 1 - Results

The supply voltage was measured at 2.4V peak (Fig 9)

The supply voltage was calculated as:

$$10 \times peak = 10 \times 2.4 = 24V peak = (48V p - p)$$

Convert supply V (peak) to rms: $rms = \frac{peak}{\sqrt{2}} = \frac{1}{1.414} = 0.7071$

$$0.7071 \times 24V peak = 16.97V rms peak$$

Caption required

Discussion

Analysis of the results shows that the shunt capacitor giving the nearest to complete correction of the phase angle is C2 (10 μ F), with a correction from 22.59° lagging to 3.64° leading. The power factor correction increased from 0.92 to 0.99, almost perfect correction. The overall effect of the 10 μ F capacitor in the circuit, on the supply was to decrease the phase angle between the voltage and current which had the resultant effect of decreasing the supply current whilst increasing the supply power. See calculations below:

The power supplied (In watts) with **no** correction capacitor in circuit was calculated as:

$$VI \cos \phi$$

Convert I (peak) to RMS $0.707 \times 491.4mA = 347.5mA rms peak$

Therefore, Power supplied: $16.97V \times 347.5mA (22.59) = 5.44W$

The power supplied with the **best** correction capacitor in the circuit (C2 @ 10 μ F)

Convert I (peak) to RMS $0.707 \times 514.2mA = 363.54mA$

$VI \cos \phi$ $16.97V \times 363.54mA (3.64) = 6.15W$

As can be seen by comparing the results of the power supplied with no correction capacitor, with that supplied with the best correction capacitor in the circuit, there is a 12.7% increase in power supplied:

$$6.15 - 5.44 = 0.69W$$

$$\frac{0.69}{5.44} \times 100 = 12.7\%$$

Caption required

This increase is due to the reduction in the phase angle caused by the introduction of the $10 \mu F$ capacitor in parallel with the load. This capacitance opposed the effects of the inductive elements and reduced the phase shift between the voltage and current. The increase in the Power Correction Factor ($\cos \phi$) due to the reduction in phase angle resulted in an increase in power supplied.

The Management Computer Inserted a Fault into the System

The module power supply was switched on. The measurements of the phase angle and current amplitude with power factor correction capacitors of $10\mu\text{F}$, $20\mu\text{F}$ and $15\mu\text{F}$ inserted in turn, were repeated. The phase angle and current amplitude were calculated and the results were recorded in table 2.

A $10\mu\text{F}$ shunt capacitor was connected in parallel to the supply and the following was observed. The measurements were repeated and recorded in table 2.

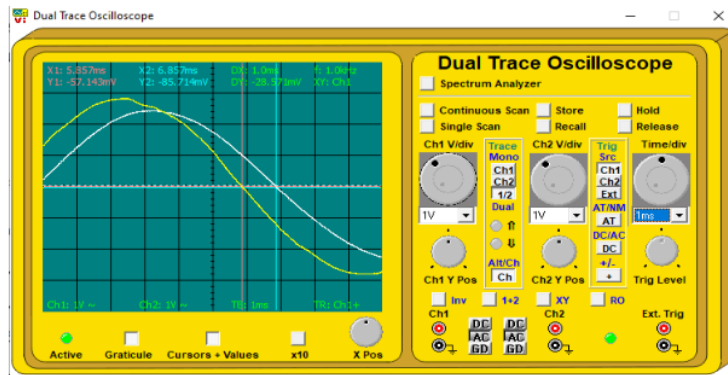


Fig 10 $10\mu\text{F}$ Phase Angle

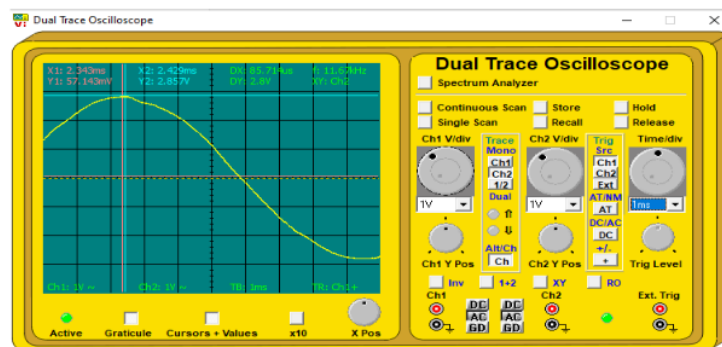


Fig 11 $10\mu\text{F}$ Current Amplitude

A $20\mu\text{F}$ shunt capacitor was connected in parallel to the supply and the following was observed. The measurements were repeated and recorded in table 2.

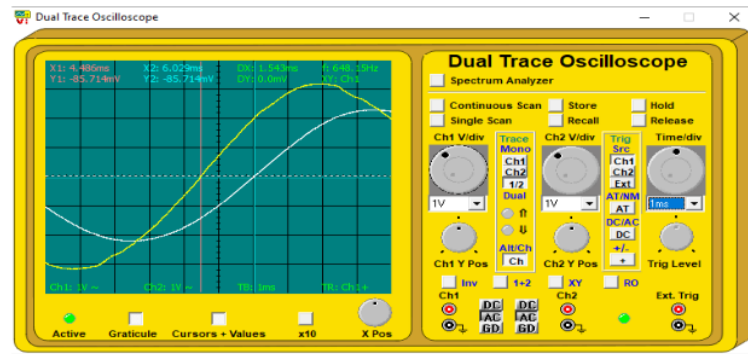


Fig 12 $20\mu\text{F}$ Phase Angle

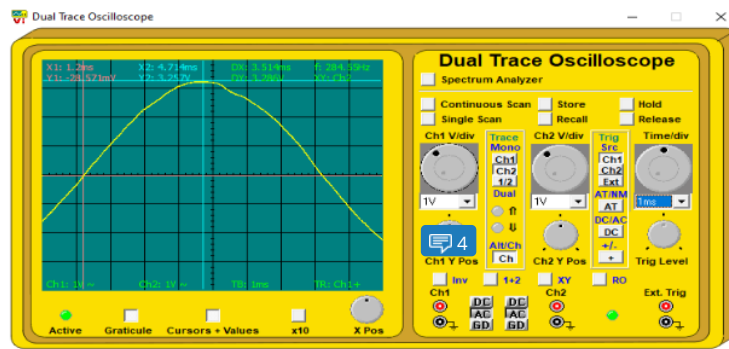


Fig 13 $20\mu\text{F}$ Current Amplitude

A 15 μ F shunt capacitor was connected in parallel to the supply and the following was observed. The measurements were repeated and recorded in table 2.

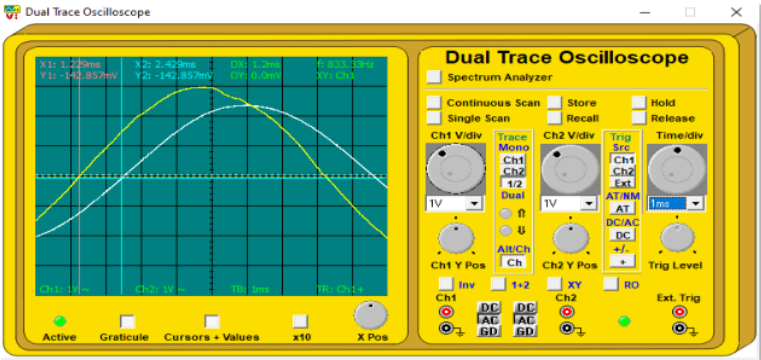


Fig 14 15 μ F Phase Angle

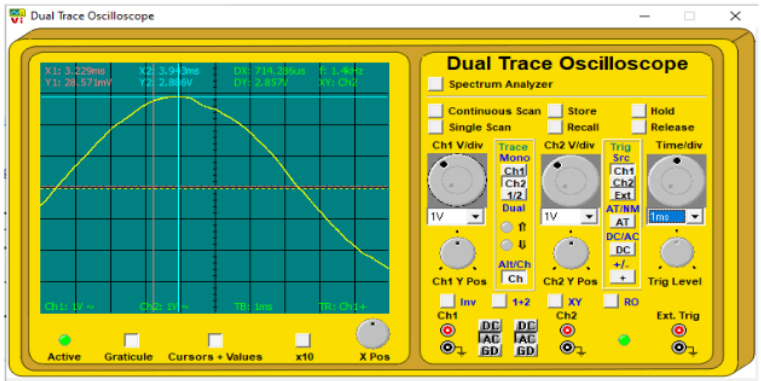


Fig 15 15 μ F Current Amplitude

Correction Capacitor	None	C2 - 10 μ F	C2 + C3 20 μ F	C2 + C4 15 μ F
Phase Angle (Lead/Lag)	22.59° Lag 0.92	25.5° Lead 0.90	39.35° Lead 0.77	30° Lead 0.86
Current Amplitude	491.4mA	560mA	657mA	571.4mA

Table 2 - Table of Results Under Fault Condition

Results

Initial

Correction Capacitor	None	C2 – 10 μ F	C2 + C3 20 μ F	C2 + C4 15 μ F
Phase Angle (Lead/Lag)	22.59° Lag 0.92	3.64° Lead 0.99	25.5° Lead 0.90	15.3° Lead 0.96
Current Amplitude	491.4mA	514.2mA	560mA	520mA

Fault Injected

Correction Capacitor	None	C2 – 10 μ F	C2 + C3 20 μ F	C2 + C4 15 μ F
Phase Angle (Lead/Lag)	22.59° Lag 0.92	25.5° Lead 0.90	39.35° Lead 0.77	30° Lead 0.86
Current Amplitude	491.4mA	560mA	657mA	571.4mA

Table 3 – Comparison of Results

Discussion

By comparing and analysing the results from table1 and table 2 it can be seen that the phase angle corrections in table 2 for all combinations of correction capacitors in circuit, results in a massive over correction of these phase angles. In order to produce values of 10 μ F, 20 μ F and 15 μ F respectively, a combination of capacitors C2, C3 and C4 was used. The common factor here is capacitor C2 (10 μ F).

Conclusion

From this analysis it was deduced that capacitor C2 (10 μ F) was causing the over-correction when switched into the circuit. Such an over-correction can only be caused by C2 being of higher value than declared i.e. greater than 10 μ F.

Three Phase Inverter

The Virtual Instrument Platform was set up and connected as shown at Annex B.

The virtual oscilloscope was set up as follows:

Timebase to 2ms/div

Dual trace

Chop mode

Position CH 1 trace two divisions down from the top of the display

Position CH 2 trace two divisions up from the bottom of the display

CH1 Y-Amplifier to 20V/div, DC Input

CH2 Y-Amplifier to 10V/div, DC input

Trigger on CH 1

The amplitude control (VR1) was set to position 3. The frequency control (VR2) was adjusted for one cycle of output on CH 1.

The following waveforms were examined, and the observations were recorded.

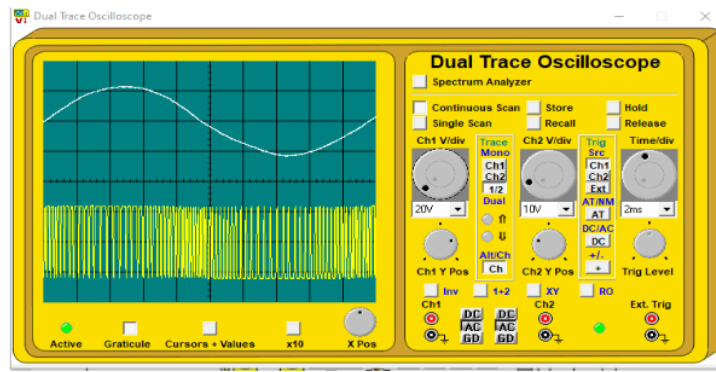


Fig 16 Three Phase Inverter Initial Setup

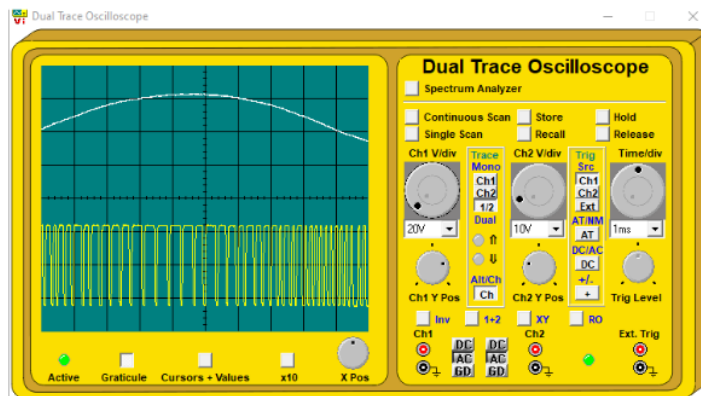


Fig 17 Positive Half Cycle

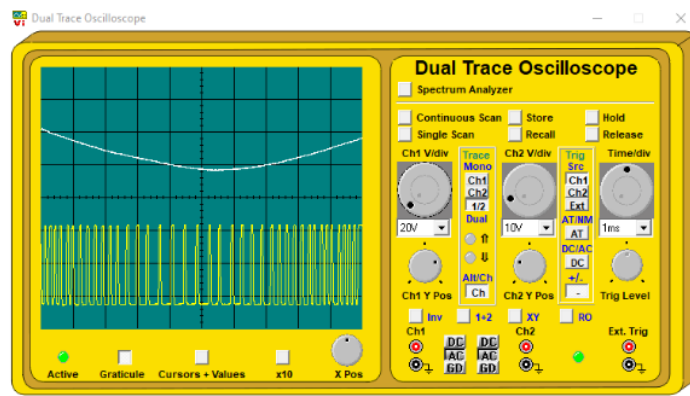


Fig 18 Negative Half Cycle

Three Phase Supply

Figure 15 shows the individual pulses of the microcontroller and the resultant AC sinewave output. The timebase was reduced to 1ms/div to display just the positive half cycle of the sine wave and the associated microcontroller output control pulses (Fig 16). It was observed that at the positive peak of the sinewave the microcontroller pulses became broader, i.e. had a larger mark/space ratio.

The triggering was changed to negative and the negative half cycle only was displayed. (Fig 17). It was observed that the negative peak of the half cycle the microcontroller pulses mark/space ratio became smaller, with narrower pulses.

It was noted that the number of pulses in one half cycle was approximately 40.

The CH1 amplifier was set to 10v/div and the waveform was observed. It was noted that there was some very finely discernible ripple in the output sinewave waveform. As the ripple did not coincide with the rise of the leading edge of the microcontroller pulse, it was attributed to the poor graphics of the simulation software. Any ripple of the output waveform can be smoothed by the inductance of an output transformer.

Overcurrent Protection

The Virtual Instrument Platform was set up and connected as shown at Annex C. The amplitude control (VR1) was poisoned for a single-phase supply and the frequency control (VR2) set to maximum to give a single-phase supply at maximum frequency. The VIP software was initiated, and the virtual oscilloscope set up as follows:

Timebase to 2ms/div

Dual trace

Chop mode

Position CH 1 trace two divisions down from the top of the display

Position CH 2 trace two divisions up from the bottom of the display

CH1 Y-Amplifier to 20V/div, DC Input

CH 2 Y-Amplifier to 10V/div, DC input

Trigger on CH 1

Multimeter connected as shown at annex C and set to 200mA range.

The module power supply was switched on and the following waveforms were observed and results recorded.

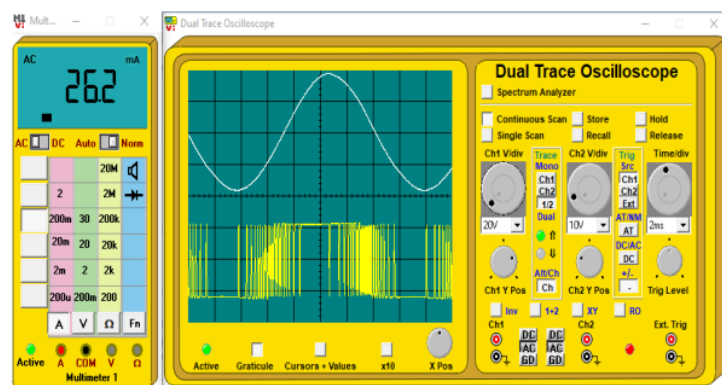


Fig 19 Overcurrent Protection Initial Current Measurement

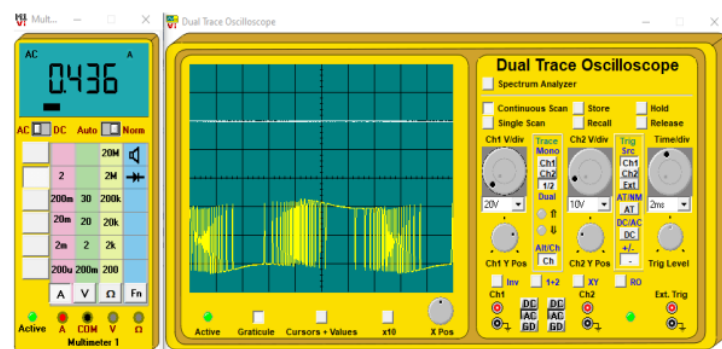


Fig 20 Short Circuit Connected Across 2.2 & 2.3

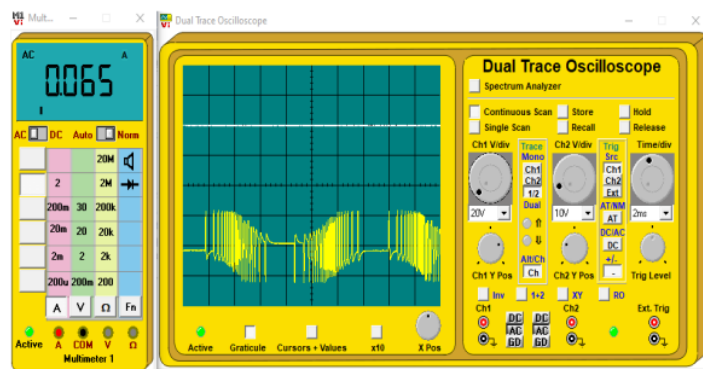


Fig 21 Short Circuit Fault T+ 120s

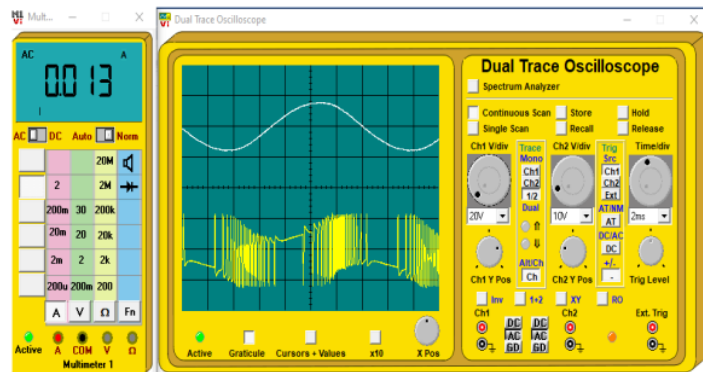


Fig 21 Short Circuit Removed

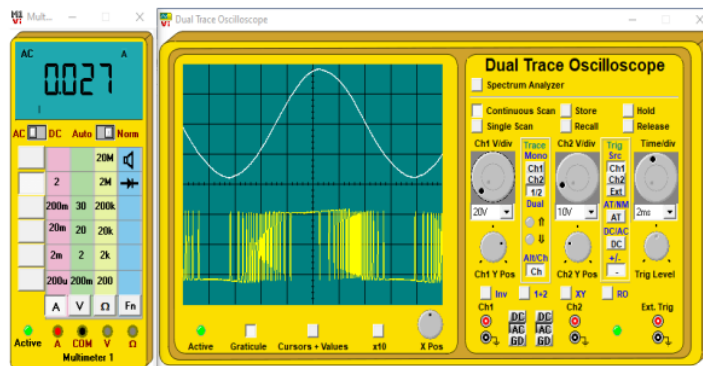


Fig 23 Power Supply Off and Immediately Back On

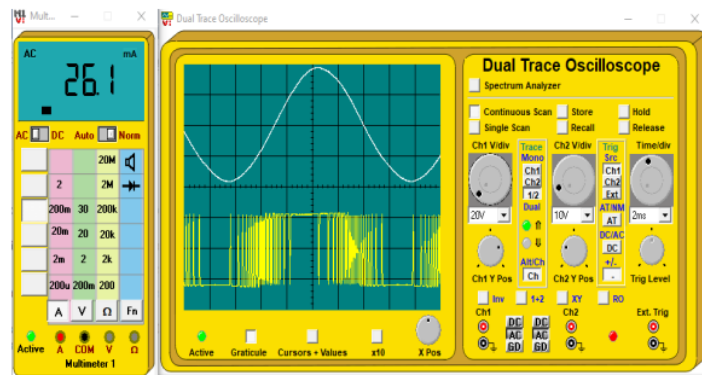


Fig 24 Power Supply Off and On After 5 Min Delay

Results

The initial load current was measured at 26.2mA AC. The supply voltage at 36V peak.

A short circuit was connected across sockets 2.2 & 2.3 and the effect on the current, voltage and microcontroller pulses was observed. (Fig 19). The immediate result was that the output pulses from the microcontroller have been altered which reduced the supply voltage to 0V, the supply current increased to 436mA. After a period of 2 minutes, it was observed that the supply current had risen to a maximum and gradually reduced to 65mA (Fig 20). The supply voltage remained at 0V.

The short circuit was removed, and the waveforms monitored. (Fig 21) It was observed that supply voltage returned to approximately 18V peak, but the supply current dropped further to 13mA. This did not match the original power supply.

The power supply was switched off and immediately on again. The supply voltage and current returned to normal at 36V and the supply current to 27mA respectively.

The power was switched off and after a delay of 5 minutes, on again. (Fig 23). The waveform was observed to be very similar to that in Fig 22 as in the supply was restored to near normal, with the supply current settling back to 26.1mA.

Discussion

Overcurrent protection is provided in a power supply to prevent it from delivering more current than its circuits and cables can safely carry. The three-phase power supply has two stage overcurrent protection built in. It is designed to immediately reduce the output voltage to a low level but allow the current to rise. If the current continues to rise to an excessively high value then a second stage thermal protection device is triggered which alters the pulses from the microcontroller to further reduce the output voltage and bring the output current back to a safe value. After the second stage thermal protection circuit has triggered, the module power supplies must be turned off for a short period of time to allow the thermal fuse to recover.

Conclusion

From the results the moment the short circuit fault was introduced the voltage fell towards 0V whilst the current rose to a peak. This mimic the effects of the first stage of the overcurrent protection. After approximately two minutes the current had peaked and fallen away, suggesting that the second stage of the overcurrent protection had been initiated. This is also supported by the observed changes in the microprocessor output pulses. With the fault removed, the supply voltage and current did not immediately return to normal, until the module power supplies were switched off and back on. Only after the momentary interruption to the module power supplies did the supply voltage and current return to normal. The fact that the supply current and voltage returned to normal so rapidly suggests

that the second stage thermal protection fuse had not experienced significant overheating effects, or the fuse recovered from those effects rapidly as soon as module power supplies were interrupted.

Single Phase Synchronous Motor

The Management Computer Has Inserted a Fault into the Circuit

The Virtual Instrument Platform was set up and connected as shown at Annex D. The amplitude control (VR1) was poisoned for a single-phase supply and the frequency control (VR2) set to maximum frequency. The VIP software was initiated, and the virtual oscilloscope set up as follows:

Timebase to 1ms/div
CH1 and CH2 Y-amplifiers to 1V/div
AC input selected
Both traces across the centre of the graticule
Fine timebase control adjusted so that one half cycle covered 9 divisions

The module power supply was switched on. The waveforms in Figs 25, 26 and 27 were observed and the following measurements were taken:

1. Supply Frequency
2. Phase angle between supply voltage and supply current
3. Amplitude of the supply current

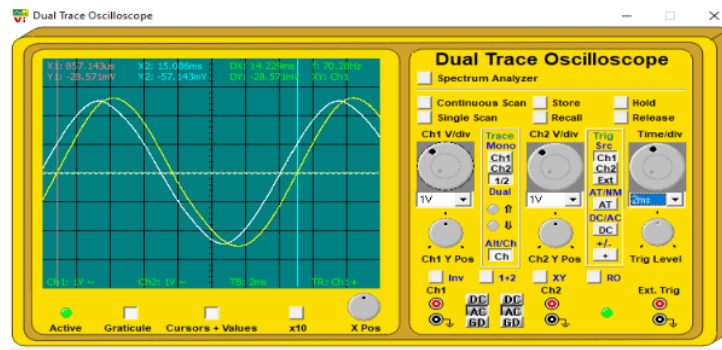


Fig 25 Supply Frequency

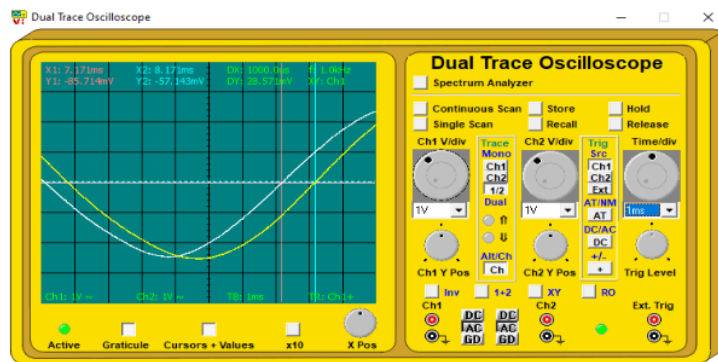


Fig 26 Supply Phase Angle

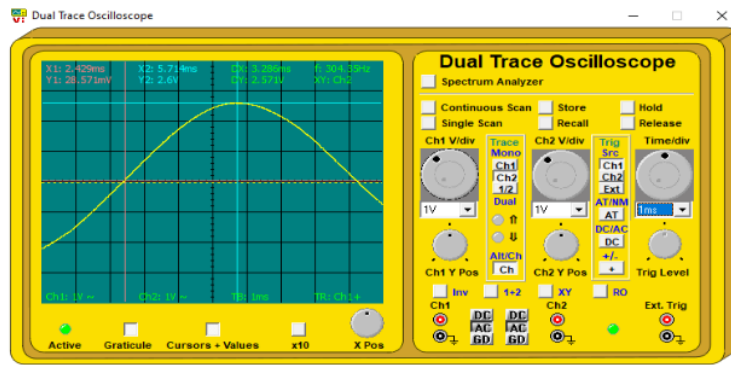


Fig 27 Supply Current Amplitude

Power factor correction was applied to the circuit by connecting a shorting link between sockets 4.3 & 7.1 (se annex C). This Connected the power factor correction components C2, C3 and C4 into the circuit. The following waveforms were observed. (Fig 28).

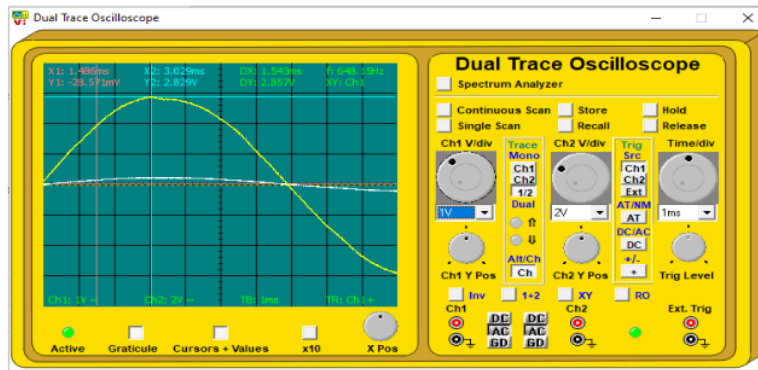


Fig 28 Fault Condition

Results

	Frequency	Current	Voltage	Phase Angle
Initial	70.8Hz	514.2mA	48V p-p	25.5°
Link in	70.8hz	571.4mA	Approx 0V	N/A

Table 4 – Comparison of results without and with shorting link

Discussion and Conclusion

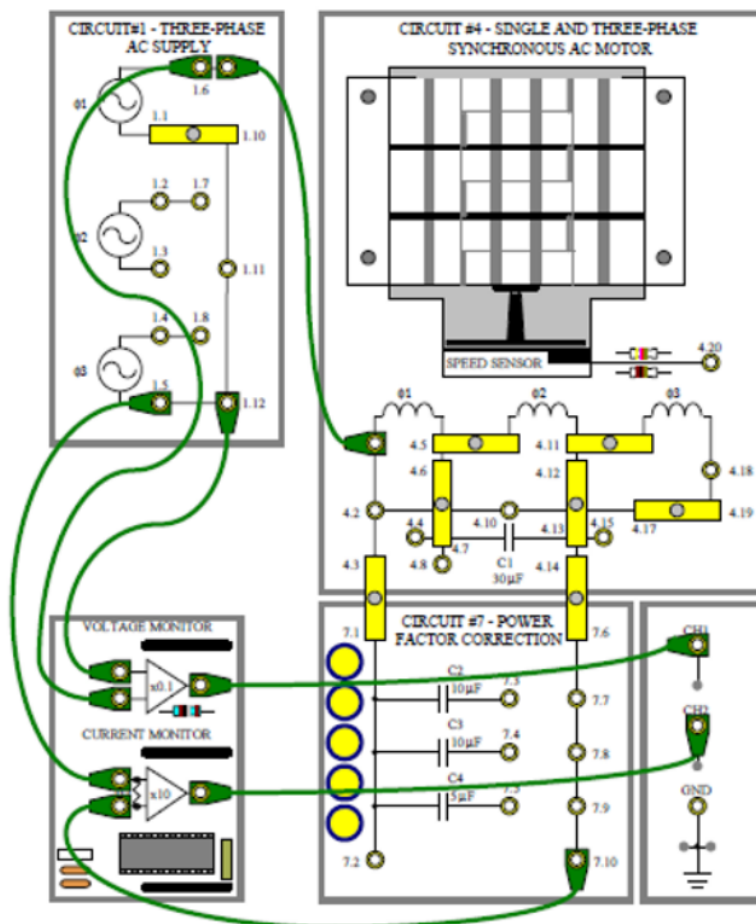
From the observations and the results in table 4 it can be seen that as soon as the shorting link is connected the supply voltage drops to near 0V. By using the multimeter and measuring the voltages across the capacitor bank at various sockets, both with the link in and the link out, it became apparent that with the link in the entire capacitor bank was short circuit, effectively between 7.3 and 7.9.

References

[1]S. Harding, "What Is OCP? Power Supply Overcurrent Protection Explained", *Tom's Hardware*, 2022. [Online]. Available: <https://www.tomshardware.com/uk/reviews/ocp-overcurrent-protection-power-supply-definition-psu,6241.html>. [Accessed: 07- Apr- 2022].

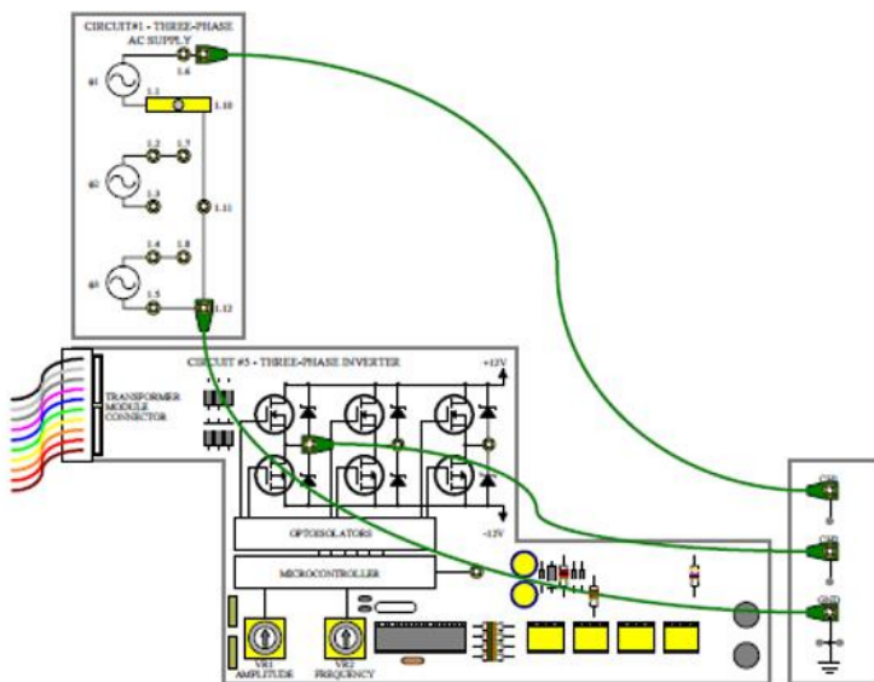
[2]"DC Motor and Controller  er - Phidgets Support", *Phidgets.com*, 2022. [Online]. Available: https://www.phidgets.com/docs/DC_Motor_and_Controller_Primer#Pulse-Width_Modulation. [Accessed: 07- Apr- 2022].

Power Factor Correction Circuit Connections



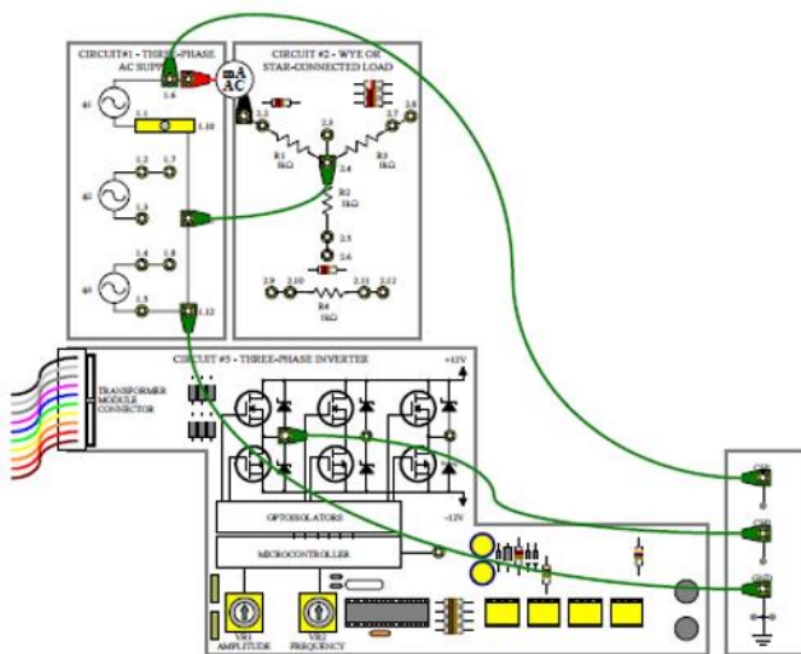
Annex B

Three Phase Inverter Connections



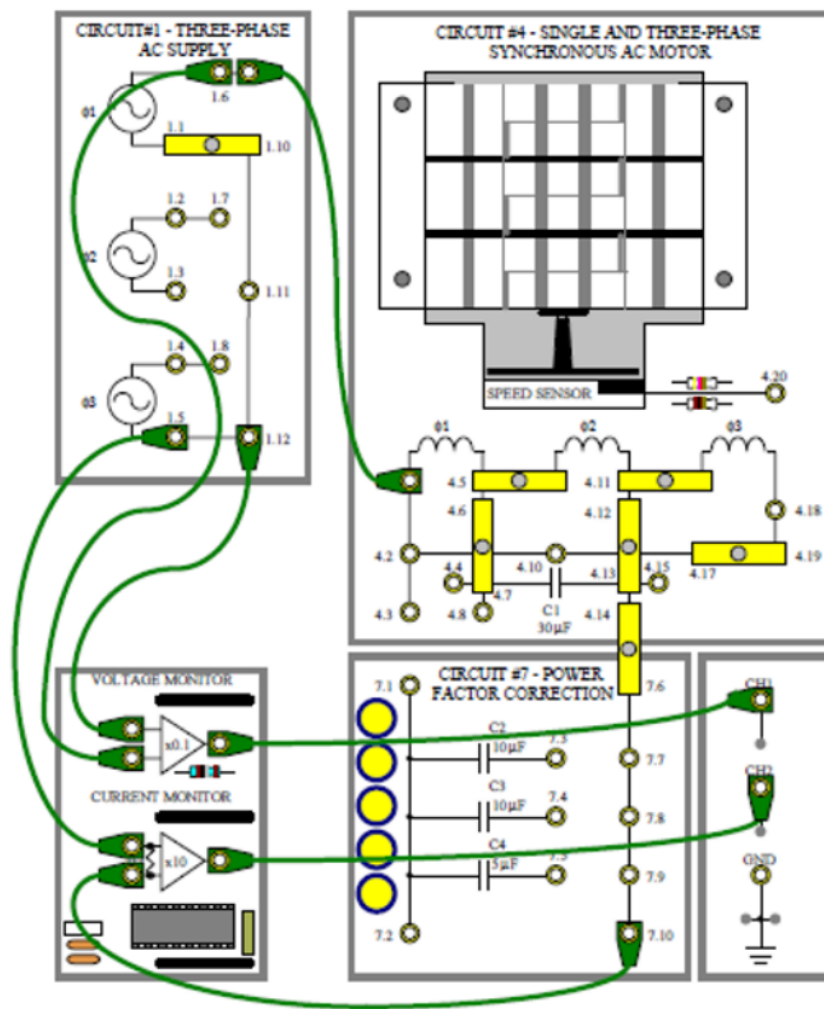
Annex C

Overcurrent Protection



Annex D

Single Phase Synchronous Motor Connections



ACDA 6004 Ass 1 John Nigel James

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

70/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4



Comment 1

Good abstract, although you should include a statement of your results. Something like "the power factor was corrected from 0.84 to 0.97 by the addition of a 20uF capacitor", or a similar statement would have sufficed.



Citation Needed

Cite Source:

Please use the link below to find links to information regarding specific citation styles:

http://www.plagiarism.org/plag_article_citation_styles.html

Additional Comment

When making statements such as these, you should support your statement with a reference.

PAGE 5



Citation Needed

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PAGE 6



Comment 2

poisoned? Assume you meant positioned?

PAGE 7

QM

Caption required

You should always include a caption on figures, equations and tables to allow you to refer to them in your text.

e.g. An illustration of this can be seen in figure 2. The relationship of the variables is shown in equation 2. Table 1 shows the results of the first experiment where the control variable, temperature in degrees celsius is shown in the first column....

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PAGE 8

PAGE 9

PAGE 10

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Comment 3

This sort of sentence would be fantastic in your abstract.



Caption required

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PAGE 11



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PAGE 12

PAGE 13



Comment 4

Are all these images of the oscilloscope really needed, or could they be replaced with one or two images to show the method and a table of results? - You don't need to prove you took the measurements, a table of results could do that.

PAGE 14

PAGE 15

PAGE 16

PAGE 17

PAGE 18

PAGE 19

PAGE 20

PAGE 21

PAGE 22

PAGE 23

PAGE 24



Ref Qual

You should try to use more high quality reference sources, such as textbooks from reputable academic publishers and articles from peer reviewed journals.



Comment 5

I was expecting to see more references cited.

PAGE 25

PAGE 26

PAGE 27

PAGE 28

GRADING FORM: SMU GENERIC_SMOSEY

JOHN JAMES

69.50

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



References to a limited range of mostly relevant sources. Some omissions and minor errors. Referencing conventions evident though not

2.05

always applied consistently. - You should cite the sources you have used in your text with the appropriate number in square brackets, as dictated by the IEEE referencing standard.

KNOWLEDGE & UNDERSTANDING

Knowledge of the basic underlying concepts and principles of a subject.



Excellent knowledge and understanding of the main concepts and key theories. Clear awareness of challenges to established views and the limitations of the knowledge base.

22.5

COGNITIVE & INTELLECTUAL

Evaluate underlying concepts and principles of a subject and interpret qualitative and quantitative data in order to develop lines of argument and make sound judgements.



Thoroughly logical work, supported by evaluated evidence. High quality analysis, developed independently or through effective collaboration. Ability to investigate contradictory information and identify reasons for contradictions. Strong, persuasive, conclusions, justifiable recommendations.

21

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



An advanced application of a range of methods, materials, tools and/or techniques. Application and

21

deployment extend beyond established conventions. Innovation and creativity evident throughout.

TRANSFERABLE SKILLS

Communicate the results of their study/work accurately and reliably, and with structured and coherent arguments; the qualities needed for employment requiring the exercise of some personal responsibility within a structured and managed environment.



Can communicate effectively in a suitable format, but may have minor errors. Mostly coherent work and is in a suitable structure.

2.95