



POWER FACTOR & INVERTER DRIVES

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Abstract

For this assignment which is an in-depth look at power factor and motor drive applications and the correlation between the two, a technical brief is to be issued upon which will guide and direct the user in the process and methods to obtain the results in which the document desires.

Poor power factor can have a detrimental effect on industrial electrical systems, with additional power consumptions of equipment, additional current being drawing and varying voltage regulation, in the coming experiments this will be shown and proven.

Introduction

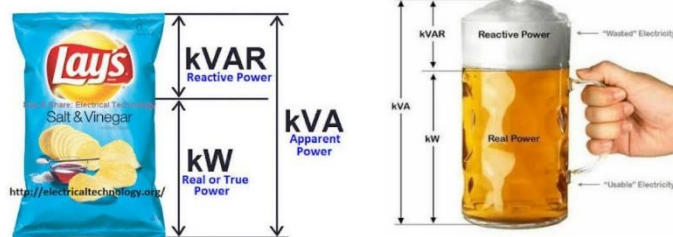
Within this document it includes the set out prerequisite requirements detailed in the assignment brief, the concise over view is detailing in inverters and power factor and the interactive relationship between the two elements.

What is power factor?..... Power factor is an expression of energy efficiency, normally portrayed as a percentage, lower the percentage the less efficient the power usage.

$$\text{Power Factor} = \frac{\text{True Power (kW)}}{\text{Apparent Power (kVA)}}$$

One of the simplest ways in which to describe the above equation in the form of a relationship is the "Beer Analogy", the beer = True Power (KW) does the useful work & the Foam = Reactive Power (KVA) this is the useless stuff but there will always be Reactive power the aim is to reduce the reactive power as small as possible.

power factor Explanation



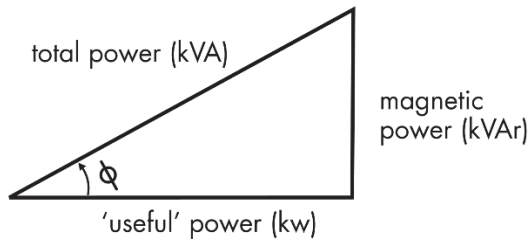
(Fig, 01)

The whole beer glass as a whole = Apparent Power (KVA) / (kW+KVA)

$$\text{Power Factor} = \frac{\text{How Much Beer (kW)}}{\text{Per Glass We Buy (kVA)}}$$

So ultimately is about value for money in how much of the good stuff we are buying, from our service providers.

This can also be expressed in a power triangle format as the below shows;



(Fig, 02)

Trigonometry Formula

- True Power (KW) = Reactive Power (KVA) x $\cos \Theta$
- Reactive Power (KVAr) = Apparent Power (KVA) x $\sin \Theta$
- Apparent Power (KVA) = $\sqrt{\text{True Power (KW)}^2 + \text{Reactive Power (KVAr)}^2}$
- Power Factor = $\cos \Theta = \frac{\text{True Power (KW)}}{\text{Apparent Power (KVA)}}$

Power factor can result in additional charges from your utility supplier, additional loads put on to facility cables/transformers causing unnecessary wear and tear on plant assets.

To correct any poor power factor this is normally done by adding capacitor banks to the electrical distribution system (normally at building incoming supply) the capacitors compensate for the reactive power demand of the inductive load and reduce the burden on the supply.

So why improve power factor?.....there are many benefits listed below which ultimately lead to a financial saving;

- Reduction in electricity bills
- Free up additional KVA capacity from the existing supply
- Reduction of voltage drop in long cable runs
- Extend equipment life, reduce electrical burden on equipment
- Reduction in I²R losses in transformers and distribution equipment

Three phase inverters

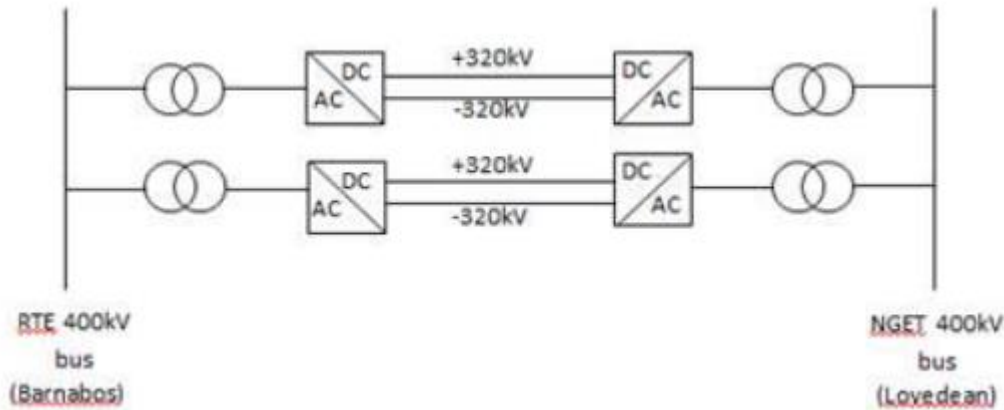
Within power electronics we can first define our 3 phase inverters into 3 distinct groups which are as follows;

1. Square Wave Inverter
2. Sine Wave Inverter
3. Modified Sine Wave Inverter

Within most if not all power applications in the UK, the utilisation of AC Sine wave voltages is wide spread, but for applications such as storage of energy AC cannot be stored this must be stored in a DC voltage, the power can be then stored in batteries and capacitors. The voltage is converted from AC to DC and then when load is required converted again from DC to AC the inverter is the units in which does the converting is called the "inverter".

A good example of a large industrial set up for this would be the UK Channel connection to France (IFA), (200MW HVDC Cross-Channel) this utilises the core principles of transformers in using solid state semiconductor thyristors.

The main benefit apart from the enabling of shearing power consumptions to the continent, is that each grid France and UK can emitting a lot of the nuisances with trying to maintain voltage/frequency levels to suit each other, in this scenario each station at the French side and the British side can control the AC output from the DC input via the thyristor inverters so that they match the local grid conditions.



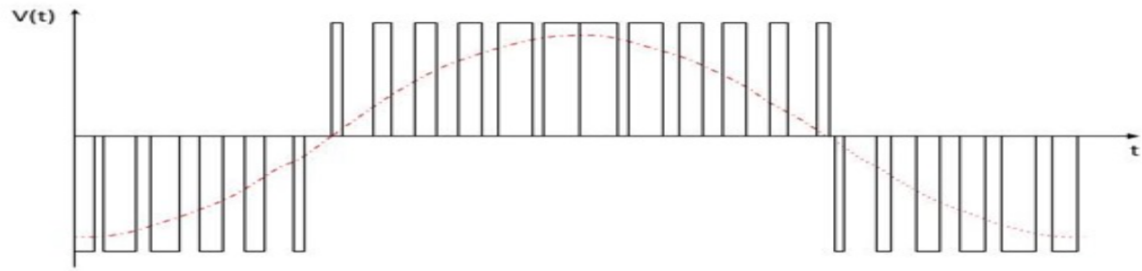
(Fig, 03)

As of 2005 imports of electricity from France have historically accounted for about 5% of electricity available in the UK. Imports through the interconnector have generally been around the highest possible level, given the capacity of the link. In 2006, 97.5% of the energy transfers have been made from France to UK, supplying the equivalent of 3 million English homes. The link availability is around 98%, which is among the best rates in the world. The continued size and duration of this flow is open to some doubt, given the growth in demand in continental Europe for clean electricity, and increasing electricity demand within France. [1] Wikipedia.org

Next, we will look at how inverters achieve this changing of voltage from DC/AC & AC/DC.....

Throughout global industry it is not general regard that inverter feed induction motor set up is the bestselling industrial drive system.

The method in which we change or modulate the voltages is a method referenced as PWM (pulse width modulation) the utility supply 3phase 400v is rectified by the diode bridge , and the resulting DC voltage is then smoothed via the DC link capacitor and the DC current smoothed via a conductor in the DC circuit, the now smoothed DC (pulse) is chopped up in the inverter stage so that it represents AC sine wave (mimics at best). So it should be clear that the secondary output of an inverter say supplying an induction motor is not a pure sine wave, it's a series of DC pulses. See (Figure-01) be for clarification.



Pulse Width Modulation - the width of pulses is varied to simulate a sine wave

Figure 04 (<https://myelectrical.com/notes/entryid/250/how-d-c-to-a-c-inverters-work>)

What are the draw backs if any ???..... as we know the huge benefits to the utilisation of inverters, there needs to be considerations taken at the design stage when introducing the technology onto a system, one such item is harmonics.

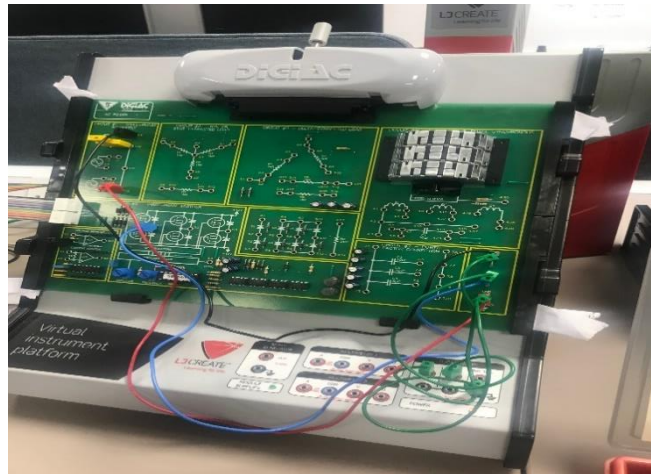
Harmonic disturbances in the building's distribution network 400V AC 3 Phase, is normally caused by the input rectifier on a A.C. drive. Now the reason for choosing to single out harmonics within systems which use inverters is becoming a more and more common issue, is you think in a factory

the number of items such as motors controlled via VSD drives, computer systems, UPS systems, electronic LED lighting, an industry rule of thumb is that if the total rectifier loads as mentioned above comprise of more than 20% of its total current capacity then a harmonic control plan should be implemented.

Method

Within the class room experiments testing rigs (Digiac) seen below in (Figure-02) were issued for live practical applications to be carried out of the effects of drive loads with the introduction of capacitor banks.

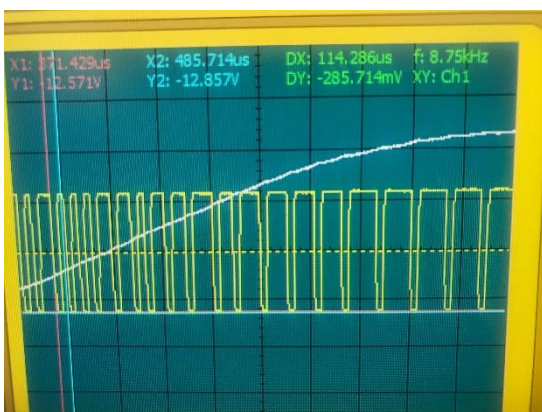
(Figure-05)



For the experiment circuit board, wiring diagrams were issued for the connection sequences to be obtained, from this the instruction manual detailed the scenario's in which each configuration was to be conducted and the results recorded and monitored.

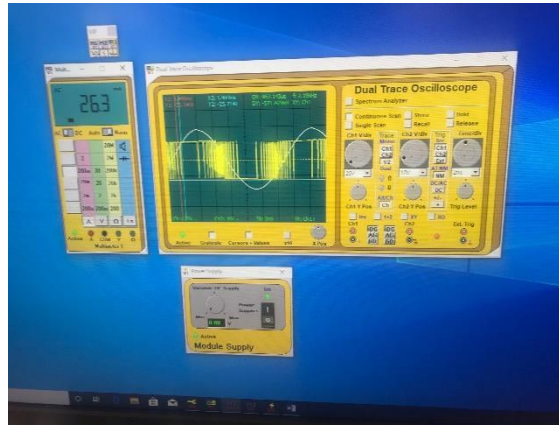
The results and monitoring of the rig were done via a computer based Dual trace oscilloscopes via the LG create software, sample screen shots from the experiment can be seen below in (Figures-03,04,05).

Figure 1(Figure-06)



(Figure-07)





(Figure-08)

Practical Experiment Results

Below is shown the results required during the practical element of the assignment;

Task 1 (Exercise 1)

Correction Capacitor	None	C2 – 10 μ F	C2 + C3 - 20 μ F	C2 + C4 - 15 μ F
Phase Angle (Lead/Lag)	$t = 1.314$ $T = 14.17$ $\frac{1.314}{14.17} \times 360$ $= 33.38^\circ$	$t = 171.42\mu s$ $T = 13.94$ $\frac{171.42\mu s}{13.94} \times 360$ $= 4.42^\circ$	$t = 800\mu s$ $T = 13.94$ $\frac{800\mu s}{13.94} \times 360$ $= 20.65^\circ$	$t = 400\mu s$ $T = 14.11\text{ms}$ $\frac{400\mu s}{14.11} \times 360$ $= 10.20^\circ$
Current Amplitude	$\frac{2 \times 2.6v \times 1000}{10}$ $= 520\text{mA}$	$\frac{2 \times 2.2v \times 1000}{10}$ $= 440\text{mA}$	$\frac{2 \times 2.4v \times 1000}{10}$ $= 480\text{mA}$	$\frac{2 \times 2.35v \times 1000}{10}$ $= 470\text{mA}$

1B = C2 @ 10 μ F, is the shunt capacitance which gives the nearest to complete correction of the phase angle.

1C = with the best value of power factor correction capacitor in circuit, the Answer is B (Phase angle and current are both a minimum)

1D = Power Factor calculated with no correction capacitor in circuit= $\cos \phi = \cos (33.38) = 0.83\text{pf}$

1E = Power factor calculated with the best power correction capacitor @ 10 μ f, $\cos \phi = \cos (4.42) = 0.99\text{pf}$

Supply Voltage = $5.31 \times 10 = 53.1$ Volts

1 F = $(53.1v \times .520\text{Ma} \times 0.83) \div 8 = 2.86\text{Watts}$

1G = $(53.1v \times .440\text{mA} \times 0.99) \div 8 = 2.89\text{Watts}$

Task 1 –(Exercise 2)

Correction Capacitor	None	C2 – 10μF	C2 + C3 - 20μF	C2 + C4 - 15μF
Phase Angle (Lead/Lag)	$\frac{t = 1.457\text{ms}}{T = 14.286\text{ms}} \times 360$ $\frac{1.457\text{ms}}{14.286\text{ms}} \times 360$ $= 36.71^\circ$	$\frac{t = 857.14\mu\text{s}}{T = 14.286\text{ms}} \times 360$ $\frac{0.857\text{ms}}{14.286\text{ms}} \times 360$ $= 21.59^\circ$	$\frac{t = 1.714\text{ms}}{T = 14\text{ms}} \times 360$ $\frac{1.714\text{ms}}{14\text{ms}} \times 360$ $= 44.07^\circ$	$\frac{t = 1.429\text{ms}}{T = 14.143\text{ms}} \times 360$ $\frac{1.429\text{ms}}{14.143\text{ms}} \times 360$ $= 36.37^\circ$
Current Amplitude	$\frac{2 \times 5.2 \times 1000}{10}$ $= 1040\text{mA}$	$\frac{2 \times 4.714 \times 1000}{10}$ $= 942.8\text{mA}$	$\frac{2 \times 5.914 \times 1000}{10}$ $= 1182.8\text{mA}$	$\frac{2 \times 5.257 \times 1000}{10}$ $= 1051.4\text{mA}$

Above table Leading or Lagging

None = Lag / C2 = Lag / C2+C3 = Lead / C2 + C4 = Lead

Leading or Lagging

None = Lagging

C2 10uf = Leading

C2 + C3 20uf = Leading

C2 + C4 15uf = Leading

Q – Deduce which component is faulty? A = The faulty component is found to be capacitor C2,

Exercise 2 – Three Phase Inverter

1a – At the positive peak of the sine wave, the microcontroller pulses become, Broader.

1b – The number of microcontroller positive pulses in one half-cycle is approximately, 40 positive pulses.

1c – No ripple is visible.

Exercise 2 – Over-Current Protection

2a – Load Current = 26.3Ma ac

2b – The short circuit across the load immediately causes the supply voltage to, reduce voltage to a very low value.

2c – As the short circuit across the load is allowed to remain it causes the load current to, rise to a maximum and then reduce.

2d – when the short circuit is removed the voltage and current, do not return to normal.

2e – the power is immediately allowed to return to normal.

2f – The power supply corrected back to normal at 0.30v

Single Phase Synchronous Motor

During the practical a fault condition was added to the simulator rig, upon testing it was established that the capacitors within the test rig were at fault, causing a short to earth.

Cause for the capacitor failure could be many factors but no limited to the following possible scenarios; (inefficient maintenance leading to catastrophic failure), (over loading/saturation of capacitors), (surges within the electricity network), (catastrophic failure leading to capacitor internal oils to seep onto internal workings and cause a short circuit).

Exercise 2 – Single Phase Synchronous Motor

1 – method used by the microcontroller to generate a 3-phase sine wave is based on PWM.

2 – An Inverter is a device for, converting DC into AC.

3 – Frequency can be varied by changing the, width of the microcontroller pulse.

4 – in the generation system of the supplies produced by the three-phase supplies, a broader pulse from the microcontroller will give, a more positive output voltage.

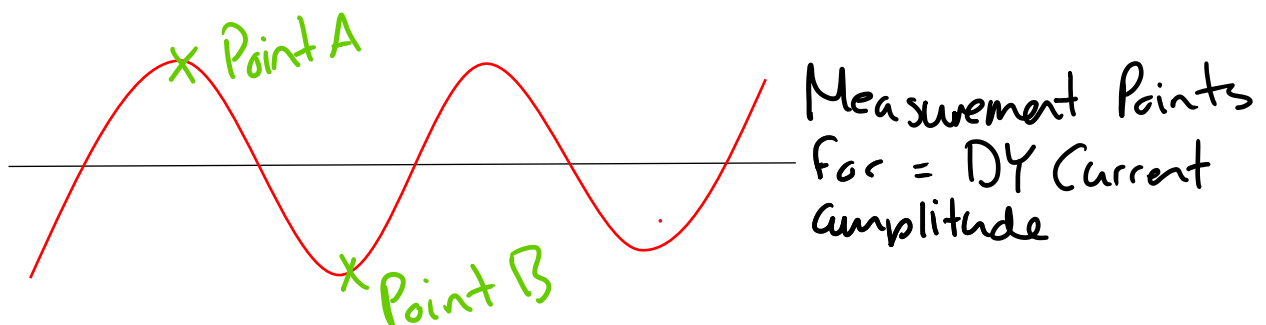
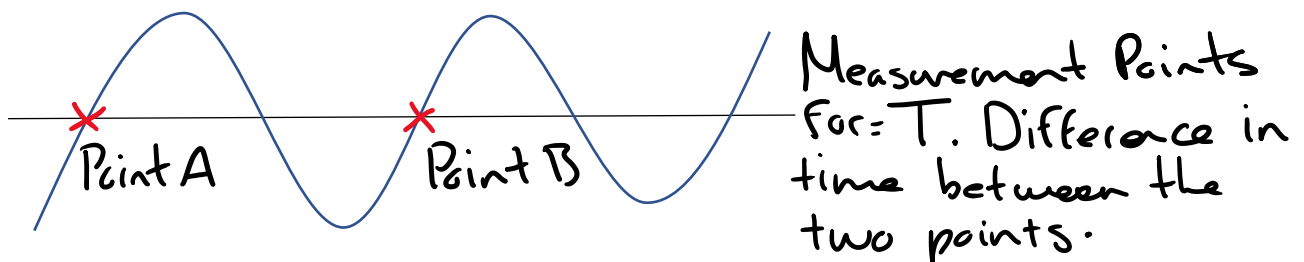
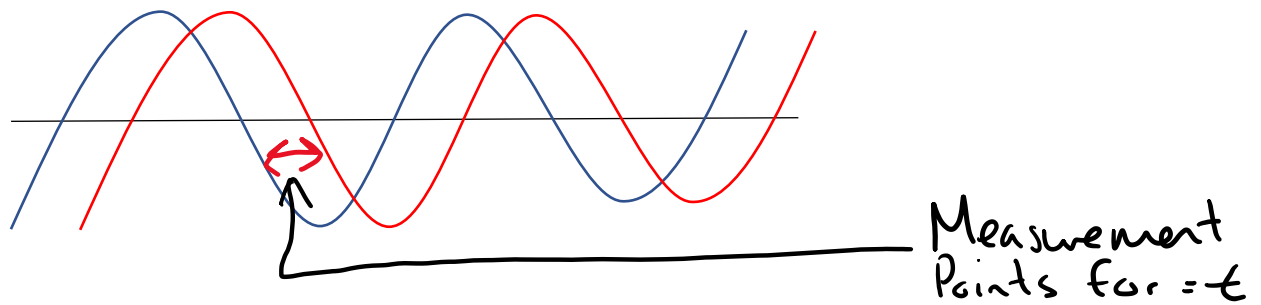
5 – The program for generating sine waves by the inverter is sorted in the RAM.

6 – The purpose of the over-current protection circuit in a power supply is to prevent, damage to the load being supplied.

Discussion

For the discussion section, this will be a detailed over look at the results obtained within the practical element, and review of how and why the results are obtained the results shown on pages 7-9of this document.

For clarification it should be noted and clarified of where the measurement point's were taken for the given results these are figured below;



Task 1 - Discussion

Taking a look at the results table for the first section in (Table 1),

Correction Capacitor	None	C2 – 10 μ F	C2 + C3 - 20 μ F	C2 + C4 - 15 μ F
Phase Angle (Lead/Lag)	$t = 1.314$ $T = 14.17$ $\frac{1.314}{14.17} \times 360$ $= 33.38^\circ$	$t = 171.42\mu s$ $T = 13.94$ $\frac{171.42\mu s}{13.94} \times 360$ $= 4.42^\circ$	$t = 800\mu s$ $T = 13.94$ $\frac{800\mu s}{13.94} \times 360$ $= 20.65^\circ$	$t = 400\mu s$ $T = 14.11\text{ms}$ $\frac{400\mu s}{14.11} \times 360$ $= 10.20^\circ$
Current Amplitude	$\frac{2 \times 2.6 \text{V} \times 1000}{10}$ $= 520\text{mA}$	$\frac{2 \times 2.2 \text{V} \times 1000}{10}$ $= 440\text{mA}$	$\frac{2 \times 2.4 \text{V} \times 1000}{10}$ $= 480\text{mA}$	$\frac{2 \times 2.35 \text{V} \times 1000}{10}$ $= 470\text{mA}$

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First measurement taken with no capacitors within the circuit which resulted in a phase angle of 33.38° , this results in a PF $\cos(33.38^\circ) = 0.81$ pf and a current amplitude of 520mA, to try and improve on this capacitance is required to be added into the circuit. Circuit overall was lagging.

This is shown on section C2 of the above table where 10uf of capacitance is added to circuit, the results promptly show a great improvement of the system performance with the phase angle to 4.42° , results in a PF $\cos(4.42^\circ) = 0.977$ pf and a current amplitude of 440Ma. Circuit overall was leading.

The third is directed to add additional capacitance with C2+C3 @ 20uf, when this arrangement was implement the resulting phase angle became worse from the previous C2 only vales, this measured at phase angle of 20.65° , this results in a PF $\cos(20.65^\circ) = 0.977$ pf and a current amplitude pf 480mA, circuit was leading.

For the final section C2+C4 @ 15uf of capacitance, this is a drop of 5uf from the last C2+C3 again this was a marked improvement for the C2+C3 arrangement @ a phase angle of 10.20° resulting phase angle $\cos(10.20^\circ) = 0.9841$ pf and current amplitude of 530Ma. Circuit was leading.

From the given results the prime capacitance for this circuits is at 10uf, this had lead me to the conclusion that the C2 capacitor is at fault in the respect that its oversized for the application, as it's the common factor in all the final results, and all are leading capacitive loads.

Taking a look at the results table for the first section in (Table 1),

Correction Capacitor	None	C2 – 10μF	C2 + C3 - 20μF	C2 + C4 - 15μF
Phase Angle (Lead/Lag)	$t = 1.457\text{ms}$ $T = 14.286\text{ms}$ $\frac{1.457\text{ms}}{14.286\text{ms}} \times 360$ $= 36.71^\circ$	$t = 857.14\text{us}$ $T = 14.286$ $\frac{0.857\text{ms}}{14.286\text{ms}} \times 360$ $= 21.59^\circ$	$t = 1.714\text{ms}$ $T = 14\text{ms}$ $\frac{1.714\text{ms}}{14\text{ms}} \times 360$ $= 44.07^\circ$	$t = 1.429\text{ms}$ $T = 14.143\text{ms}$ $\frac{1.429\text{ms}}{14.143\text{ms}} \times 360$ $= 36.37^\circ$
Current Amplitude	$\frac{2 \times 5.2 \times 1000}{10}$ $= 1040\text{mA}$	$\frac{2 \times 4.714 \times 1000}{10}$ $= 942.8\text{mA}$	$\frac{2 \times 5.914 \times 1000}{10}$ $= 1182.8\text{mA}$	$\frac{2 \times 5.257 \times 1000}{10}$ $= 1051.4\text{mA}$

First measurement taken with no capacitors within the circuit which resulted in a phase angle of 36.71° , this results in a PF $\cos(36.71^\circ) = 0.80$ pf and a current amplitude of 1040mA, to try and improve on this capacitance is required to be added into the circuit. Circuit overall was lagging.

This is shown on section C2 of the above table where 10uf of capacitance is added to circuit, the results promptly show a great improvement of the system performance with the phase angle to 21.59° , results in a PF $\cos(21.59^\circ) = 0.929$ pf and a current amplitude of 942.8Ma. Circuit overall was lagging.

The third is directed to add additional capacitance with C2+C3 @ 20uf, when this arrangement was implement the resulting phase angle became worse from the previous C2 only vales, this measured at phase angle of 44.07° , this results in a PF $\cos(44.07^\circ) = 0.7184$ pf and a current amplitude pf 1182mA, circuit was leading.

For the final section C2+C4 @ 15uf of capacitance, this is a drop of 5uf from the last C2+C3 again this was a marked improvement for the C2+C3 arrangement @ a phase angle of 36.37° resulting phase angle $\cos(36.37^\circ) = 0.805$ pf and current amplitude of 1051Ma. Circuit was leading.

From the given results the prime capacitance for this circuits is at 10uf, which resulted in the best performance results.

Exercise 2 – Single Phase Synchronous Motor

The method predominantly used by the microcontroller to generate a 3-phase sine wave is based on PWM this is shown by figure 01 within the introduction, by modulating the voltage source output voltage we can control more efficiently via electronic switching. The inverter section of the process its primary job is to convert the voltage source from one type to another such as DC to AC, a very common type which most can relate to is your mobile phone charger, which takes the AC voltage and out puts a DC voltage.

For frequency changes within a system, we can control the frequency by varying the width of the microcontroller pulse, wider the pulse higher the frequency shorter pulse intervals lower the frequency range, so when we look at the figure 01 the verifying pulse widths and frequency heights can be seen in better detail.

For the method of generating sine waves the program would be stored with in the equipment RAM, this stores the specific software parameters to trigger the switching operations of the IGBT's / Thyristors etc in order to product /mimic the sine wave, within all electrical systems there is normally always by good design overcurrent protecting in the form of Fuses/MCB/ACB's depending on load current and required trip times, the main purpose of a overcurrent device is predominately to protect the load its supplying, were this maybe a cable supplying a distribution board which will also have its own internal fusing.

Conclusion

Overall it's a very important feature of any electrical installation to ensure high quality efficient power systems, this can be done via power factor correction as shown within this study, by appropriately monitoring the system and designing the right capacitance/inductance units to maximise investment returns.

The theory suggested with in the introduction of this report, is attainable and accurate this is proven within the practical element of the assignment and the results and values given.

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Referencing

1. [1] - https://en.m.wikipedia.org/wiki/HVDC_Cross-Channel
2. https://watfordcontrol.com/power-factor-correction/?gclid=EAlaIQobChMI9rCl1a-w5gIVWOR3Ch2VoQG6EAAYAiAAEgL17_D_BwE