



Course: BEng Electrical and Electronic Engineering
Module: ACDA6004 Power Electronics & Drives
Assignment 1: Power Factor Correction & Variable
Frequency Drives

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Abstract

This report details how motor control can be effectively and efficiently achieved, crucial to the manufacturing industry and power electronic devices in today's expanding world.

This report investigates some of the key points to consider for motor control and the purpose of Power factor correction (PFC) as well as how it can be calculated and improved using a range of methods. The report proves the huge benefits to using Power factor correction such as reduced energy and hardware costs but also highlights the legal requirement for large business to carry out effective PFC.

The second part of this report investigates pulse width modulation (PWM) and details some best practices such as using over current protection devices and how to effectively fault find when circuits go wrong.

1. Introduction

1.1. What is Power Factor correction (PFC)?

Power factor is a ratio between the output power of a device versus the input power.

It is a key point when designing electrical devices and is highly regulated. This is because it increases the load on the national grid. Most loads in industry are inductive loads such as motors which cause a lagging or poor power factor. [1]

A common analogy is to use the beer method. Business or homeowners will pay for the apparent power. However, this is made up of the active power and Reactive power.



Figure 1: Power Factor Explained [2]

1.2. Phasor diagrams

The reactive power (VAr) can then be calculated from a phasor diagram using trigonometry.

Reactive power = Apparent power (kVA) $\times \sin\phi$.

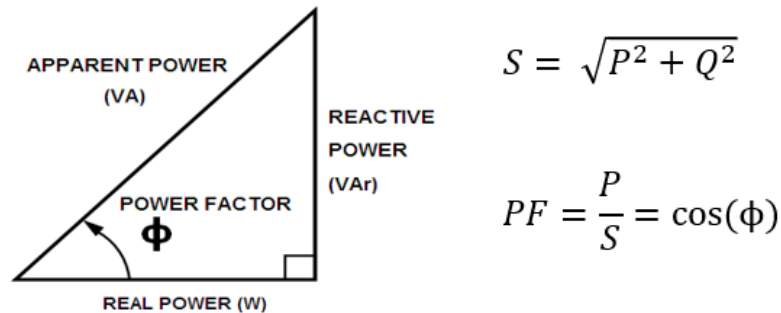


Figure 2: Phasor Diagram [1]

Power factor can be calculated using the following formula: $PF = \text{Real power(kW)} / \text{Apparent Power(kVA)}$. The power factor will be shown between 0 and 1.

- 1 being an ideal Power factor, however this is typically unlikely to be achieved.
- Good Power Factor between 1 and 0.95
- Poor Power Factor between 0.95 and 0.85
- Bad Power factor anything below 0.85.

However, it is also in the interest of the company/business to have a good or high-power factor ratio as they will pay for the apparent power (True power + Reactive power) and therefore pay less for their energy consumption, which has become ever more important with the recent rise in energy costs. Businesses may also get penalized for poor power factors by energy suppliers and face increased cost for power equipment's such as cable sizes. Using less power also has another effect of being better/greener for the environment. [2]

1.3. Power Factor Correction Capacitor

Power factor can be improved by introducing a power factor correction capacitor (passive) which are leading components or by using active power factor correction. However, a big disadvantage to this is if the load on the motor changes, then the PFC may be under or over correcting resulting in a poor power factor.

1.4. Active power factor correction

Industry now use active power factor correction as it automatically monitors the voltage and current and calculates the phase angle/power factor and uses a switching regulator operating at a high frequency, which enables companies to achieve a good power factor over 0.95.[3]

1.5. Power Factor correction Applications

- Transmission network/National Grid
- Systems containing motors
- Welding machines
- Electric arc furnaces
- Inductors

[4]

1.6. What is an Inverter?

An Inverter is a power electronic device that converts DC to AC. Power inverters contain power electronic devices such as IGBT or MOSFETS, the amount will vary depending on the type of inverter. There are several types of inverters available depending on the application such as:

- Single Phase inverter
- 3-Phase inverter
- Sine wave Inverter
- Square wave inverter
- Modified sine wave inverter

[5]

Three-Phase Inverter Applications:

Three-phase inverter are used in a range of applications such as:

- VFD for Controlling Conveyors, Fans, Cranes, and presses
- HVDC (High voltage Direct current) Transmission
- PV (photovoltaics) Solar panels convert DC to AC with maximum power point tracking
- UPS (uninterruptible power supply)

[6]

1.7. Variable Frequency Drives

A variable Frequency drive (VFD) or also commonly referred to as an inverter are the most common way of controlling an AC motor. A variable frequency drive gives a wide range of control of a motor, with a variable frequency drive, you can change the torque and speed characteristic curves of the motor allowing you to either change the speed or torque easily to suit the application. This is also advantageous if the motor will have different loads applied for different products enabling a quick change over time.

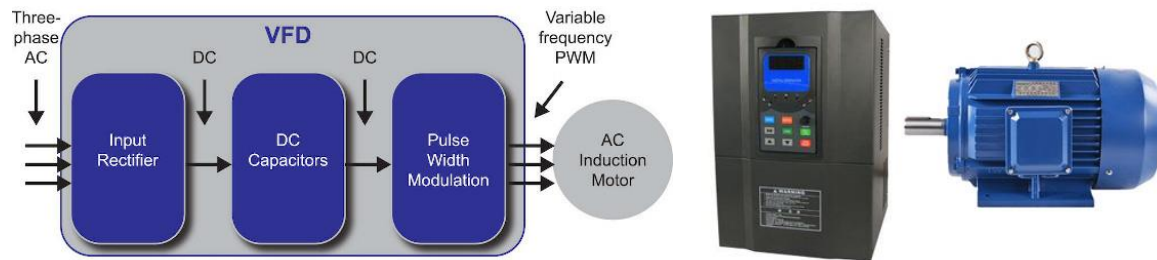


Figure 3:VFD Block diagram[7] [8]

1.8. Operation of a Variable Frequency Drive (VFD)

A VFD is made up of three stages.

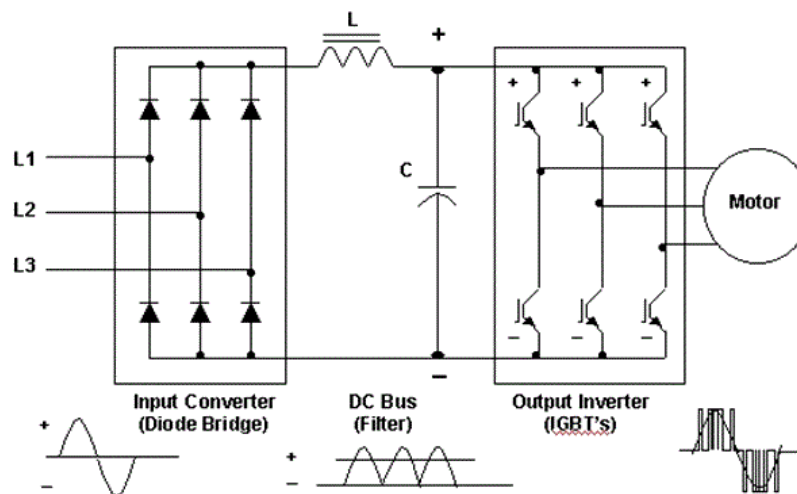


Figure 4:VFD block Diagram2

Rectifier stage:

The rectifies or converts the AC waveform into DC. This is a diode based full wave rectifier circuit. this might be a variable input (single or three phase).

Capacitor Filter:

This smooths the output from the rectifier and reduces ripple.

Inverter Stage:

The output section of the VFD commonly uses insulated gate bipolar transistors (IGBT) or less common Silicon controlled rectifier (SCR) which uses high-speed switching to create a simulated AC waveform (Known as Pulse Width modulation/PWM). To gain a 3-phase output, 6 IGBT's would be used where at least 3 of these would be in use at any given time to ensure the positive and negative half cycle are utilized.

The Frequency of the Output (PWM) is then varied as required to control the speed of the AC motor.

The program for generating sine waves by the inverter is stored in EPROM (erasable programmable read-only memory). [9]

1.9. Latest VFD's available in industry

Many VFD'S can now be purchased with option cards such as communication cards. Some of the common connections used are Ethernet I/P and EtherCat allowing fast remote control and monitoring which is useful if the VFD is not accessible easily or if many VFD's are used in a system. This also enables real time monitoring and could even provide information useful for maintenance/breakdowns such as production hours or fault alarms.



Figure 5:Omron VFD EtherCat

[9] [10]

1.10. AC Synchronous Motor

An AC synchronous motor is made from two main parts: the stator (stationary part) and the rotor (the rotating part). The two parts work together to transfer electrical energy into mechanical energy.

It's called a synchronous motor because the rotor spins at a constant speed same speed as the rotating magnetic field from the stator) if it's within the specification of the motor. If the load exceeds the specification, then the rotor will slip and stall. Synchronous motors are normally used for high precision applications.

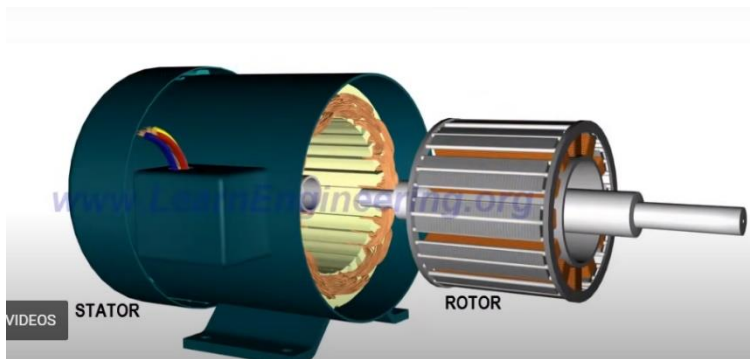


Figure 6: Rotor & Stator

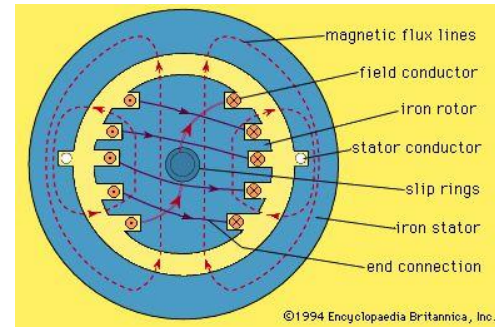


Figure 7: Motor Internal [11]

Stator

The stator is made up from three phase windings placed in slots within laminations.

The speed of a synchronous motor can be calculated easily by using this formula: $n_s(\text{rpm}) = 120f/p$
where:

f = frequency

p = number of poles

Rotor

The rotor has pairs of poles and are connected to a DC power source via two slip rings.

However, a synchronous motor with only a field winding is not self-starting, due to the fast speed of the rotating magnetic field, the rotor wouldn't lock on or synchronise instead it would just oscillate.

To overcome this, often Synchronous motor rotors have squirrel cages to bring the motor up to synchronous speed, then the rotor field coils are energized.

Advantages

- Can achieve a very good power factor
- Runs at a constant speed (good for high precision applications)
- It can handle high voltage drops before stalling (50%)

Disadvantages

- Difficult to start (Needs a direct online starter or disconnected from load to start)
- Potential to stall if torque exceeds maximum specified limit.

[12] [13]

1.11. Risk assessment

The exercises will be carried out following instructions and precautions provided by the equipment manufacturer (LJ Create). The equipment is CE Marked and is designed for low power office/classroom use and poses a low risk.

1.12. Equipment

The Equipment used in proceeding Lab tests:

- LJ Create virtual instrument platform Digiac 3000 – 1.7
- LJ Create software (including virtual multi-meter, oscilloscope, and power supply control)
- Various Patch leads
- Shorting links/ bridge connectors

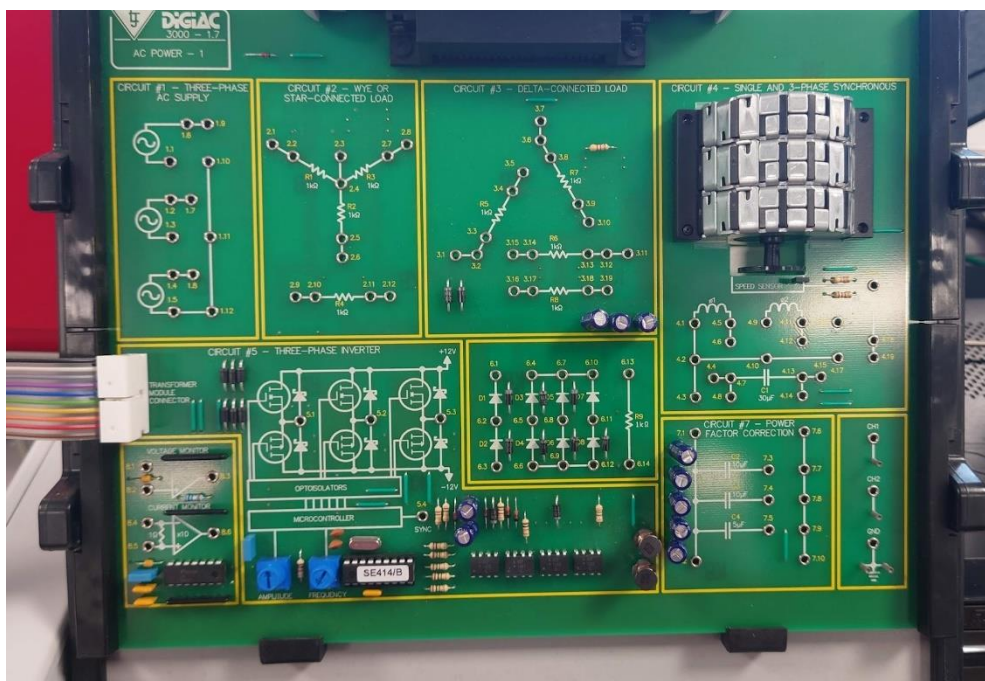


Figure 8: LJ Create Equipment

2. Lab 1: Power factor correction

2.1. Method

The purpose of the following lab is to calculate the power factor of this circuit and how to improve/find the best power factor correction capacitor.

2.2. Power factor correction Circuit Setup

Following the instructions and wiring diagram provided, the equipment set up as follows:

Single phase supply connected to a Synchronous motor with a voltage and current monitor in circuit.

The amplitude (VR1) and the frequency control (VR2) set to maximum as per instructions provided.

The virtual oscilloscope is also connected to the circuit.

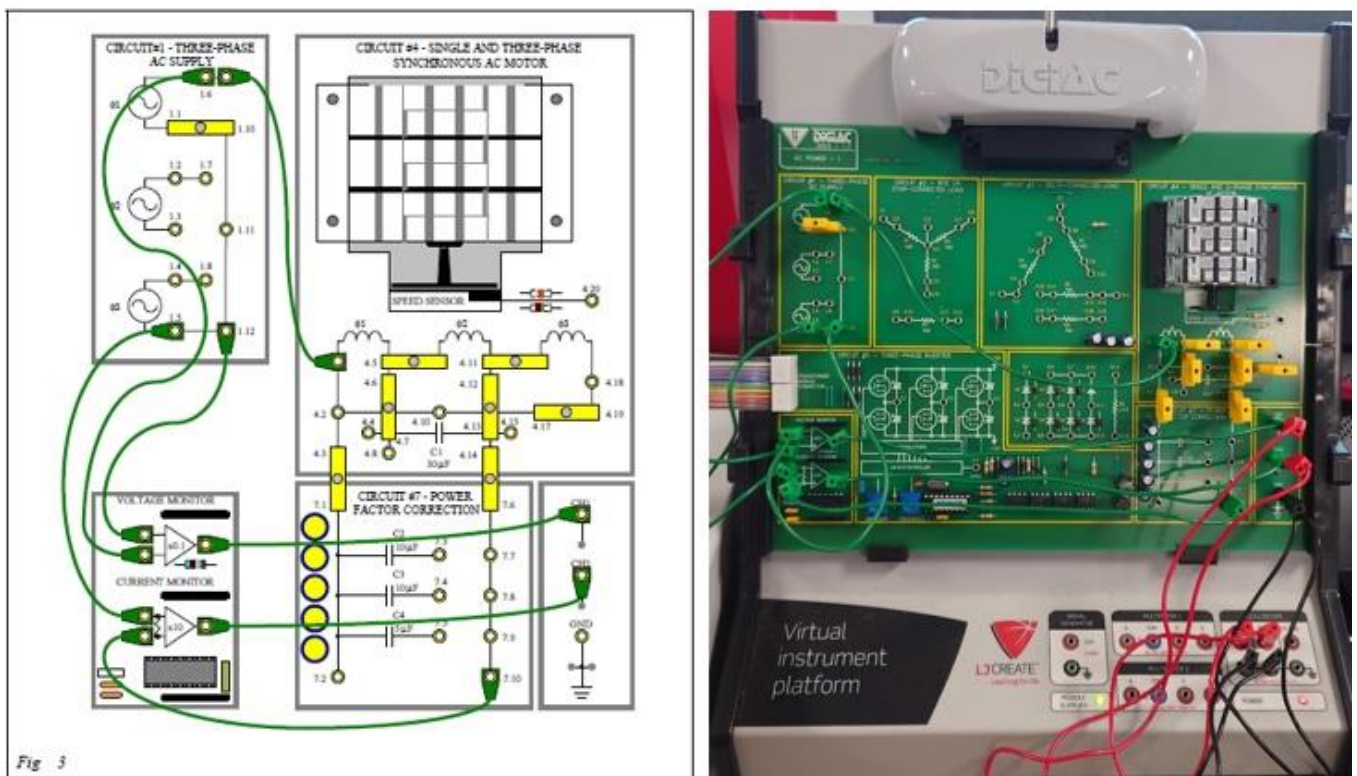


Figure 9: Lab 1 Circuit & diagram

2.3. Lab 1 Results

Using the Oscilloscope, the phase angles and current amplitude can be recorded for each circuit and from this the Power factor can be calculated. The results are as follows:

Correction Capacitor	None	C2 -10 μ F	C2 + C3 -20 μ F	C2 + C4 -15 μ F
Phase angle	30.64°Lag	1.53°Lead	15.34°Lead	7.67°Lag
Current Amplitude	502.8 mA p-p	445.8 mA p-p	508.6 mA p-p	462.8 mA p-p
Power factor cos (ϕ)	0.860	0.999	0.964	0.991

Table 1: Lab 1 Results

The phase angle can be calculated by using the formula:

$$\text{Phase angle (in Degrees)} = \Delta t / T \times 360$$

Where:

Δt = Delay/difference between the two waveforms

T = Time period

Utilizing the virtual oscilloscope to take measurements and complete the table above changing the power factor correction capacitor as required.

Current of the circuit is shown on channel 2 (Yellow) Lagging the voltage on channel 1 (White).

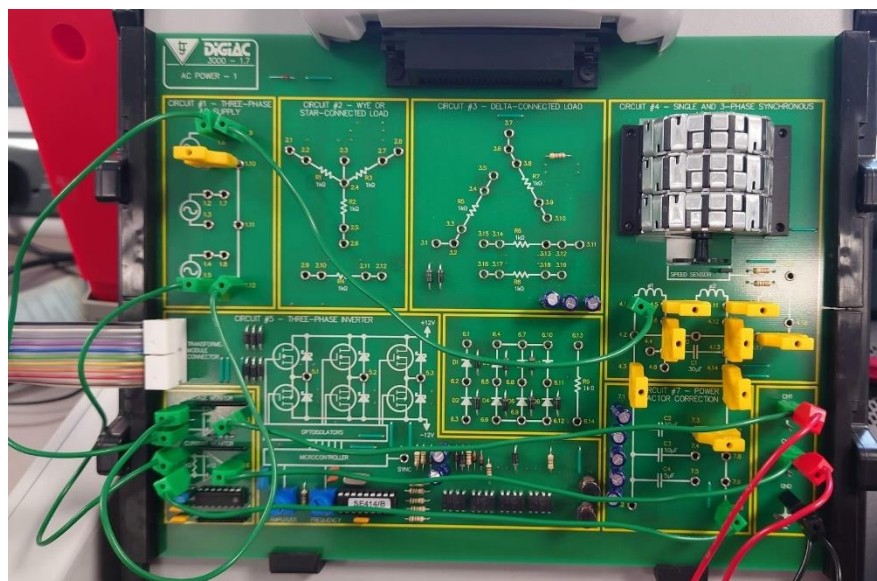
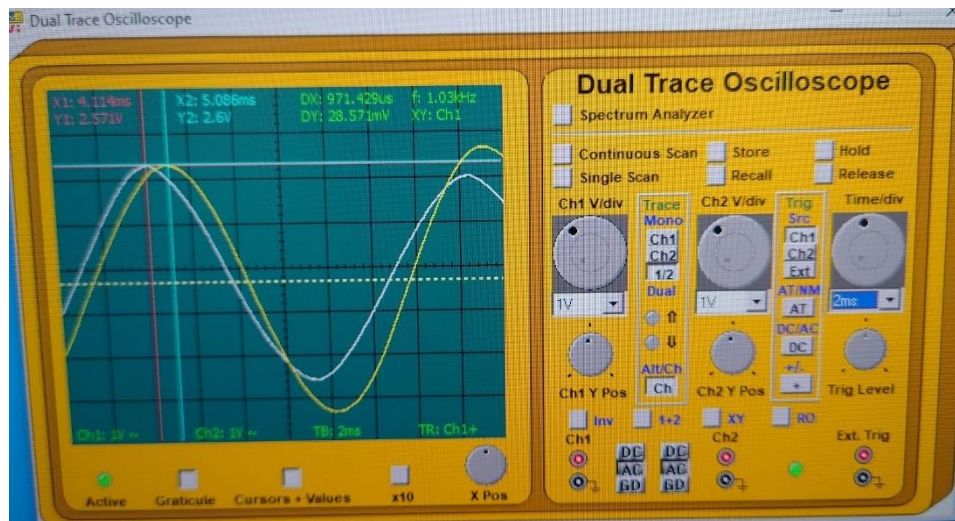


Figure 10: Lab1, No Capacitor

with 10 μ F P.F. Correction capacitor in circuit. Very small Lag.

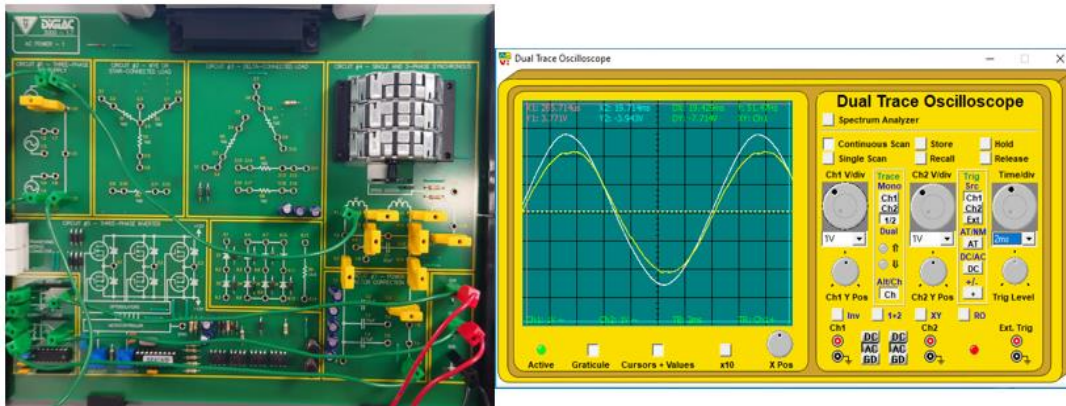


Figure 11:Lab1, 10 μ F Capacitor

With 20 μ F P.F. Correction capacitor in circuit. Current Leading.

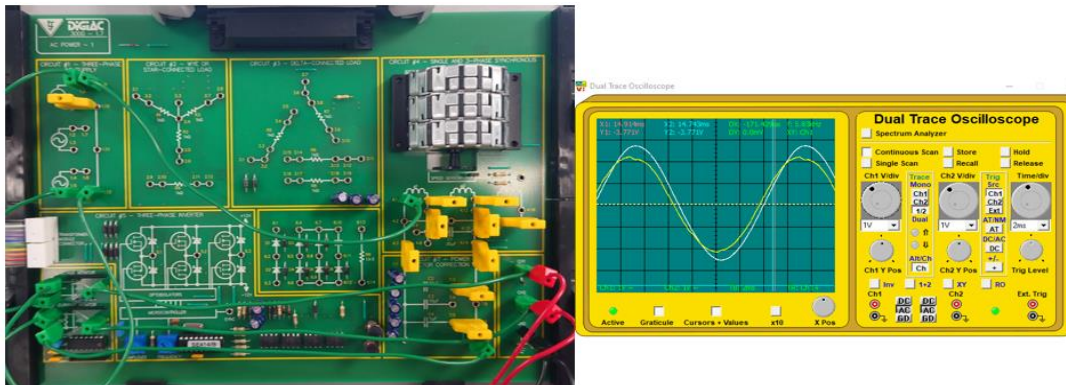


Figure 12:Lab1, 20 μ F Capacitor

With 15 μ F P.F. Correction capacitor in circuit. Current Leading.

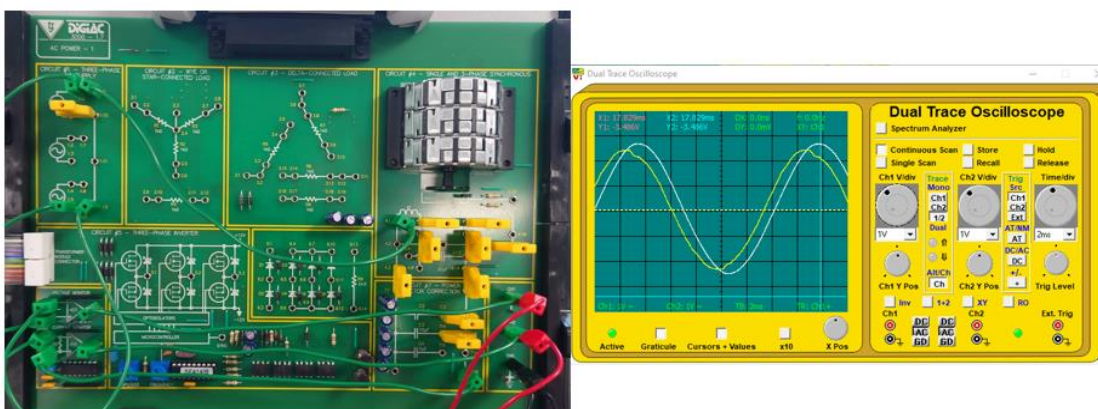


Figure 13:Lab1, 15 μ F Capacitor

Analysing the results, the amount the current leads or lags the voltage (phase angle) can be varied simply by introducing a PFC capacitor. The results also show a drop in current draw when the phase angle is at a minimum.

Any of the shunt capacitor setups was an improvement in phase angle and power factor compared to having no power factor correction. However, from the results the best capacitor used was when C2 (10 μ F) was in circuit or when the phase angle and current are both at a minimum. The power factor can be calculated using the formula: Power factor= Cos(ϕ)

The power factor with no correction capacitor in circuit is:

$$\text{Cos}(\phi) = \text{Cos}(30.64) = 0.86$$

This is a very bad power factor; a good power factor is typically considered to be within 0.95 and 1/unity which is the ideal.

The new power factor with C2 10 in circuit is:

$$\text{Cos}(\phi) = \text{Cos}(1.534) = 0.9996$$

This is a very good power factor. If this was outside of the 0.95 and 1 range, then it may have been worth trying a different value capacitor. Capacitor come in standard sizes or values. However, with the rising cost of energy it may now be cost effective to make an equivalent circuit if a standard capacitor isn't available. This shows a big improvement in the power factor of the circuit with C2 introduced.

The supply voltage measured with C2 in circuit was 25.23v p-p

The power supplied can be calculated as follows:

$$\text{VICos}(\phi) = (25.23 * 0.707) * 502.8 \times 10^{-3} * \cos 30.64 = 7.717\text{W}$$

With the power factor correction capacitor, the power supplied is:

$$\text{VICos}(\phi) = (23.1 * 0.707) * 445.8 \times 10^{-3} * \cos 1.53 = 7.28\text{W}$$

As expected, this shows a noticeable difference (decrease) in power consumption after the power factor was improved using a power factor correction capacitor.

As discussed in section 1.1. this provides several benefits such as reducing the strain on the grid and reduced energy costs.

3. Lab 2: Fault finding on power correction circuit

Following the instructions and wiring diagram provided, the equipment was set up as per below image.

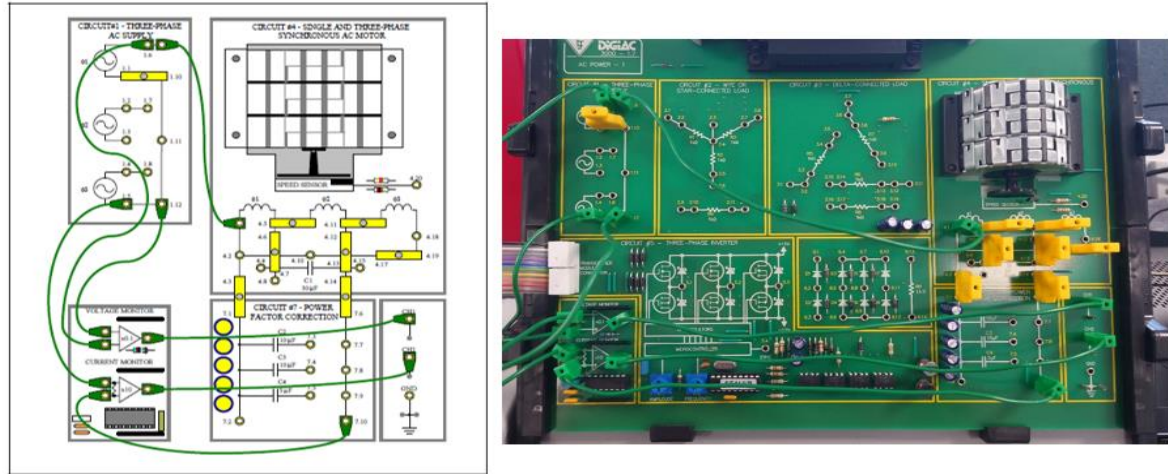


Figure 14: Lab 2, Fault finding PFC

A fault was added to the current setup by the management computer. The same readings were taken again.

3.1. Lab 2 results

The results are as follows:

Current of the circuit is shown on channel 2 (Yellow) Lagging the voltage on channel 1 (White)

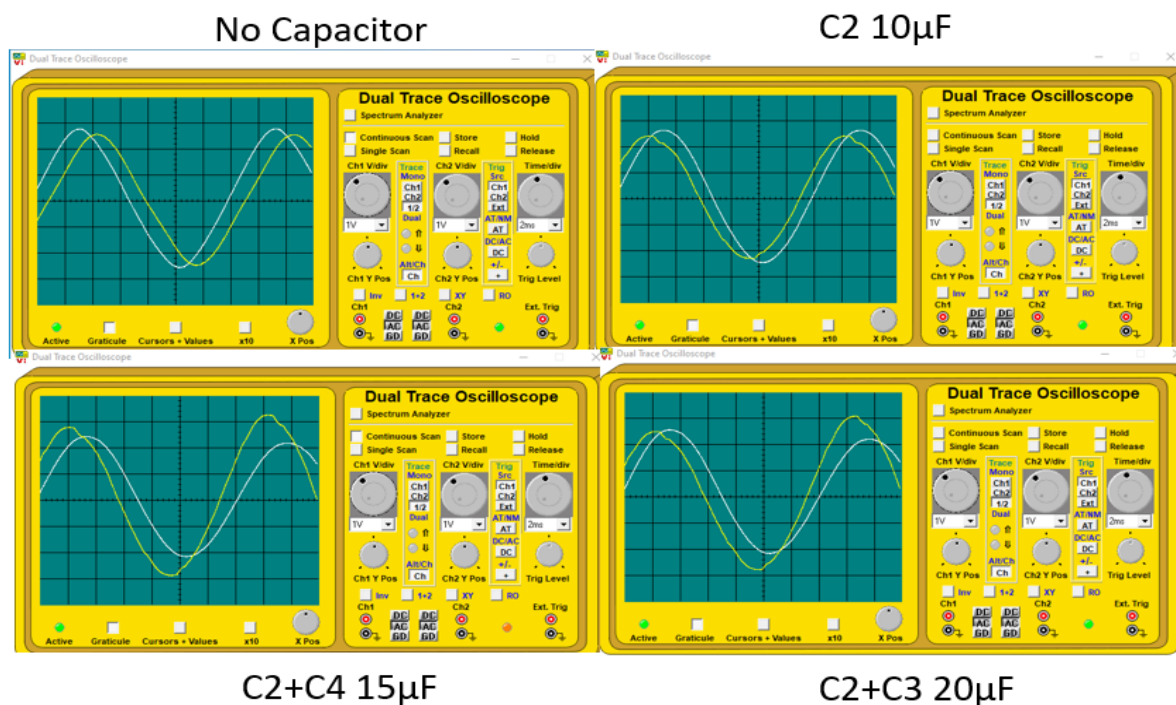


Figure 15: Lab 2, Results various capacitors

Correction Capacitor	None	C2 -10 μ F	C2 + C3 -20 μ F	C2 + C4 -15 μ F	C3-10 μ F
Phase angle	15° Lag	7.67° Lead	15° Lead	15.34° Lead	16° Lag
Current Amplitude	497.2mA p-p	457.2mA p-p	640mA p-p	480mA p-p	496 mA p-p

Table 2: Lab 2 Results

The results differ compared to Table 1 the current is now leading the voltage whenever a capacitor is introduced. If the current leads the voltage with a large phase angle this is just as bad as having a poor power factor with the phase angle lagging.

C2(10 μ F) still had the lowest current Amplitude and smallest phase angle and therefore the best Power factor.

The power supplied and power factor can be calculated as follows:

With no PFC:

$$\cos(\phi) = \cos(15) = 0.966$$

$$VI\cos(\phi) = (27.14 * 0.707) * 497.2 \times 10^{-3} * \cos 15 = 9.215W$$

With C2(10 μ F):

$$\cos(\phi) = \cos(7.67) = 0.991$$

$$VI\cos(\phi) = (25.7 * 0.707) * 457.2 \times 10^{-3} * \cos 7.67 = 8.23W$$

Using C2 was still an improvement to the power factor over no PFC capacitor even with the fault inserted but uses more power than Lab1 in both cases.

C3 was added into the circuit during fault finding, C2 and C3 should have shown the same result as they are the same capacitance, however the reading isn't the same. This highlights a potential fault in the circuit or component.

The fault present is a change in capacitance/too much capacitance, the current is now leading the voltage the load has become Capacitive rather than inductive which is just as bad. The fault also had the knock-on effect of increasing the power usage and therefore decreasing the power factor.

4. Lab 3: Three Phase inverter

4.1. Method

The purpose of the Lab is to investigate how variable frequency drives work and how they use Pulse width modulation (PWM) to effectively control a motor.

4.2. Three Phase Inverter Circuit Setup

Following the instructions and wiring diagram provided, the equipment was set up as per below image.

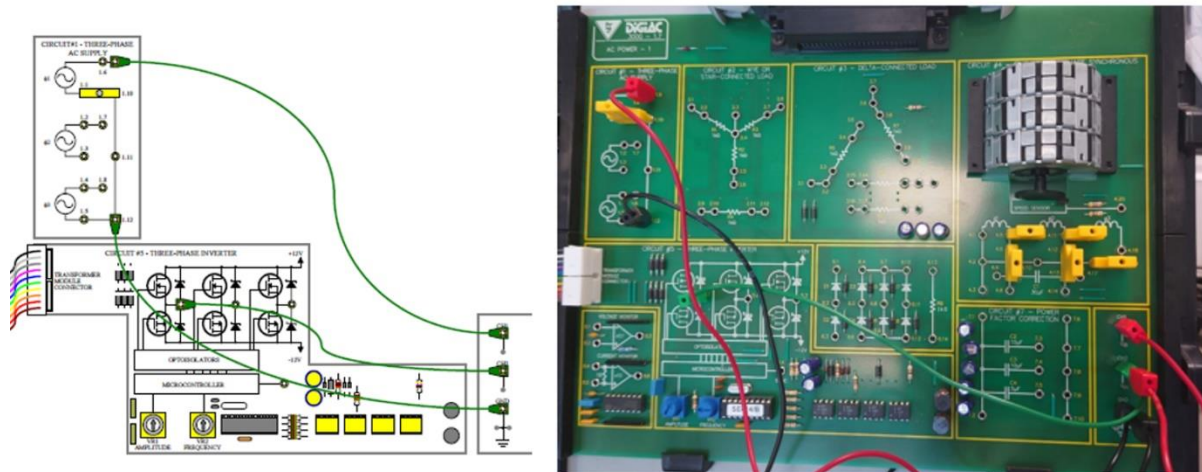


Figure 16: Lab3, 3 Phase Circuit & Diagram

The method used by the microcontroller to generate three-phase sine wave supplies is based on PWM (Pulse width modulation)

At the positive peak of the sine wave, the microcontroller pulses become broader. The number of microcontroller positive pulses in one half-cycle is approximately 60.

The frequency of the supplies produced by the three-phase generator can be varied by changing the width of the microcontroller pulse.

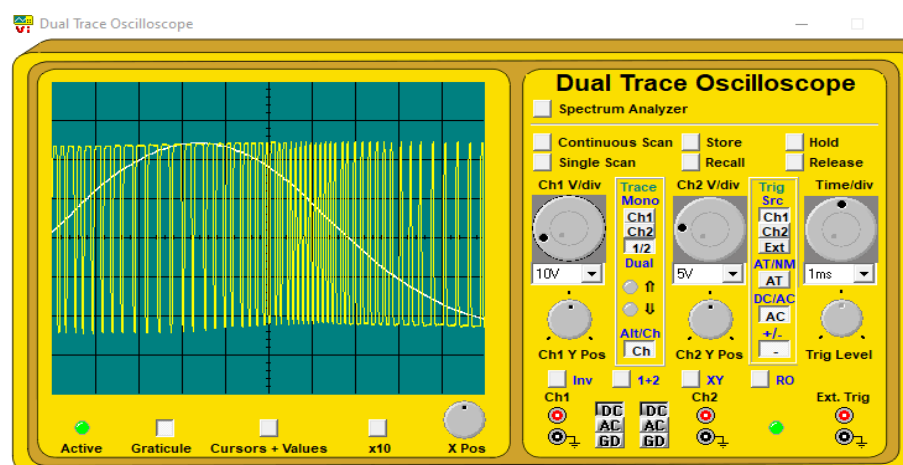


Figure 17: Lab3, PWM1

By Varying the frequency(VR2) there was a notable difference in the PWM waveform. In the generation system of the three-phase supplies, a broader pulse from the microcontroller will give a lower frequency of output

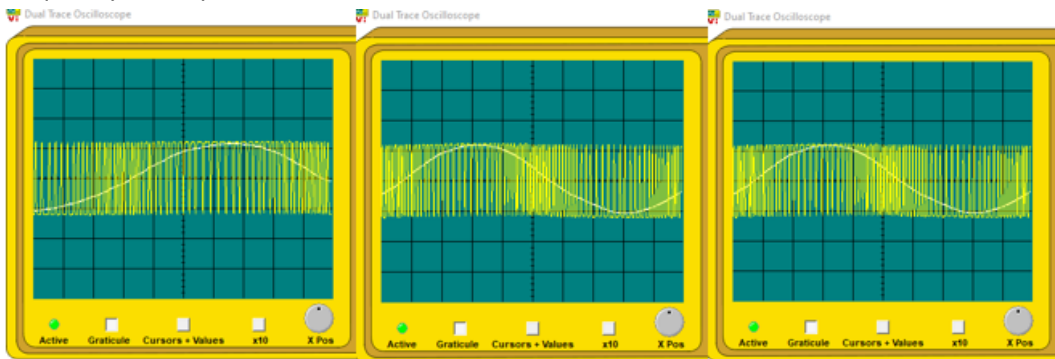


Figure 18:Lab3, PWM VARIOUS FREQ.

Looking at the waveform using the oscilloscope there is some noise or ripple visible.

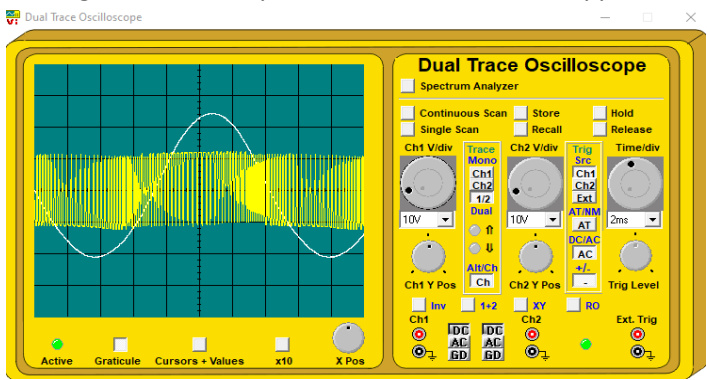
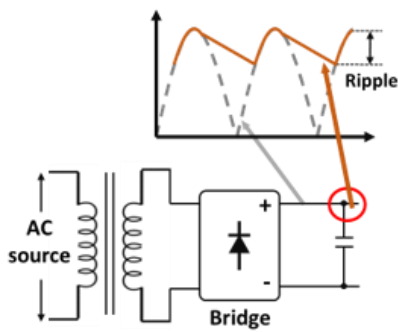


Figure 19:Lab3, PWM RIPPLE

4.3. What is Ripple?

Ripple is typical when converting AC to DC. the waveform AC waveform can still be seen as it hasn't been totally eliminated or smoothed in the rectification circuit. It can also be commonly referred to as noise as its unwanted and not useful.



	C	LC filter	CMC filter	C multiplier
Part count	1	2	3	3
Layout space	1	2	3	3
Ripple & Noise suppression	2	1	1	1
Output current	1	1	1	3

Figure 1 Full Bridge Rectifier Circuit

1→Good, 2→Middle, 3→Poor

Figure 20:PWM Ripple 2 Table 3:Ripple Filters

The simplest way to reduce ripple is to use a smoothing capacitor, however there may still be some ripple present. There are also some other ways to reduce ripple such as using a low pass filter, Common Mode Choke Filter, or a Capacitance Multiplier.

The best solution to remove ripple will depend on the circuit in question, as they have different complexity and current output. [14]

5. Lab 4: Over-Current Protection

5.1. Method

The purpose of this Lab is to replicate a short circuit and record what happens to the motor, current and voltage when an over current protection circuit is used.

Following the instructions and wiring diagram provided, the equipment was set up as per below image.

5.2. Over-current Protection Lab 4

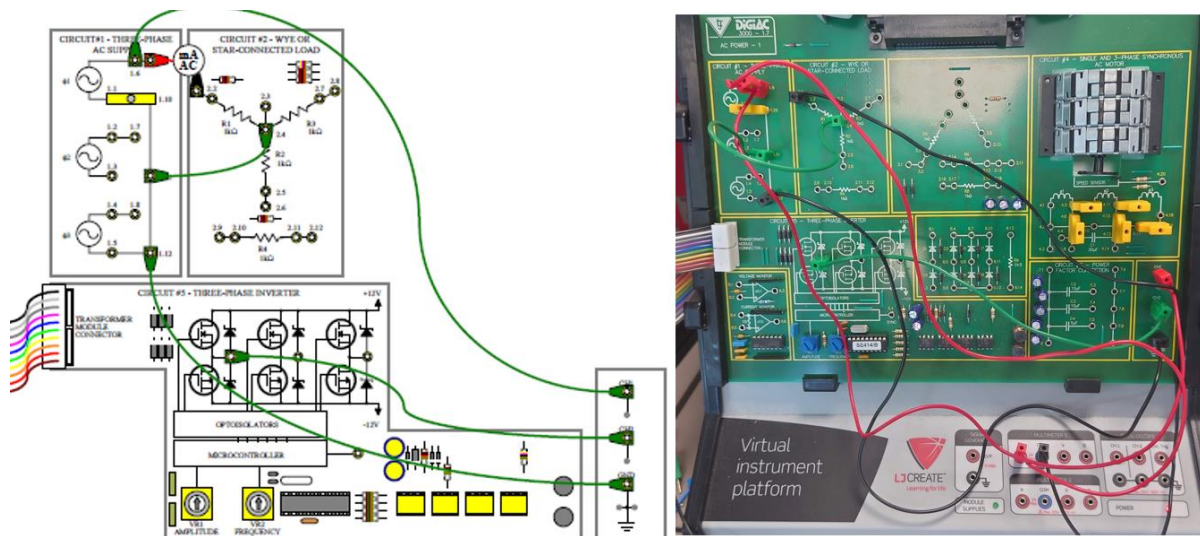


Figure 21: Lab4, Circuit and Diagram

Using the multi-meter to measure current in series, The load current measured = 26.3 Ma AC

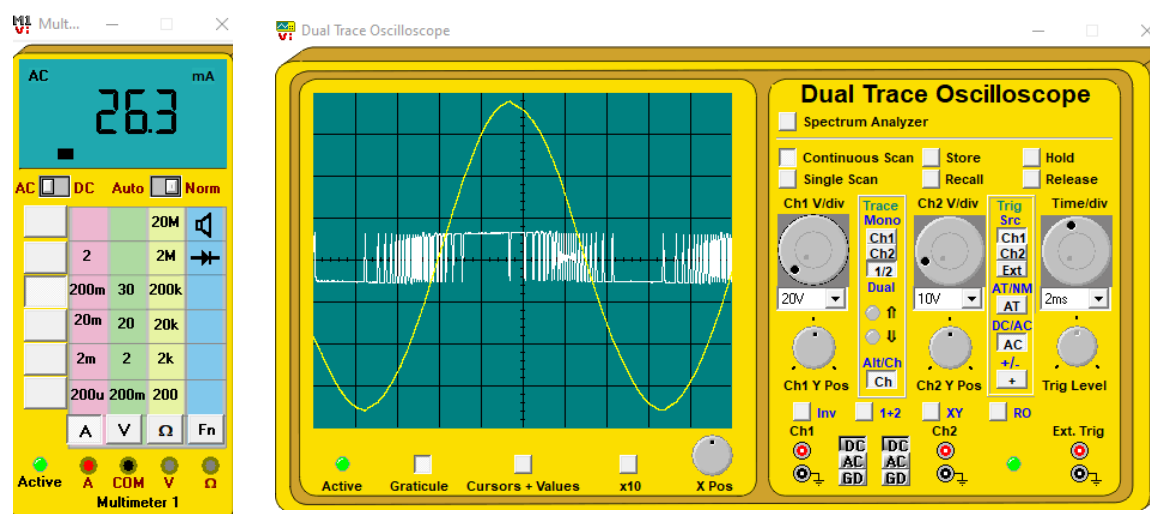


Figure 22: Lab4, Load current

A short circuit was introduced between 2.2 and 2.3. When this occurred, the voltage immediately reduced to zero and the current increased to a maximum but as the short circuit was left for a period of time (approx. 2 minute) the load current then reduced to zero.

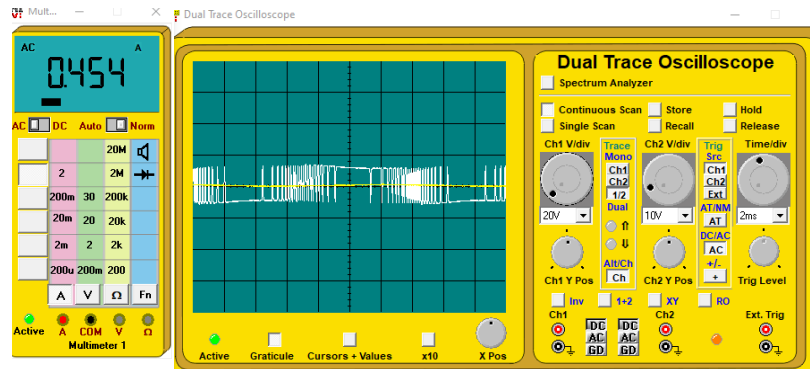


Figure 23: Lab4, Short Circuit 1

After approx. 2 minutes:

The short circuit was then removed from the circuit (between 2.2. and 2.3.) but the power supply doesn't return to normal conditions.

The power supply is then cycled off and on immediately, but the power supply still doesn't return to normal operating state.

Switching off the power supply again but this time leaving it for five minutes before switching it back on, this time the power supply reset and returns to normal. This reset the Over-Current Protection within the power supply circuit.

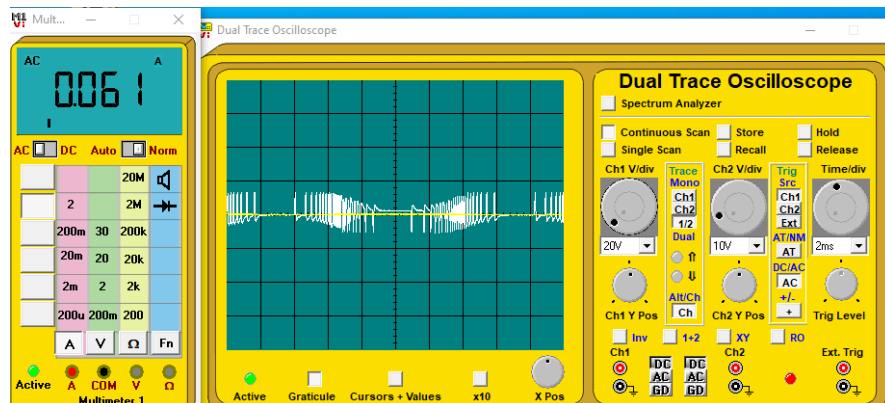


Figure 24: Lab4, Short Circuit 2

The purpose of the over-current protection circuit in a power supply is to prevent damage to the power supply itself. [15]

6. Lab 5: Fault finding on Over-Current Protection - Fault 2

Following the instructions and wiring diagram provided, the equipment was set up as per below image.

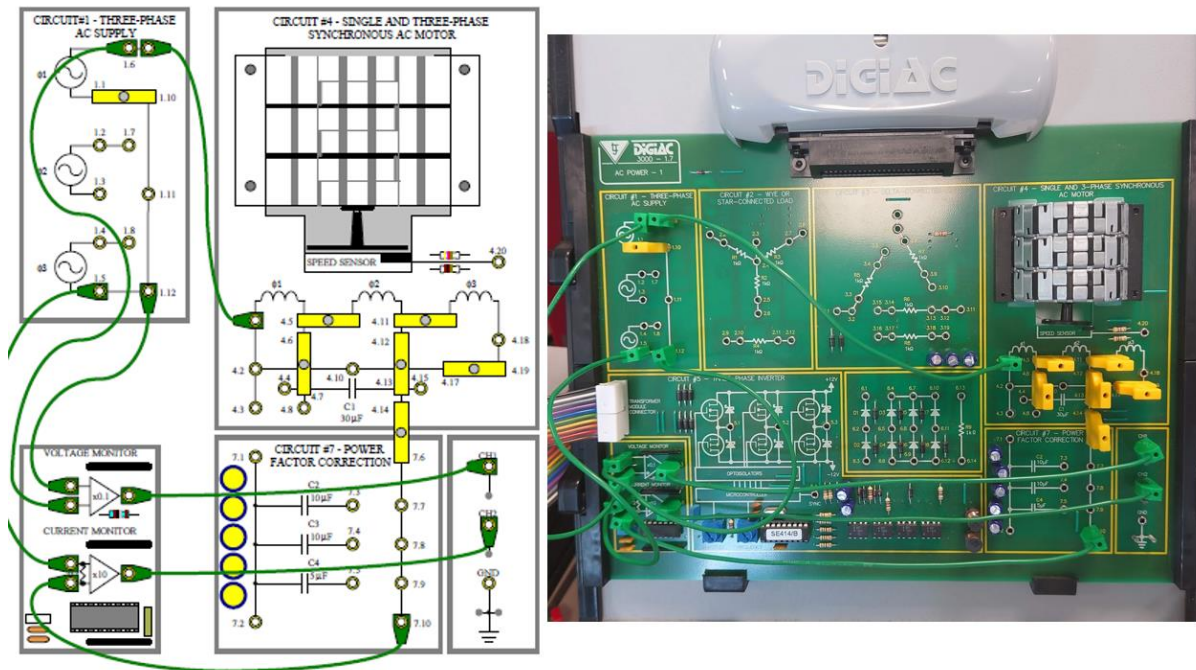


Figure 25: Lab5, Fault finding OC protection

The power supply was turned on, the resulting waveform was shown on the oscilloscope:

Current lagging voltage, with no power correction introduced.

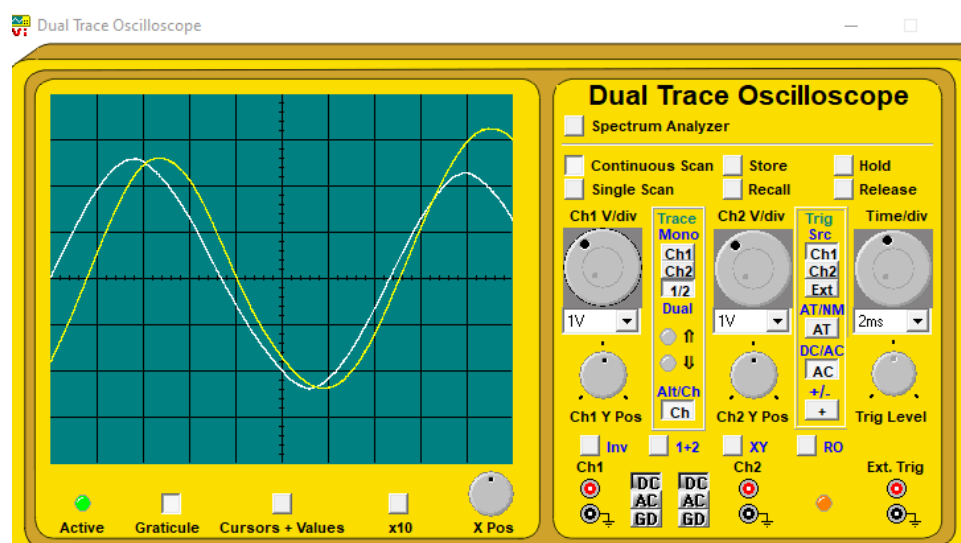


Figure 26: Lab5, Fault finding OC protection 2

The shorting link between 4.3 and 7.1 was then introduced to connect the power factor correction circuit.

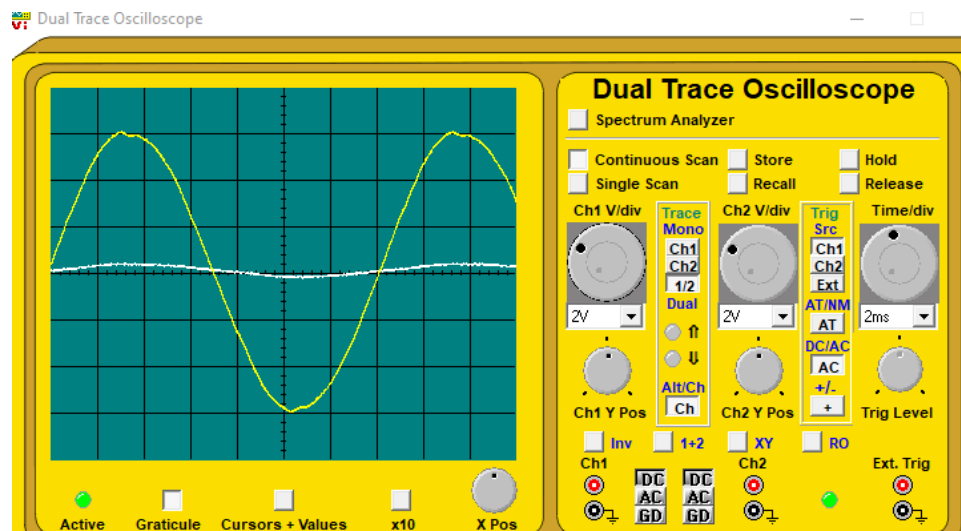


Figure 27 Lab5, Fault finding OC protection 3

The voltage drops to a minimum and the motor stops.

The fault only occurred when introducing the power factor correction circuit. Therefore, it's likely within that circuit so this should be the area of focus for fault finding.

Using a half-split method and measuring the resistance across the capacitors with a multi-meter it was reading zero. This would suggest a short circuit is present.

The fault is a short circuit between 7.2 and the 7.6- 7.10 rail.



Figure 28: Lab5, Fault finding OC protection 4

7. Conclusion

In this investigation, it can be seen that:

- Power factor Correction (PFC) is important to get right, not only to save lots of money due to potential fines and paying for more energy than required but also to reduce strain on the national grid and reduce our impact on the environment. A good solution to this may be investing in an active power factor correction system for large applications as it would be beneficial in terms of cost providing a ROI (Return on investment) and also removing a lot of manual workload of checking the power factor of a given circuit.
- Over current protection is useful to protect the hardware in case of a short circuit and if there is a component failure within the system. This circuit will prevent further damage and potentially a risk of fire.
- Pulse width modulation (PWM) Is a very effective and flexible way of controlling a device such as a three-phase motor. It also has high efficiency and low power consumption. As discussed in section 1.10 using a VFD with a communication protocol like EtherCat means you can easily change speed/frequency for specific moves if the application was complex. [16]
- A synchronous motor is ideal for high accuracy applications but also for gaining a good power factor. However, can be difficult to start, as noticed in Lab 1 where the Frequency had to be increased slowly to start the motor.
- To reduce downtime of a machine in the potential case of a short circuit, it may be worth investing in a power supply with over current protection and a LED indicator or a circuit breaker with an indicator to inform the engineer that the power supply or Circuit breaker has gone into over current protection mode. This will reduce the need and time spent checking the circuit with an oscilloscope and multi-meter.

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