



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Power Electronics & Drives

ACDA6004

By Matthew Taylor

TABLE OF CONTENTS

Abstract	3
Introduction.....	3
Method	6
Power Factor Correction and Fault Finding.....	6
Part One	6
Part Two.....	8
Three-Phase Inverter and Over-Current Protection	9
Results.....	11
Power Facor Correction and Fault Finding.....	11
Part One	11
Part Two.....	13
Three-Phase Inverter and Over-Current Protection	14
Discussion	15
Power Factor Correction and Fault Finding.....	15
Part One	15
Part Two.....	15
Three-Phase Inverter and Over-Current Protection	16
Conclusion	16
References.....	18

ABSTRACT

I completed a number of experiments on the LJ Create Visual Instrument Platform fitted with the AC motor PCB. My aim was to investigate:

- Power factor correction using capacitors on an inductive load,
- Variable frequency drives and controlling them with a PWM signal,
- Over-current protection,
- fault finding.

I used an oscilloscope to measure the phase difference between the voltage and current and used that to find the most suitable capacitor. I probed parts of the VFD to observe its operation, and I intentionally caused a short circuit, to observe how the system reacted.

INTRODUCTION

Pulse width modulation (PWM) is a square wave that can be used to create an analogue voltage between 0V and the maximum amplitude of the square wave. This is done by changing the duty cycle of the wave. The duty cycle is a ratio of the time that the square wave is at the peak compared to 0V and corresponds to the average power of the wave. For example, a square wave with a duty cycle of 50% will be at the peak voltage for half of the period of the wave and at 0V for the other half of the time period. [1]

When using PWM, a frequency will be chosen that's suitable for the application and the frequency will remain consistent even as the duty cycle changes. The simplest use for PWM is to reduce the average voltage across a device like a DC motor or an LED, which will reduce the speed of the motor or the apparent brightness of the LED.

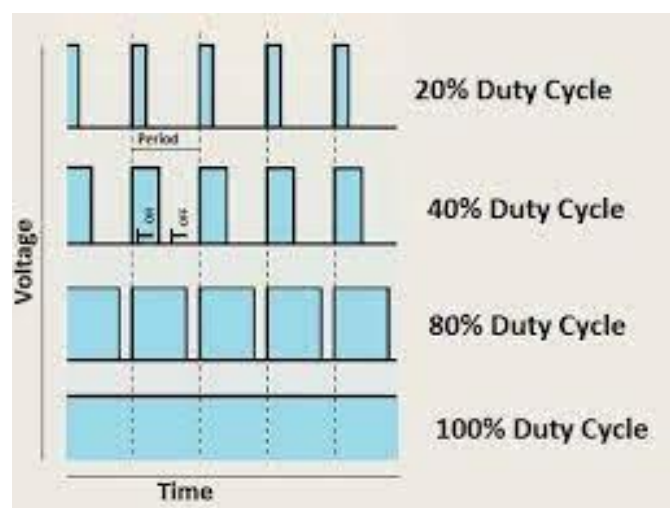


Figure 1 - PWM Duty Cycle [2]

A PWM signal is also used in Variable frequency drives (VFD). A VFD is used to control AC motors by varying the frequency of the AC supplied to the motor. Induction and synchronous motors speeds are set by the frequency of the VFD output.

A VFD is made up of several stages, the first stage is the rectifier. The rectifier takes the 3 phase mains supply and rectifies it to a DC voltage, this can be done with six diodes, but Thyristors or IGBTs can also be used for additional functionality. There may be a high pass filter made with inductor chokes and a low pass filter made with capacitors to limit fluctuations and smooth the incoming mains. The DC then is passed through smoothing and filtering to remove the ripple from the AC source. The smoothed DC is then passed into the inverter. The inverter generates AC from DC, using six transistors. Different types of transistors can be used each with their advantages and disadvantages, the options include BJTs, Mosfets, Thyristors, or IGBTs. A controller can be used to control the transistors with a PWM signal which dictates the frequency and amplitude of the VFD output. [3]

Additional functions can be built into a VFD, including Flux Vector Control, which controls the slip and torque of an inductor motor and torque of a synchronous motor, by controlling the magnetic flux in the stator. VFDs can also control: the resistance in inductor motor rotor coils, deceleration, reversing, breaking, and include motor protection.

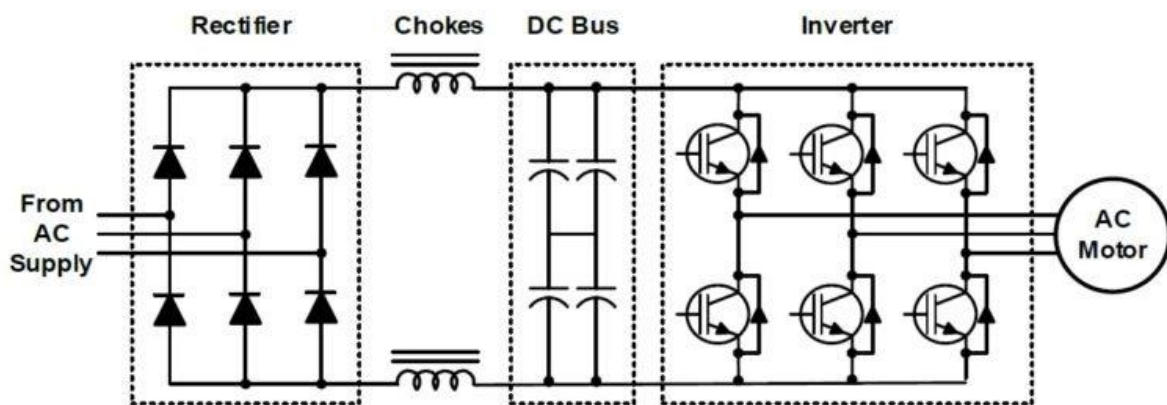


Figure 2 - VFD Block Diagram [4]

synchronous motors spin at a very precise speed, that can be calculated with the equation (1), and have a consistent speed and torque irrespective of load, as long as it's within the rated specification. The rotor of a synchronous motor is made up of coils connected to a DC source through slip rings creating a permanent magnet, and if the synchronous motor is self-starting then there will also be a squirrel cage. The stator is made up of coils that are excited by the 3 phase supply.

Induction motors aren't as accurate as synchronous motors as their speed is affected by slip. Their stator is of a similar construction to synchronous motor but their rotor is only made up of a squirrel cage. The rotor can include a coil, and when the resistance of the coil changes the speed of the motor is affected. Slip is represented as a percentage of the synchronous speed and can be calculated with equation (2).

$$N_s = \frac{120f}{P} \quad (1)$$

Where:

N_s = Synchronous speed

F = Supplied frequency

P = Number of poles in the rotor

$$Slip = \frac{(N_s - N_a)}{N_s} * 100\% \quad (2)$$

Where:

N_s = Synchronous speed

N_a = Actual speed

The concept of slip is that an induction motor can never quite reach the synchronous speed. This is due to the forces generated by the squirrel cage cutting through the magnetic lines of the rotating magnetic field will reduce as the motor approaches the synchronous speed and causing the torque to reduce. The speed will drop until there is enough torque being generated by the rotor again. [5]

Many devices connected to a mains supply will not be purely resistive and will have an overall inductive or capacitive reactance. Transformers and motors are common loads that are inductive. Industry is usually responsible for their own power factor correction, which can be done by using capacitors for an inductive load, and inductors for a capacitive load. As inductive loads are most common many large outfits will have a bank of capacitors that can be added to the circuit.

METHOD

POWER FACTOR CORRECTION AND FAULT FINDING

Part One

The synchronous motor was connected to the AC power supply following the wiring diagram in figure (3). The motor was configured as a capacitor run motor using a single AC phase to power it. Channel one (ch1) of the oscilloscope was measuring the voltage of the power supply. Channel two (ch2) measured the current of the circuit by measuring the voltage drop across a 1 ohm resistor in series with the circuit.

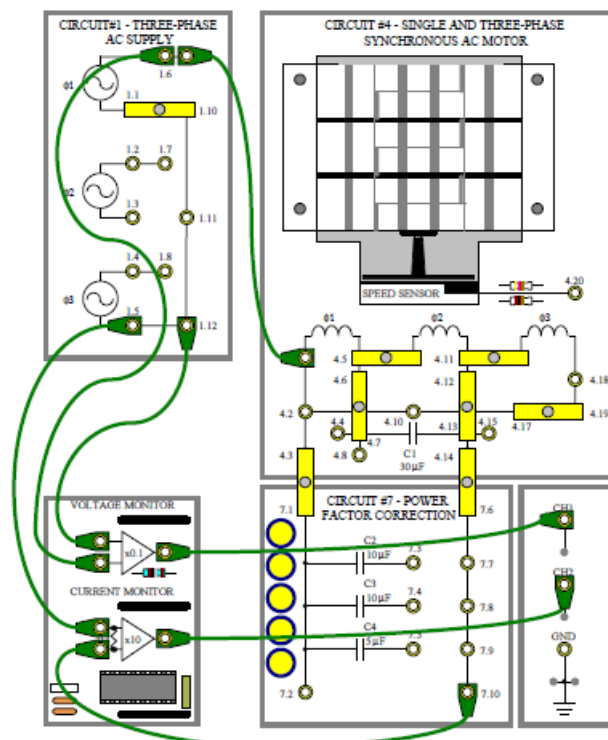


Figure 3 – Wiring Diagram

I set the oscilloscope's trigger, scan, and time base so that one period of the waveforms were being displayed. The cursor tool of the oscilloscope reads the voltage where the cursor is placed and the time difference between the two cursors, I used this tool to take the measurements.

I recorded the time difference between the peaks of the two waves and the peak voltage of ch2. The time difference can be used to calculate the phase angle with a formula and the peak voltage of ch2 can be converted into the current for the circuit.

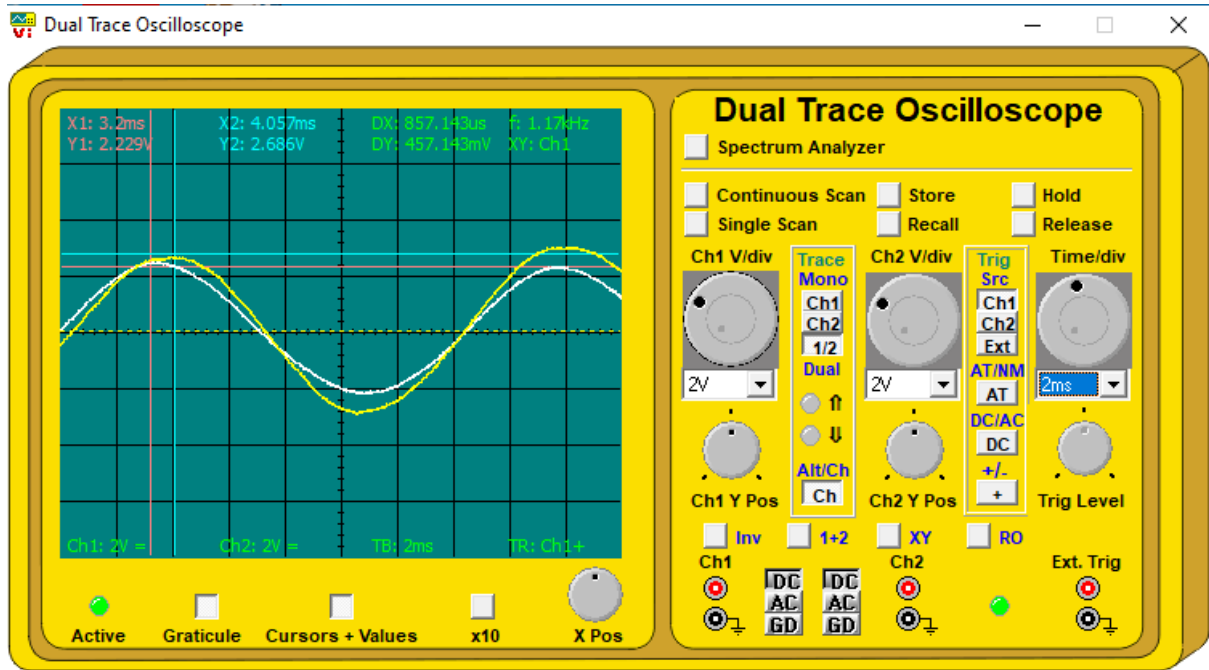


Figure 4 – Oscilloscope display with no PF capacitor

I added a range of capacitor values in parallel to the motor and took the same measurements for each configuration, recording them in excel.

I reset the circuit, following the wiring diagram, and a fault was added to the circuit. The motor continued to rotate so I continued to add the power factor correction capacitors and take the same measurements as before. I hope to be able to deduce the error by looking at the measurements from the two different runs.

Part Two

I reset the circuit following the circuit diagram below then A different fault was added to the circuit. The motor continued to rotate so I continued to add the power factor correction circuitry which caused the motor to stop spinning. With the fault found I took some measurements with the oscilloscope and discussed the fault in a later section.

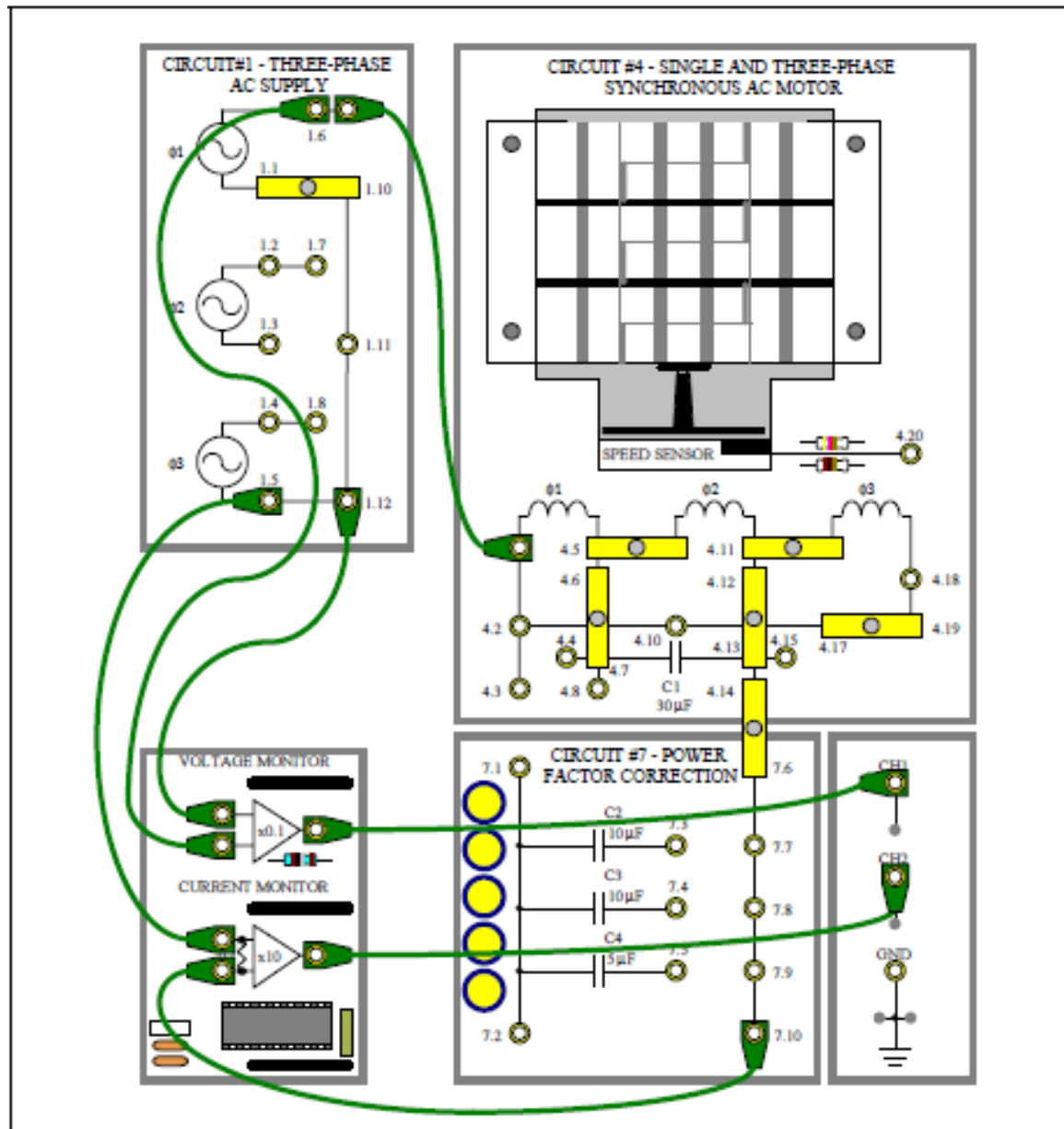


Figure 5 - Wiring Diagram

THREE-PHASE INVERTER AND OVER-CURRENT PROTECTION

I connected the AC supply and the PWM signal from the variable frequency drive (VFD) to the two channels of the oscilloscope following the wiring diagram in figure (6). With this setup I was able to see the output of the AC supply and the VFD on the oscilloscope. I discuss the results later.

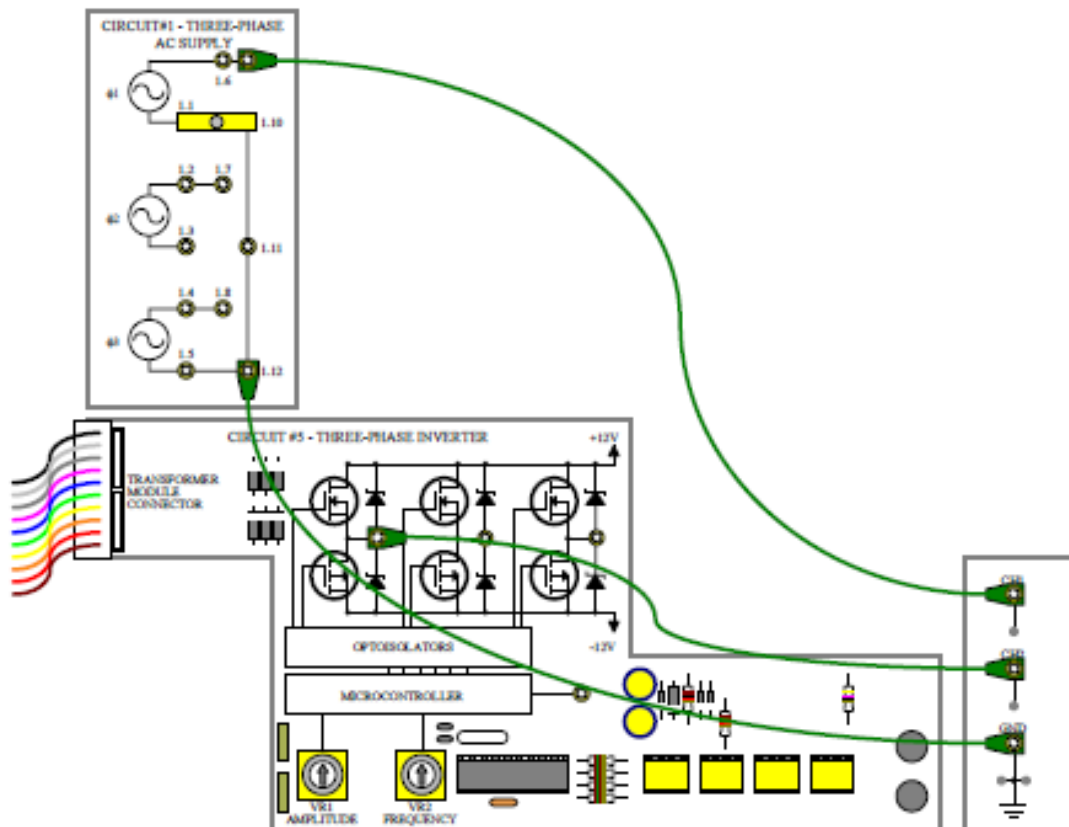


Figure 6 – wiring diagram

I took the open circuit from the previous experiment, and I connected the live side the AC supply via a multimeter to a 1K resistor, and connected the other side of the resistor to the neutral side of the AC supply like shown in the wiring diagram in figure (7). I discuss the results later.

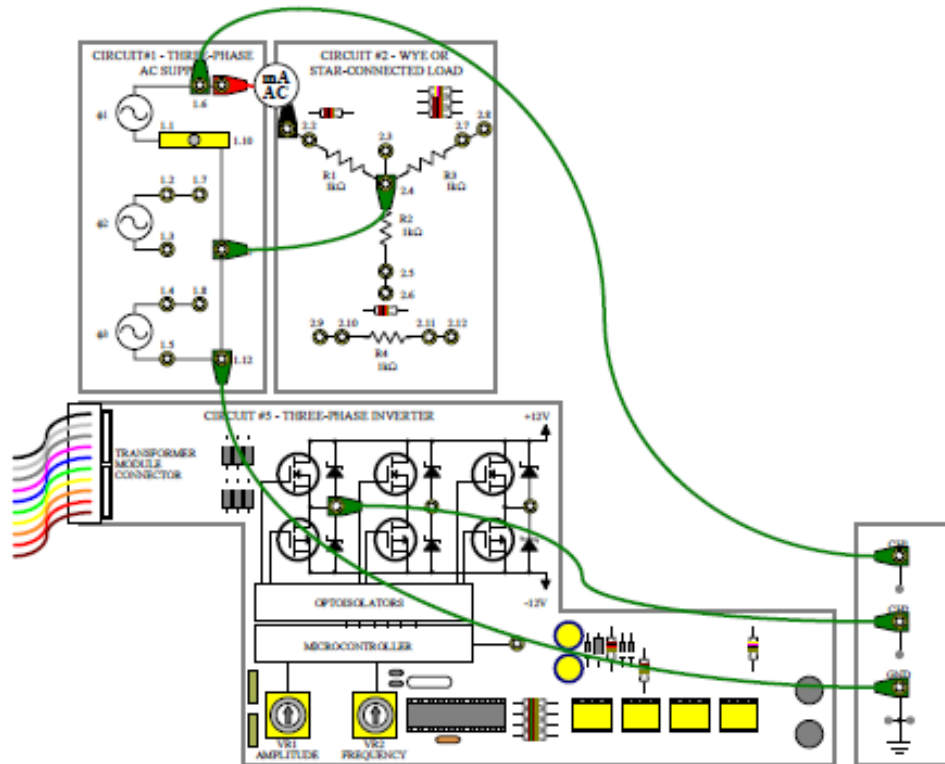


Figure 7 – wiring diagram

RESULTS

POWER FACTOR CORRECTION AND FAULT FINDING

Part One

After running the circuit in each configuration and recording the measurements, I compiled a table, using excel to calculate the remaining data. I used equation (3) to calculate phase angle and I used equation (4) to convert the peak voltage on ch2 to peak current.

$$\text{Phase Angle} = \frac{\Delta t}{T} * 360 \quad (3)$$

Where:

Δt = Time difference between peaks in seconds
 T = Time period

$$\text{Current} = \frac{2 * \text{peak voltage} * 1000}{10} \quad (4)$$

correction capacitor	none	C2 (10uF)	C2+C3 (20uF)	C2+C4 (15uF)
delta t (between peaks)	0.001429	0.000571429	-0.001029	0.000228571
phase angle	36.0108	14.4000108	-25.9308	-5.7599892
Peak (V)	2.914	2.343	2.629	2.457
current amplitude peak - peak (mA)	582.8	468.6	525.8	491.4

Figure 8 – excel table

The power factor can be calculated with equation (5) using the phase angle. Calculating the power factor for the circuit with no power correction capacitor results in a power factor of 0.809. The phase angle closest to 0° will be the circuit with the best power factor correction. The circuit with the 15uF of capacitance in parallel with the motor had a phase angle closest to 0° with a power factor of 0.995.

$$PF = \cos \phi \quad (5)$$

$$\begin{aligned} PF &= \cos 36.0108 \\ PF &= 0.809 \text{ (current lagging)} \end{aligned} \quad (6)$$

$$\begin{aligned} PF &= \cos -5.76 \\ PF &= 0.995 \text{ (current leading)} \end{aligned}$$

(7)

I can calculate the voltage of the power supply by taking the peak voltage from the oscilloscope and this reading can be converted into RMS with equation (8). I also converted the current to RMS using the equation (9). With the voltage of the supply calculated and using the recorded current from the table, I was able to calculate the real power of the motor using equation (11). I also calculated the real power of the circuit with the power factor correction capacitor with equation (12).

Peak - Peak to RMS:

$$V_{RMS} = V_{peak\ to\ peak} * \frac{1}{2\sqrt{2}} = V_{peak\ to\ peak} * 0.35355 \quad (8)$$

Peak to RMS:

$$C_{RMS} = C_{peak} * \frac{1}{\sqrt{2}} = C_{peak} * 0.7071 \quad (9)$$

Supply voltage (under load):

$$\begin{aligned} 2.286V * 10 &= 22.86V\ Peak \\ 45.72V\ (peak - peak) &= 16.164V\ (RMS) \end{aligned} \quad (10)$$

With no capacitor:

$$\begin{aligned} 0.5828\ A\ (peak) &= 0.412\ A\ (RMS) \\ \\ Real\ Power &= VI \cos \phi \\ 16.164 * 0.412 \cos 36.011^\circ & \\ &= 5.388W \end{aligned} \quad (11)$$

With the 15uF capacitor:

$$\begin{aligned} 0.4914\ A\ (peak) &= 0.347\ A\ (RMS) \\ \\ 16.2633 * 0.347 \cos -5.76 & \\ &= 5.588W \end{aligned} \quad (12)$$

Table of results from testing capacitors while a fault was present.

correction capacitor	none	C2	C2+C3	C2+C4	C3+C4	c3
delta t (between peaks)	0.0013	-0.0007	-0.0017	-0.0012	-0.0002	0.0004
phase angle	33.1128	-18.72	-43.1928	-30.24	-5.76	10.08
Peak (V)	2.857	2.629	3.257	2.914	2.343	2.39
current amplitude peak - peak (mA)	571.4	525.8	651.4	582.8	468.6	478

Figure 9 - table of results after error

Part Two

When the short circuit was in the system, the oscilloscope displayed the waveform in figure (10). The volts/division for the AC supply is set to 1V/div and the peak of ch1 is about 2/10ths of a division so the peak voltage is about 2V. When I found the short circuit and removed it from the system, the oscilloscope displayed a raise in voltage on ch1 to about 2.3 divisions, which is equal to 23V peak as shown in figure (11).

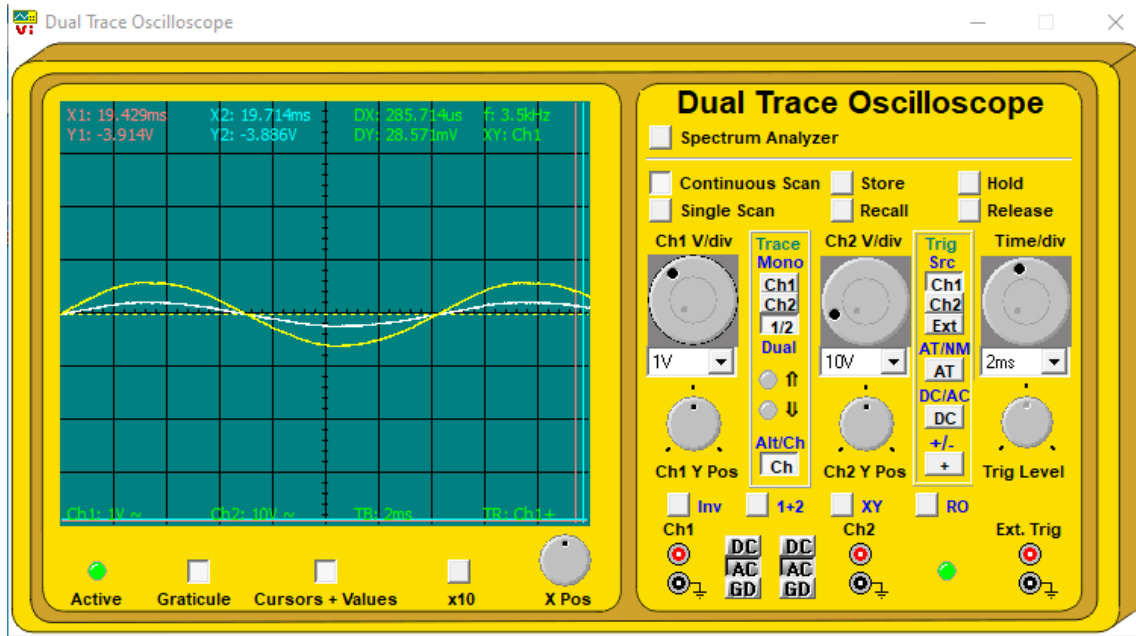


Figure 10 – When short is present

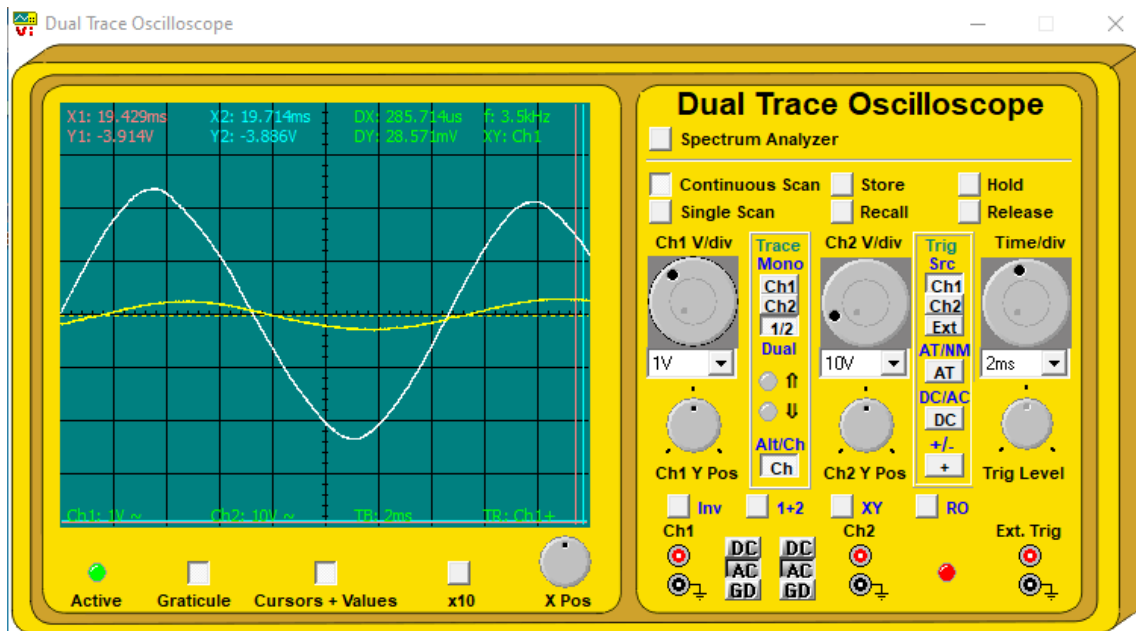


Figure 11 - when short has been removed

THREE-PHASE INVERTER AND OVER-CURRENT PROTECTION

Figure (12) shows the PWM signal of the VFD in yellow, and the AC supply in white.

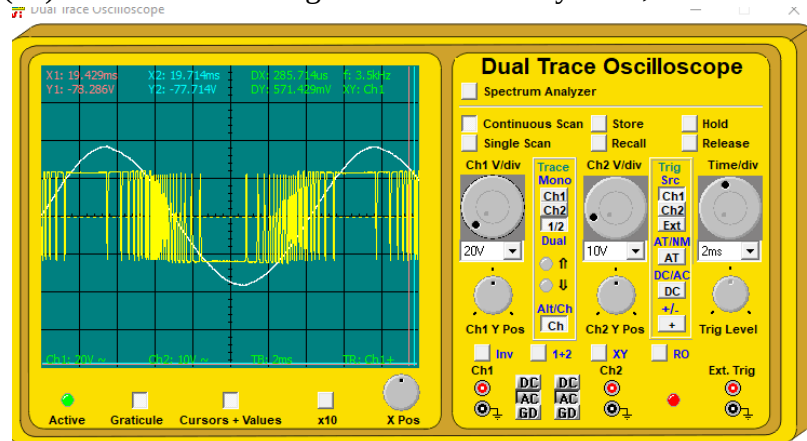


Figure 12 - Oscilloscope display of PWM

The multimeter measured a current of 0.443A (13) when I shorted the AC supply. After about 10 minutes the current dropped to 71.5 mA and remained the for the duration of the short.

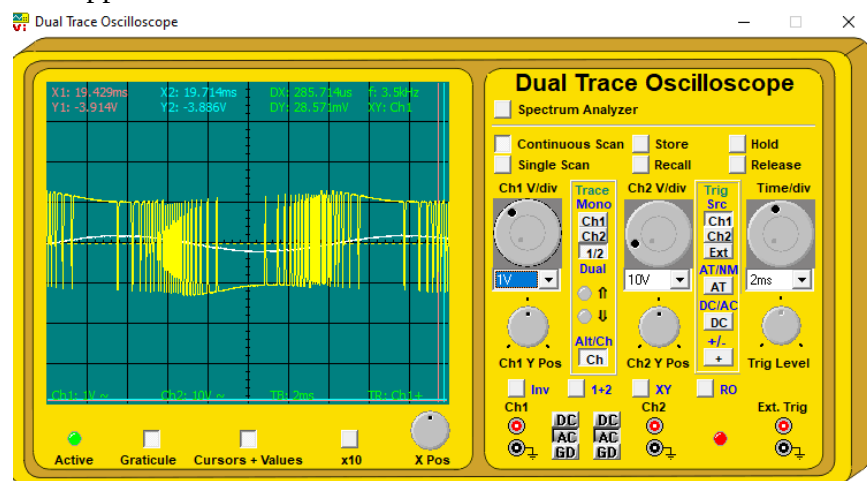
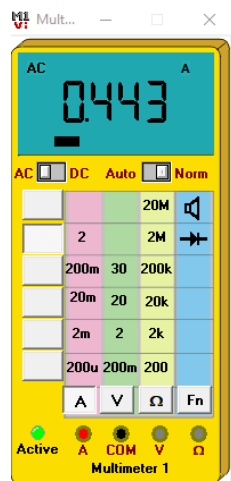


Figure 13 – Multimeter reading for the first 10 minutes

Figure 14 - Oscilloscope during the first 10 minutes

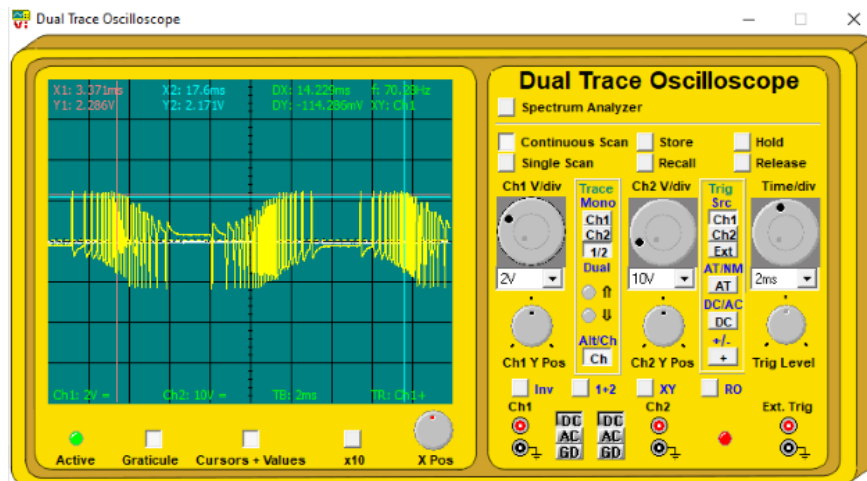
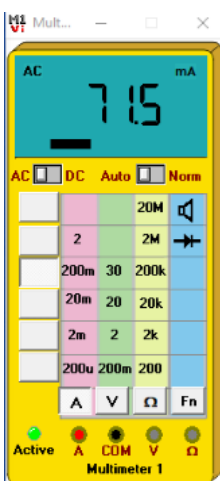


Figure 15 - Multimeter reading after 10 minutes

Figure 16 - oscilloscope after 10 minutes

DISCUSSION

POWER FACTOR CORRECTION AND FAULT FINDING

Part One

I was able to calculate the power factor of the circuit with each of the capacitor values, using phase angle. A power factor of one, has a phase angle of 0° , so the capacitor most suitable for the correction the power factor of this circuit is the 15uF capacitor, with a power factor of 0.995.

After I had taken all my measurements A fault was added to the circuit. The fault wasn't immediately apparent so took the same measurements with the various capacitors and recorded my results. My first reading with no capacitor was similar to my reading with no fault. My next three readings, all of which included capacitor C2, were very different from the run with no error. The phase angle for these readings were indicating that the load was much more capacitive than on the no fault measurements.

As I was compiling my results, I could see that the measurements including C2 were different from my previous tests, so I ran two additional tests, I tested C3 on it's own as it is 10uF, the same value as C2 and my results for C3 were similar to C2 before the fault occurred. The second test I ran was C3 and C4 in parallel as that is equal to 15uF, which is also a value I tested before the fault occurred and the result from that one was similar to the pre-fault test. This confirms that C2 is faulty and has a higher capacity than stated.

When I calculated the real power of the motor with and without the 15uF power factor correction capacitor I expected the same wattage as power factor correction doesn't affect the real power. I found my results to be within 3.5% of each other, so the difference is likely due to the tolerance in readings and rounding errors.

Part Two

Once I had built the circuit, a fault was added to the circuit, but the motor kept rotating. I next went to add power factor correction, which I started by adding the link from the motors input to the bank of capacitors (4.3-7.1). When I added this link the motor stopped rotating, revealing that there is an issue in the circuit.

I measured the voltage of the of the AC supply with the oscilloscope and the peak was approximately 2V compared the expected peak voltage of 23V. When the voltage of the supply drops, it is normally the over-current protection engaging, which reduced the output voltage to limit the current. I removed the link I just added to the circuit and the motor started rotating again. With no other components of the power factor correction circuitry connected when the fault occurs, I would deduce the short is between the power rails of this section of the circuitry.

THREE-PHASE INVERTER AND OVER-CURRENT PROTECTION

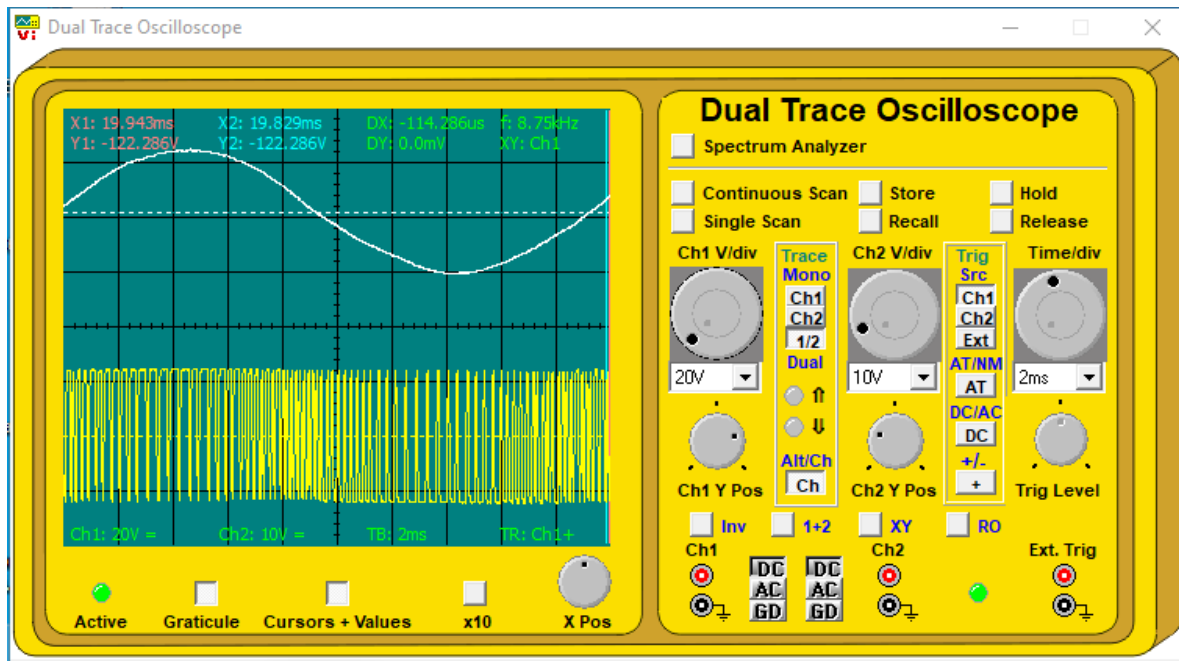


Figure 17 – PWM signal next to AC supply

I first tested the over-current protection by shorting the AC supply with a 1K resistor but the current was 26mA and not considered over current. So I tried shorting the power supply without a resistor and after turning on the module power supply, the voltage of the AC supply being generated by the VFD was a fraction of the voltage compared to when the AC supply was open circuit and the multimeter measured the current of the circuit as 0.433 amps. With ch2 of the oscilloscope connected to the PWM signal of the VFD, I could see that the PWM signal changed when the short circuit was introduced, as the duty cycle increased the voltage of the wave sloped towards 0V.

after the 10 minute mark when the current dropped further, the PWM signal sloped even more steeply towards 0V. High currents will result in additional thermal losses, and as I was operating the transformer outside of its specified range, the thermal cooling was likely not sufficient and a thermostat was triggered which further limited the current to 71.5mA. To confirm this, I left the unit off to cool down, for several minutes before trying again and the AC supply and PWM were back to their original performance.

CONCLUSION

During the process of researching the topics for this report I have learned in detail about Power factor correction, synchronous motors, Pulse Width Modulation, Variable Frequency Drives, and Over-Current Protection.

When I was testing for the best capacitor for power factor correction of the motor, I tried calculating it by trying to calculate the reactive power. My final value was 152mF which is a long way of from 15uF which had a power factor of 0.995.

$$\begin{aligned}
S &= IV \\
&= 0.412 * 16.164 \\
&= 6.659 \text{ VA}
\end{aligned}
\tag{13}$$

$$\begin{aligned}
Q &= S * \sin\theta \\
&= 6.659 * 0.412 \\
&= 3.915 \text{ VAR}
\end{aligned}
\tag{14}$$

$$\begin{aligned}
X_c &= \frac{Q}{V^2} \\
&= \frac{3.915}{16.164^2} \\
&= 0.0149 \Omega
\end{aligned}
\tag{15}$$

$$\begin{aligned}
X_c &= \frac{1}{2\pi fC} \\
C &= \frac{1}{2\pi fX_c} \\
C &= \frac{1}{2\pi * 70 * 0.0149} \\
C &= 0.1526 \text{ F}
\end{aligned}
\tag{16}$$

REFERENCES

- [1] A. Raj, “what-is-pwm-pulse-width-modulation,” 2018. [Online]. Available: <https://circuitdigest.com/tutorial/what-is-pwm-pulse-width-modulation>. [Accessed 8 4 2022].
- [2] m. aqib, “Arduino PWM Tutorial,” 2018. [Online]. Available: <https://create.arduino.cc/projecthub/muhammad-aqib/arduino-pwm-tutorial-ae9d71>. [Accessed 8 4 2022].
- [3] C. Hartman, “What is a Variable Frequency Drive?,” 2020. [Online]. Available: <https://vfds.com/blog/what-is-a-vfd>. [Accessed 8 4 2022].
- [4] ee.co.za, “Variable-frequency-drive-main-circuit-diagram,” [Online]. Available: <https://www.ee.co.za/wp-content/uploads/2019/11/Fig-2-Variable-frequency-drive-main-circuit-diagram-e1573116506850-768x332.jpg>. [Accessed 8 4 2022].
- [5] Engineering ToolBox, “Electrical Induction Motors - Slip,” 2004. [Online]. Available: https://www.engineeringtoolbox.com/electrical-motor-slip-d_652.html. [Accessed 8 4 2022].