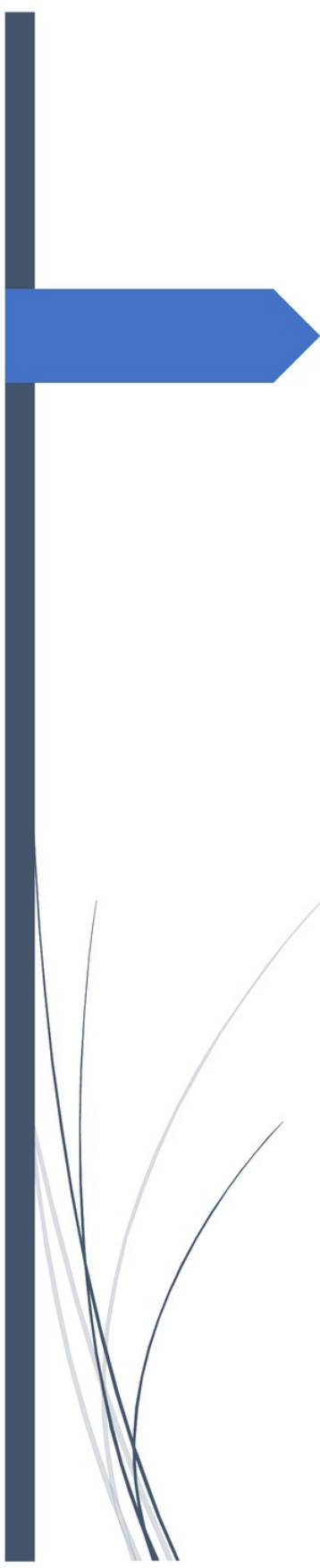


Assignment 2 PED

by Michael Lewis

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PSDE 6016 – Power Electronics and drives

Assignment 2

Michael Lewis

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1. Introduction

The aims of this assignment are to investigate AC frequency drives and various high-frequency techniques used in controlling the drives.

The objectives that will be used to achieve the aims of the assignment are:

- Critically analyse and show understanding a DC to AC conversion circuit that uses high frequency techniques
- Critically analyse and show understanding a DC to DC conversion circuit that uses high frequency techniques *check the brief, it should be AC to AC*

The assignment will involve background research, simulation of the previously mentioned circuits, and a practical experiment carried out on a drive that employs the same techniques. The specific drive being used in the practical experiment is the Allen Bradley 'Powerflex 40' inverter drive.

The research will be compared with simulated and practical results, with the findings critically analysed.

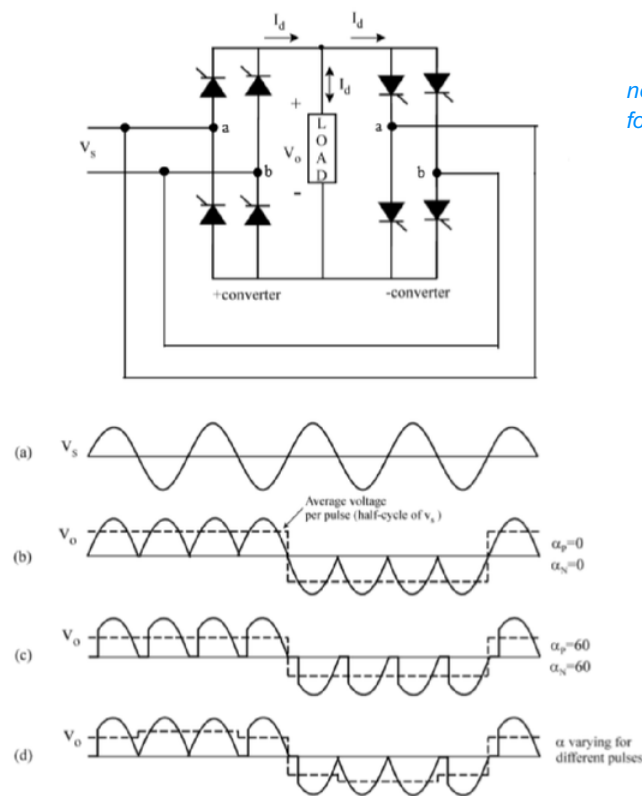
2. Research

Cycloconverters

A cycloconverter is a method of motor speed control by switching the mains supply. Figure 1 shows a simple single-phase to single-phase cycloconverter, fed from mains AC supply and has a simplified load. The waveform labelled (a) shows the input waveform, (b) to (d) shows the effect of changing the firing angle, the dotted line shows the average voltage per pulses. (d) shows how varying the firing angle as the cycloconverter is performing a half-cycle can create a slightly more sinusoidal waveform, as well as highlighting how the average voltage can be changed. The example below takes 4 mains supply cycles to create 1 cycloconverted sine wave, which equates to:

$$Frequency = \frac{F_s}{4} = \frac{50}{4} = 12.5Hz$$

(Babu, 2016)



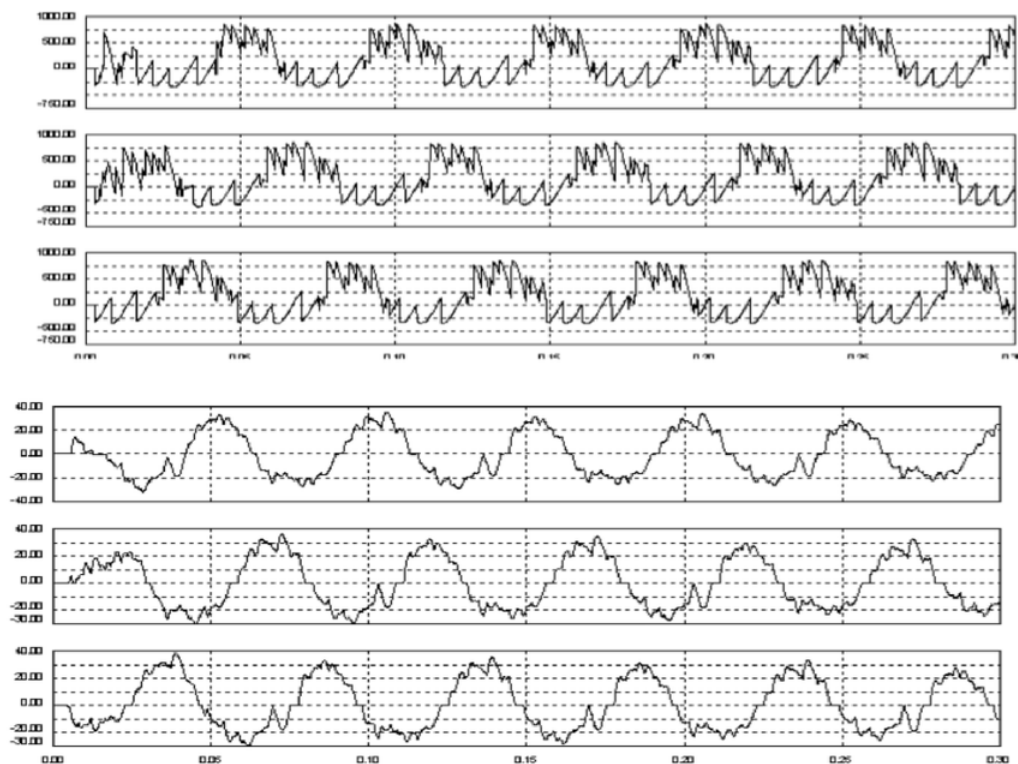
note that the research task asks for 3-phase cycloconverters only

(Burak Ozpineci, n.d.)

Figure 1- Cycloconverter operation

One manufacturer of cycloconverter controller's states that their units can power 1 to 27MW synchronous machines. One of the most impressive applications they specify is the main propulsion for a (sea) ship. (ABB, 1998) So even though the technology is not as cutting edge and relatively simple compared with other motor speed control methods, it is still a valid solution as manufactures offer different topologies and types of cycloconverter to suite the customers' requirements.

Figure 2 shows the simulated voltage and current waveforms respectively produced by a three-phase cycloconverter. The voltage waveform is very messy and is sure to contain many unwanted harmonics. The current waveform produced is a little bit smoother, due to the inductive load, but not nearly as smooth as a waveform produced by a modern PWM inverter.



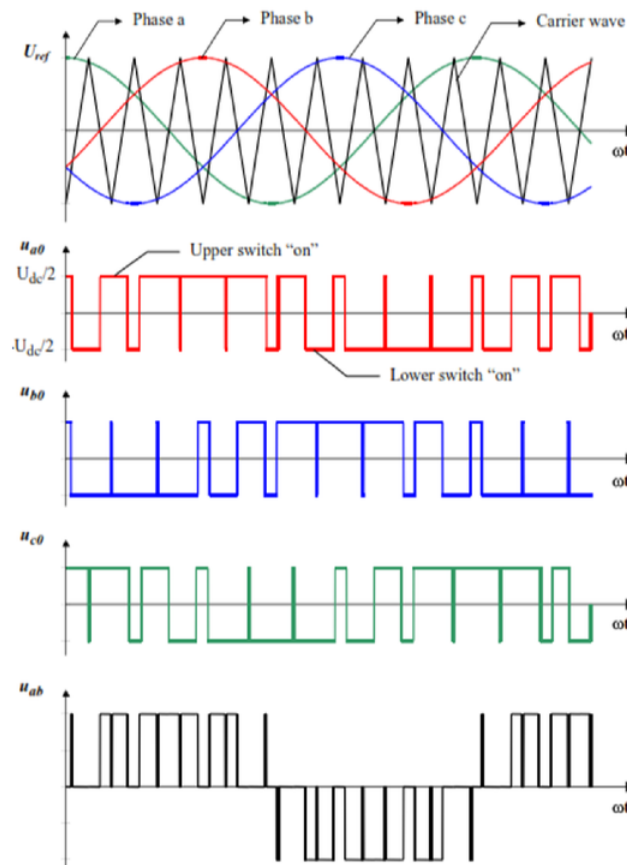
(Sandeep Pande, 1963)

good information but you could have found a more up to date source

Figure 2- Three phase cycloconverter voltage and current

Three phase PWM inverter

The basic operation on a three phase PWM inverter consists of: Saw tooth carrier waveform, overlaid by three sinusoidal waves which are 120 degrees out of phase with each other. The point at which each individual phase crosses the triangular carrier wave determines the duty cycle at any given point. This is best explained in diagrammatical format, shown in Figure 3. It's clearly shown that when the sine wave is at its peak, the corresponding PWM equivalent is almost completely on. The same is true for the negative peak of the sine wave. The diagram also shows when the "negative" switch for the corresponding phase is switched on. This means that 6 switch blocks are needed for a circuit like this, a positive and negative switch for each phase. Figure 4 clearly shows how the reference sine wave modifies the duty cycle of the PWM wave depending on its position on the timing triangular wave.



*a circuit diagram
would have been
helpful here*

Figure 3- PWM generation

(ZELICI, 2012)

Citation Needed

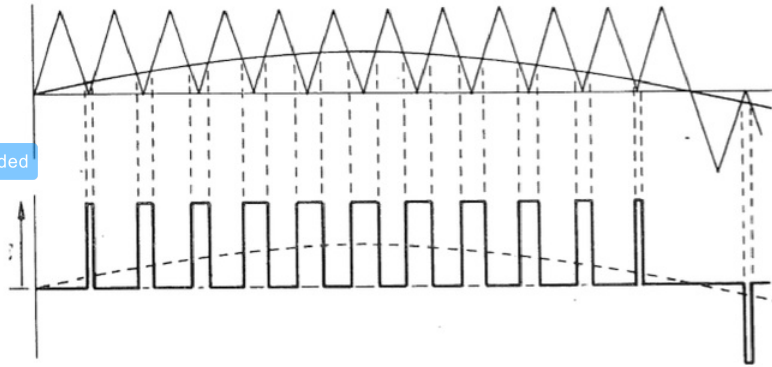
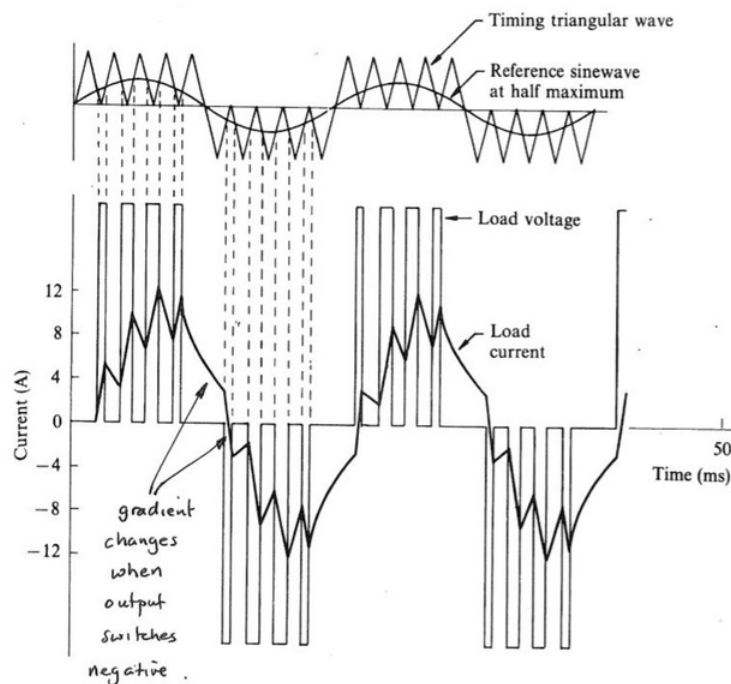


Figure 4 - PWM varying duty cycle

The current waveform for a PWM inverter does not resemble the voltage waveform. The shape of the current waveform resembles a conventional sine wave, albeit a very 'fuzzy' sine wave. This is because the load is inductive and thus stores current, this stops the current "instantly" dropping to 0 when the voltage drops to 0. Instead the current decays over time. When the voltage raises, the inductive load is energised and the current **raises again** (Lander, 1993, p. 235). This is best explained from the diagram in Figure 5.



Citation Needed

Figure 5 - Current stored in load example

For a single-phase supply, the first stage of the PWM inverter is a single-phase full wave uncontrolled rectifier circuit. This rectifying circuit is what supplies the DC link. In theory, a single phase full wave uncontrolled rectifying circuit has a mean DC link voltage of $\frac{2V_{max}}{\pi}$. The mean current is calculated as

$\frac{2V_{max}}{\pi \cdot R}$. These equations have been derived by integrating the input sine wave from 0 to π , and then

Citation Needed transposing to the simpler form. A simplified simulation has been setup to prove this; using a 240v 50HZ AC power source, an uncontrolled rectifier, an inductive and resistive load with arbitrarily chosen values. The mathematics suggests that the average DC voltage for the DC link is:

$$\frac{2 * 339}{\pi} = 215VDC$$

This information is helpful but your research should be based purely on published sources not on simulations

The simulation in Figure 6 shows that the average DC link voltage is 213.6V, which confirm the previous calculations. If a capacitor is added to the DC link it has the effect of increasing the average voltage on the link, the magnitude of the increase and the amount of ripple introduced depends on the size of the capacitor. After numerous failed attempts at simulating the DC capacitor circuit on Multisim, any results could not be obtained due to convergence errors. The effect of adding a capacitor will smooth out the 'bumpy' rectified AC waveform coming out of the diode bridge, by providing a voltage source in the troughs of the waveform. This has the effect of raising the average DC link voltage. This is why in reality, the voltage measured on the DC link of a commercial inverter may be higher than $\frac{2V_{max}}{\pi}$. However, The DC link voltage cannot be raised past the peak value of the sine wave with just a capacitor. If a constant current is required on the DC link, an inductor would be placed in series with the + rail and would act as a current storage device.

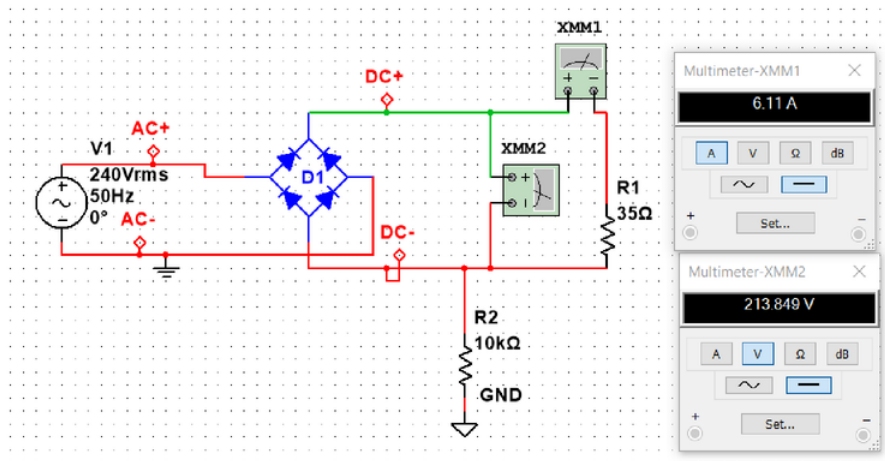


Figure 6- Testing average DC link Voltage

you should limit your research to published sources.

Sp.

In lieu of a simulated result, the annotated waveform in Figure 7 shows the effect of adding a capacitor on the DC link. The size of the capacitor dictates the ripple and thus the average DC link voltage. The rate of decay on the annotated graph was chosen purely to make a point. The average DC link voltage has been slightly raised, but still below the peak voltage value.

Citation Needed

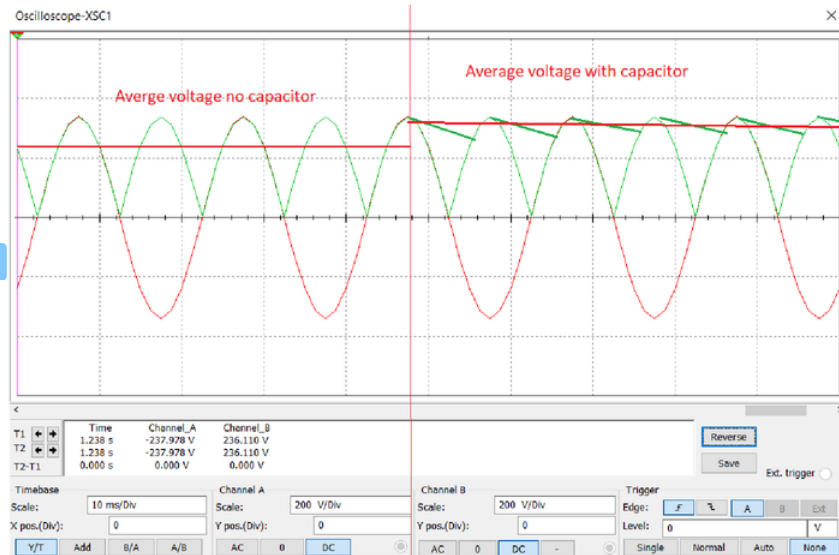


Figure 7- Capacitor effect DC link

Examination of the theory of a three-phase inverter shows this storage capacitor on the DC link. The only difference between the single phase and three phase PWM inverters are that the single-phase rectifier uses only 4 diodes in the rectification stage, instead of 6. The DC link and inverter stages are identical in terms of components used as both inverters are connected to a three-phase motor. The three-phase supply obviously allowing even more power into the system than a single-phase supply could unaided.

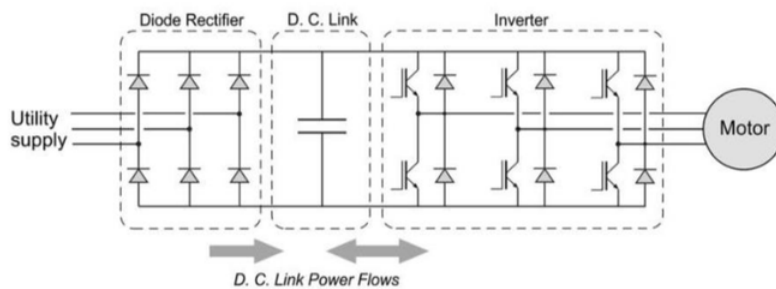


Figure 8- DC link three-phase-input PWM inverter

(Hughes, 1990, p. 256)

Calculating line and phase voltages

Each phase voltage of the connected three-phase motor can be referred to as: V_a , V_b and V_c (Relative to star point). The line voltages are referred to as: V_{ab} , V_{bc} , V_{ca} . An example sketch is shown below to help explain how the voltages are derived, and an explanation of the circuit's operation. The circuit in Figure 9 is the inverter circuit which feeds the power to the motor windings, depending on the gate signals fed to each transistor. The transistors have been replaced with switches in the sketch.

The line voltages are calculated by:

$$V_{ab} = V_a - V_b$$

$$V_{bc} = V_b - V_c$$

$$V_{ca} = V_c - V_a$$

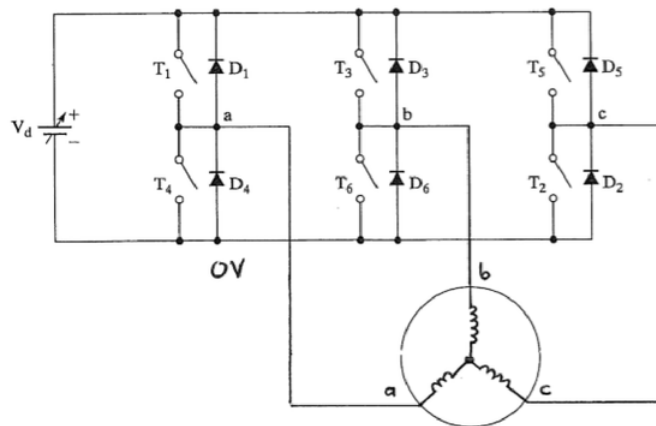
The phase voltages can be calculated from:

$$V_a = \frac{V_{ab} - V_{ca}}{3}$$

$$V_b = \frac{V_{bc} - V_{ab}}{3}$$

$$V_c = \frac{(V_{ca} - V_{bc})}{3}$$

(Krishnan, 2001, pp. 320-323)



Citation Needed

Figure 9- Simplified inverter circuit

*you could have considered
CSI and VSI configurations*

Powerflex 40 drive

The variable frequency drive being used in the practical experiment is the 'Allen Bradley Powerflex 40' adjustable frequency AC drive. A picture of the drive is shown in Figure 10. The diagram in Figure 11 shows the control circuitry used within the Powerflex drive. This will be essential if a drive is being wired up from scratch and will also be very useful for fault finding purposes.

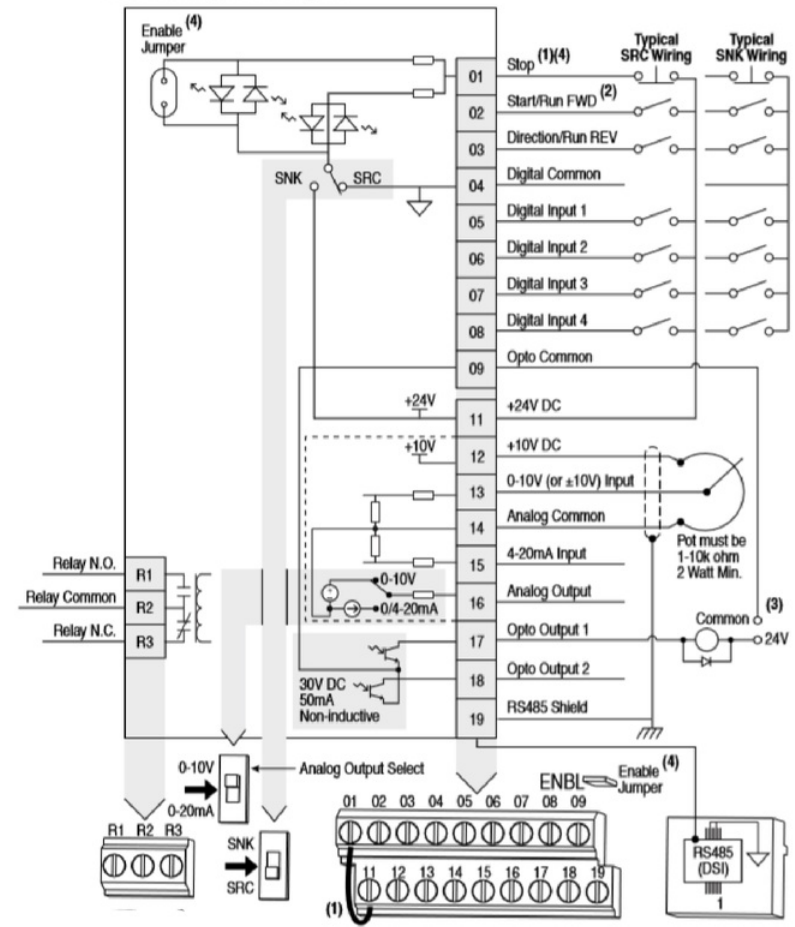


(Allen Bradley, 2013)

Figure 10 - Powerflex 40 drive

Control Terminal Block

Control Wiring Block Diagram



(Allen Bradley, 2013)

Figure 11 - Powerflex 40 Control diagram

Punctuation Error

The manufacturers datasheet contains all the information needed to set the drive up from scratch. Other essential information is listed in the datasheet, such as: Wiring specs, fault codes, how to operate the screen, values of various auxiliary components etc. For this assignment, the referenced control diagram and the power wiring connections (Figure 12) are the most essential. If the experiment setup does not go according to plan, the fault-finding section will become very important. (Allen Bradley, 2013, p. 20). The fault-finding sections details the codes that will be displayed on the drive when it is a fault condition. Like many manufacturers datasheets, the fault code section contains detailed descriptions of possible fixes for each fault condition. This is extremely useful as it allows people who work on these drives to solve issues much faster than if no information was provided.

Power Terminal Block

B Frame		C Frame	
R/L1	S/L2	R/L1	S/L2
T/L3	U/T1	T/L3	U/T1
V/T2	W/T3	V/T2	W/T3
DC-	DC+	DC-	DC+
BR+	BR-	BR+	BR-
⊕	⊕	⊕	⊕

Terminal ⁽¹⁾	Description
R/L1, S/L2	1-Phase Input
R/L1, S/L2, T/L3	3-Phase Input
U/T1	To Motor U/T1
V/T2	To Motor V/T2
W/T3	To Motor W/T3
P2, P1	DC Bus Inductor Connection (C Frame drives only) The C Frame drive is shipped with a jumper between Terminals P2 and P1. Remove this jumper only when a DC Bus Inductor will be connected. Drive will not power up without a jumper or inductor connected.
DC+, DC-	DC Bus Connection
BR+, BR-	Dynamic Brake Resistor Connection
⊕	Safety Ground - PE



Switch any two motor leads to change forward direction.

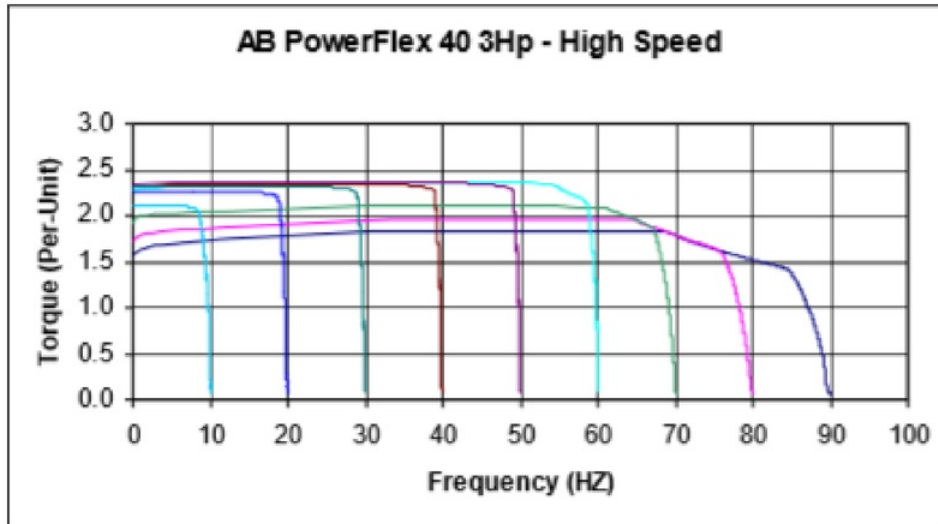


⁽¹⁾ **Important:** Terminal screws may become loose during shipment. Ensure that all terminal screws are tightened to the recommended torque before applying power to the drive.

(Allen Bradley, 2013)

Figure 12 - Powerflex 40 power connections

A slightly more technical datasheet provided by Allen Bradley shows the torque/frequency curve for the Powerflex 40 Drive, shown in Figure 13. The graph clearly shows a consistent torque from the frequency range of 20 to 60Hz. The frequency can be increased beyond 60Hz, but with declining torque output. The same is true for decreasing the frequency lower than 20Hz.



(Allen Bradley, 2013)

Figure 13- Powerflex 40 torque/frequency curve

You could have explained the meaning of the term flux vector

You could have summarized your research and produced a table of comparison of ranges, applications etc to assist an engineer in selecting a drive for a particular application

3. Simulation of inverter circuit

The circuit being simulated is a three-phase PWM circuit, which is connected to a star configured load which contains a 100Ω resistor and a 50mH inductor. Multisim is the software package used to Simulate the circuit. As the -full circuit is too large to be clearly seen on A4 paper, it will be split into two parts and explained separately. See Figure 14 for part of the simulation. The component labelled U1 is the PWM sinusoidal three-phase generator which generates PWM signals which will control the 6 switch blocks. Shown on the screenshot as well is the load that contains the specified inductance and resistance. The battery that supplies the switch blocks is effectively the DC link power source that will be switched to the load. The configuration of the switch blocks is like three-phase full wave rectifiers that has been previously studied. The difference being the use of sub-circuits instead of thyristors/diodes.

The switch block sub circuit, shown in Figure 15, is a simple circuit that isolates the signal voltage. What is being referred to as top or upper switches, and lower or bottom switches are annotated in Figure 5.

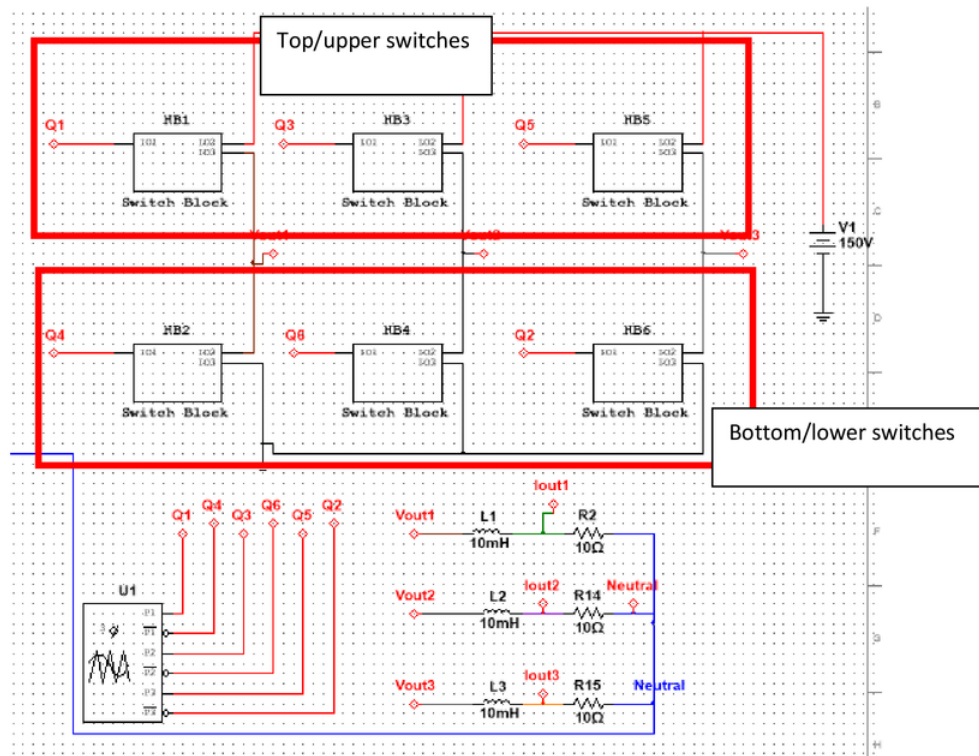


Figure 14- Simulation p1

The switch block circuit is actually very simple. The signal voltage used to switch the transistor on has been optically isolated from the mains supply. This is a safety technique that can protect component and reduce the potential risk for anyone using the electrical equipment, or anyone the electrical equipment is being used on. This is particularly important when producing medical equipment. This is best said on an article on EDN network; *"In the portions of the medical equipment transmitting digital data, designers can isolate sensitive circuitry or patients from high-voltage environments using optocoupler- or transformer-based approaches."* (Yeo Siok Been, 2007). The obvious benefit to using optocouplers is their relatively small size compared to a transformer.

The rest of the circuit consists of measuring equipment, specifically oscilloscopes. A screenshot is shown in Figure 16 showing the oscilloscopes and connections.

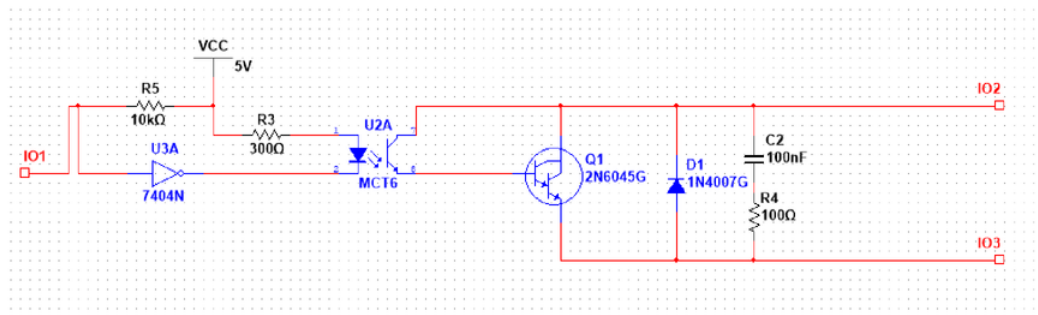


Figure 15- Switch block

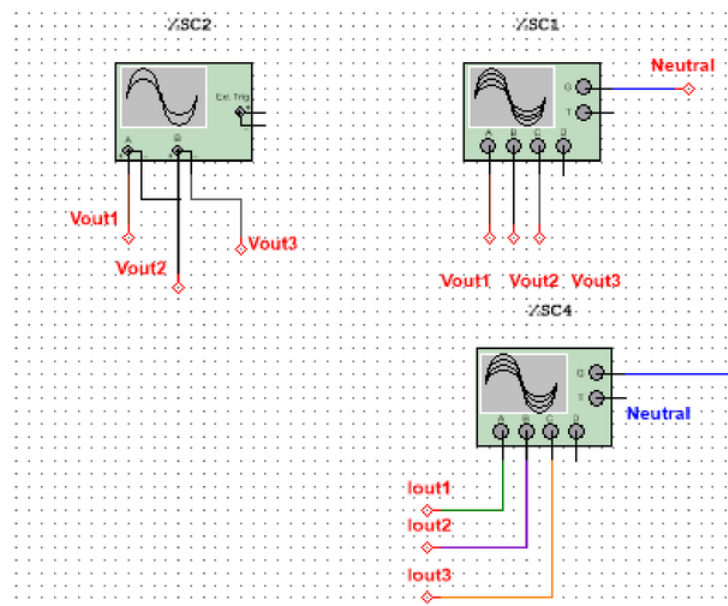


Figure 16- Simulation oscilloscopes

Simulation results

The output from XSC1 is going to be examined first, with the voltage at various points on the waveform being measured to compare with theoretical predictions. Marker 2 on Figure 18 shows the 0 point on the bottom phase on the scope, marker 1 shows the 'middle' step. 0v and 49V respectively.

Figure 19 shows the voltage level of the 'top' step of the 'bottom' waveform on the scope, 99V. The negative half of the 'bottom' waveform on the scope is the negative equivalent of the positive cycle: 0V, -49V and -99V. This can be confirmed by examining either Figure 18 and Figure 19. Each waveform on the oscilloscope is effectively the phase voltages V_a (Vout1), V_b (Vout2) and V_c (Vout3). The shape of the phase voltage waveforms can be explained by using the calculation on page 10, and the oscilloscope output for the line voltages V_{ab} (Vout1 to Vout2) and V_{bc} (Vout2 to Vout3), see Figure 17. Take V_b (Vout2) for example: Figure 17 has 2 markers where the values are:

Marker 1: $V_{ab} = 145V$ & $V_{bc} = 3V$

Marker 2: $V_{ab} = 146V$ & $V_{bc} = -146V$

Putting values into the equations from page 10.

$$V_b = \frac{V_{bc} - V_{ab}}{3} = \frac{3 - 145}{3} = -47.33V$$

$$V_b = \frac{V_{bc} - V_{ab}}{3} = \frac{-146 - 146}{3} = -97.33V$$

Other voltage levels from the waveform in Figure 17 can be put into the equation to give:

$$V_b = \frac{V_{bc} - V_{ab}}{3} = \frac{145 - 3}{3} = 47.33V$$

$$V_b = \frac{V_{bc} - V_{ab}}{3} = \frac{146 - (-146)}{3} = 97.33V$$

$$V_b = \frac{V_{bc} - V_{ab}}{3} = \frac{0 - 0}{3} = 0V$$

As can be seen from the equations above, 3 voltage steps become apparent when putting the line voltages into the researched equations. The results also closely match the measured phase voltage steps of: 0V, 49V, 99V, -44V and -99V.

The results gathered from performing the practical experiment will be compared with the results from the simulation. Theory suggests that the levels of the phase voltages can be calculated by using these calculations with the measured line voltages.

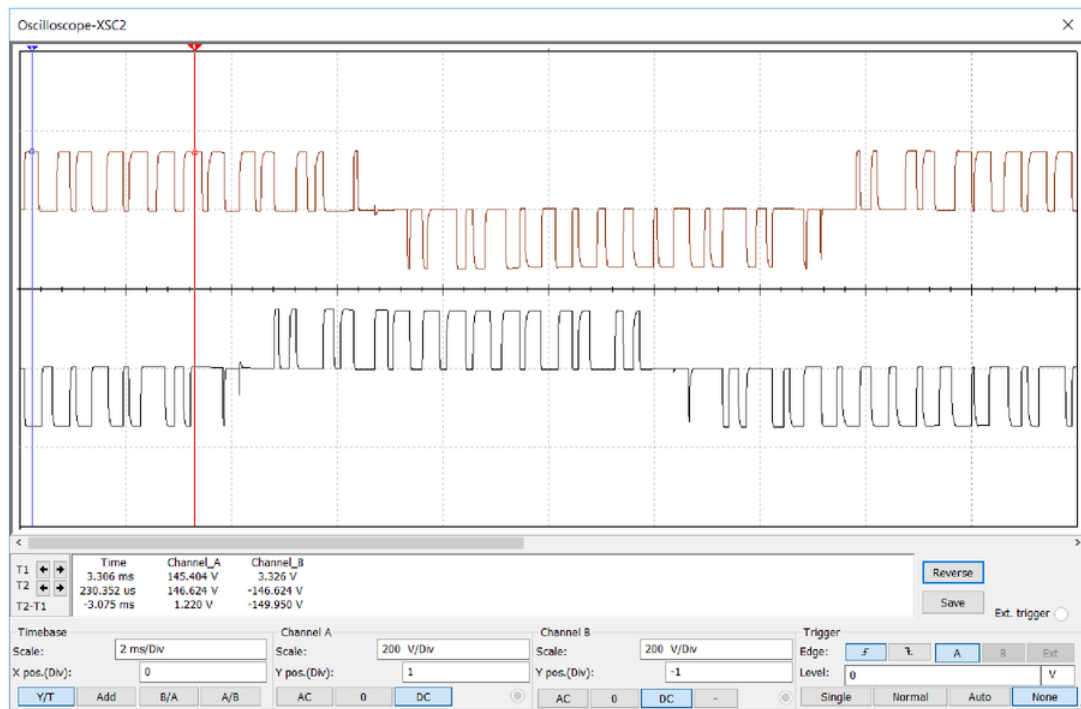


Figure 17 - XCS2 - Line voltages

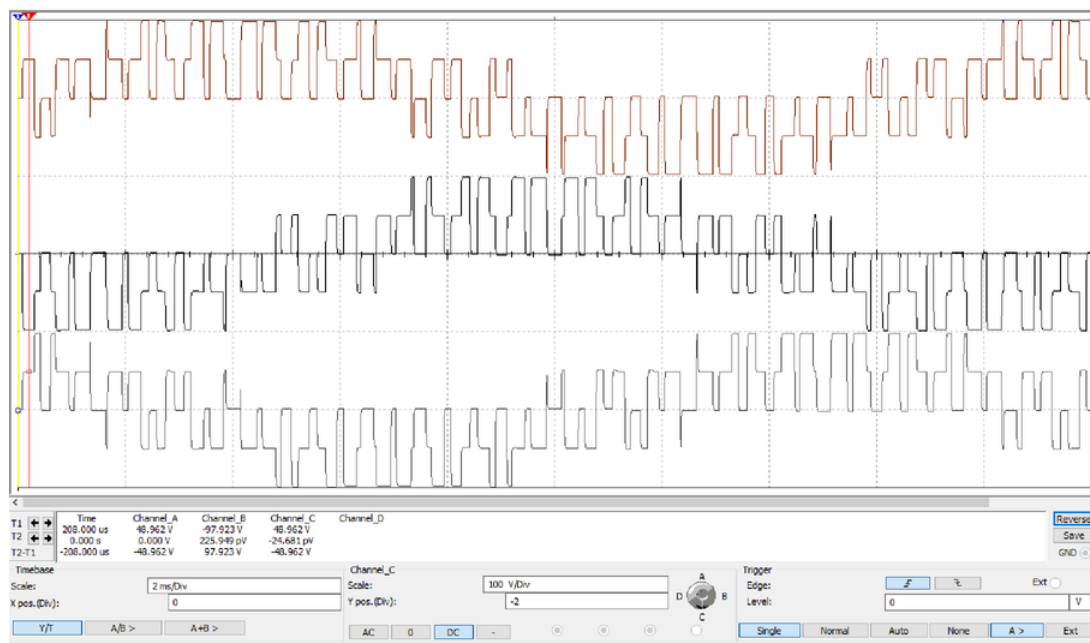


Figure 18-XCS1 - 1

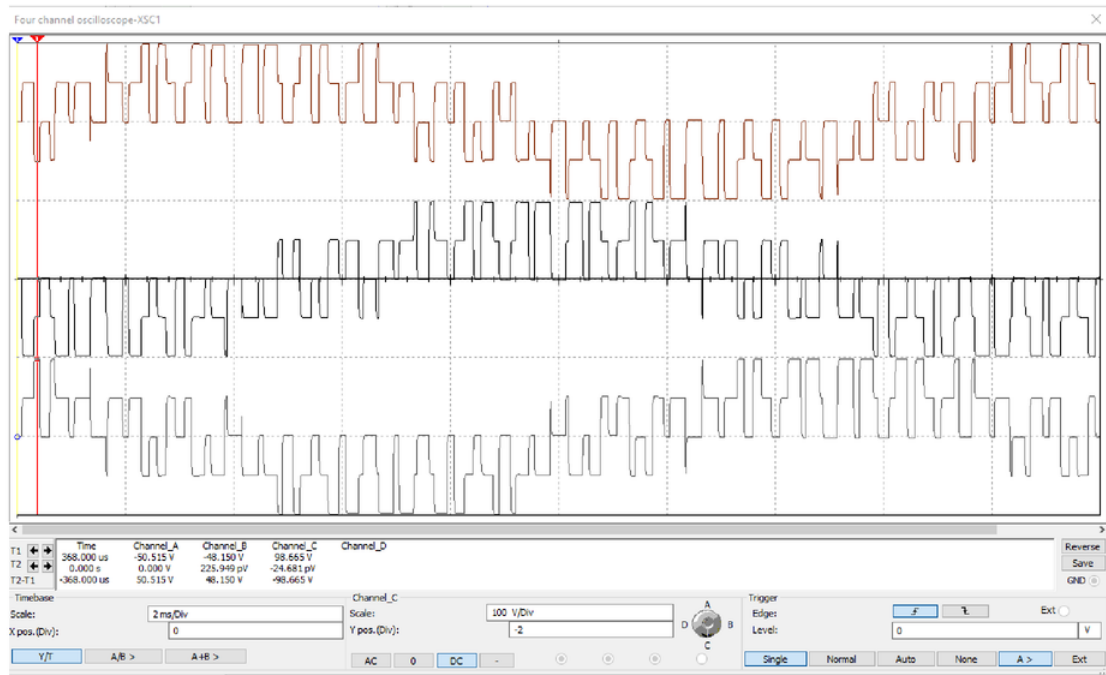


Figure 19 - XCS1 – 2Q

*you could have measured
 the 1/3, 2/3, -1/3 and -2/3
 points to compare with the
 theory*

Simulated current

Another comparison that can be made from the simulation is the shape of the current waveform. Theory suggests that the current should resemble a sine wave, with the exception of some ripple. This has previously been explained in Figure 5. The oscilloscope waveform from XSC4 shows the current waveforms for; Iout1, Iout2 and Iout3, see Figure 20.

The current waveforms clearly resemble a sine wave, each current waveform is 120 Degrees out of phase with each other, as is the input three-phase sine waves, which together add up to 360 degrees (One complete cycle). This agrees with all the theory and research so far. The current waveform has been annotated to show the phase difference.

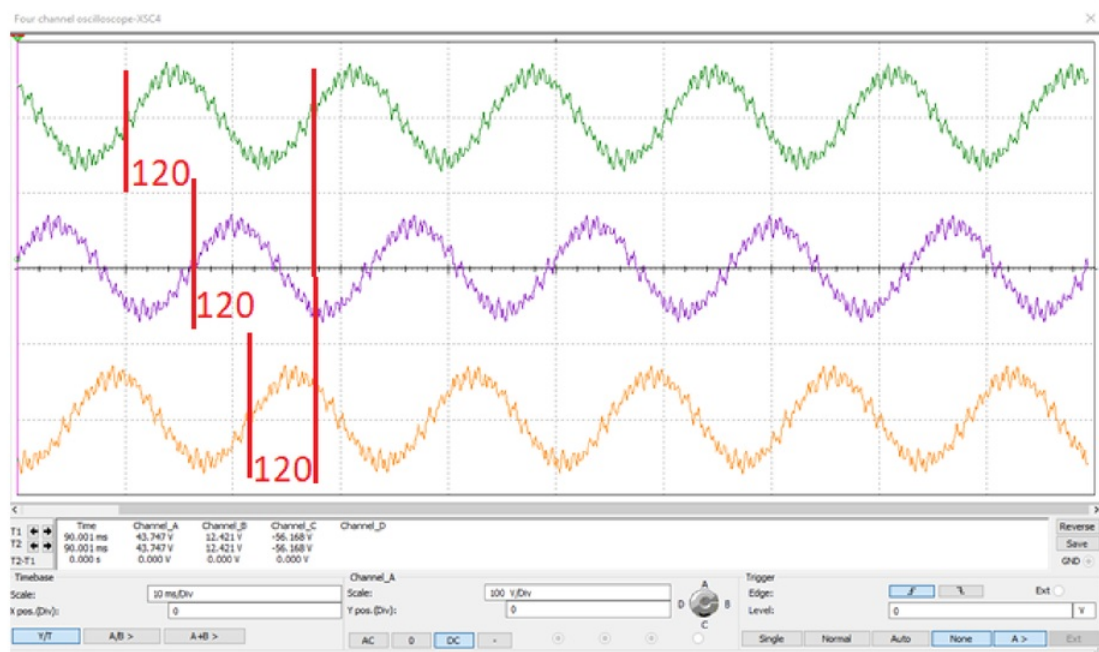


Figure 20 - Simulation current waveform

*you should have
proved these angles
using the data in the
window with cursors*

4. Practical AC Drive investigations

Unfortunately, photos of the practical experiment were lost and could not be re-created in time for the assignment. Instead, photos of some of the equipment used (but not setup for the experiment) have been included instead, see Figure 21.

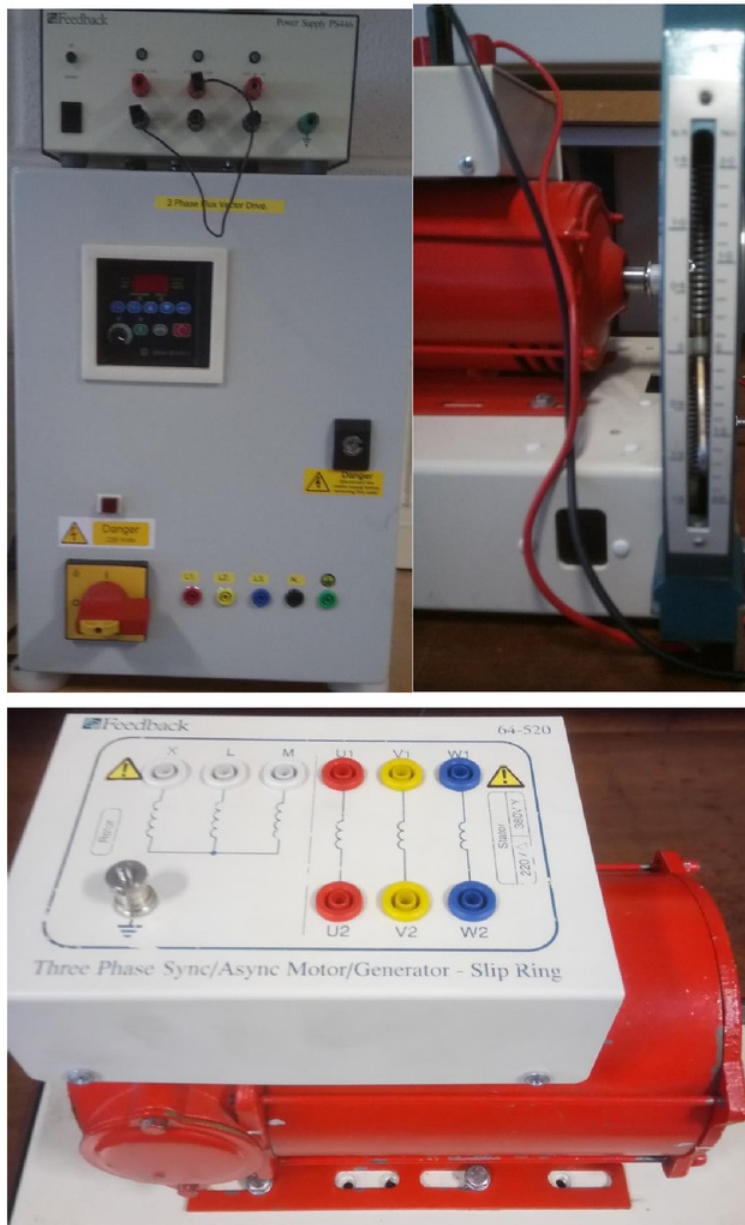


Figure 21- Experiment - PowerFlex40 panel, prony brake and three phase motor

The practical side of the assignment was carried out in a small team. The experiment involves an Allen Bradley Powerflex 40 drive, connected to a suitable induction motor. Other equipment used was; Pico logger, Laptop, Prony brake, tachometer. Correct health and safety procedures were followed throughout the experiment.

The first set of tests involved running the motor at three different set-point speeds. Stator voltage and current waveforms were recorded for each speed.

The second set of tests involved running the motor at a chosen set-point speed and applying three different loads using the Prony brake. Current and voltage waveforms will be recorded for each load.

Varying speed set-point

The first speed set-point chosen is 50Hz. The blue line which isn't at all smooth represent the stator voltage, the smoother red line represents the current, see the waveform in Figure 22. One noticeable point that is immediately obvious from the waveform is how smooth the current waveform is compared to the voltage. This was expected and confirm the initial research, see Figure 5 on page 7. Studying all three waveforms at different setpoints shows that the amplitude of the blue voltage waveform stays consistent, at roughly 2.05mV which is equivalent to 205V. Especially clear in Figure 22 are the different steps along the voltage waveform, the top being roughly 200V and the second step around 100V. The theory so far suggests that the top step is 2/3rds of the DC link and the bottom step is 1/3rd the DC link voltage, so it would be safe to estimate the DC link voltage to be around 300V.

The calculation $\frac{2V_{max}}{\pi}$ Which describes the DC output from a full-wave uncontrolled rectifier, gives a result of 215V when Vmax for the mains is entered. The difference in value suggests that a capacitor is connected in parallel to the DC link acting as a constant voltage source for the DC link.

As the speed setpoint is lowered, the current waveform keeps its smooth shape, but the frequency of the current sine wave can clearly be seen lowering, as the setpoint is lowered. The voltage steps are not as clear when the setpoint is lowered to 25Hz. Not only does the current frequency change, the RMS amplitude of the current also slightly decreases: 50Hz has the highest current amplitude and it gradually slightly decreases as the setpoint is lowered. The current values are not exact on the Pico logger, there is a scaling factor of $\frac{10}{66}$ due to the way current was measured.

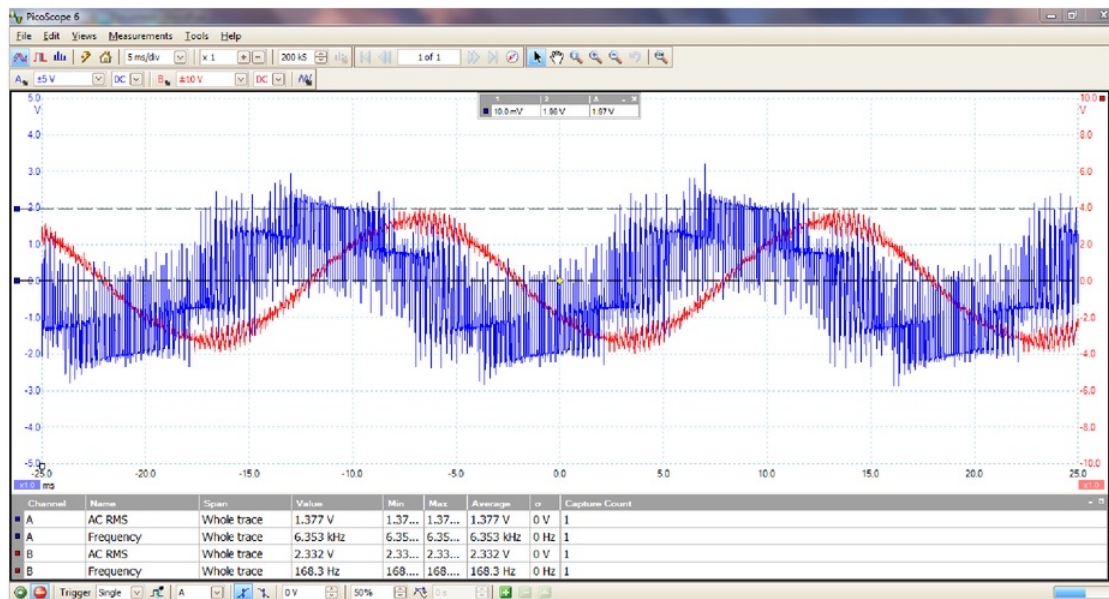


Figure 22 - 50Hz setpoint

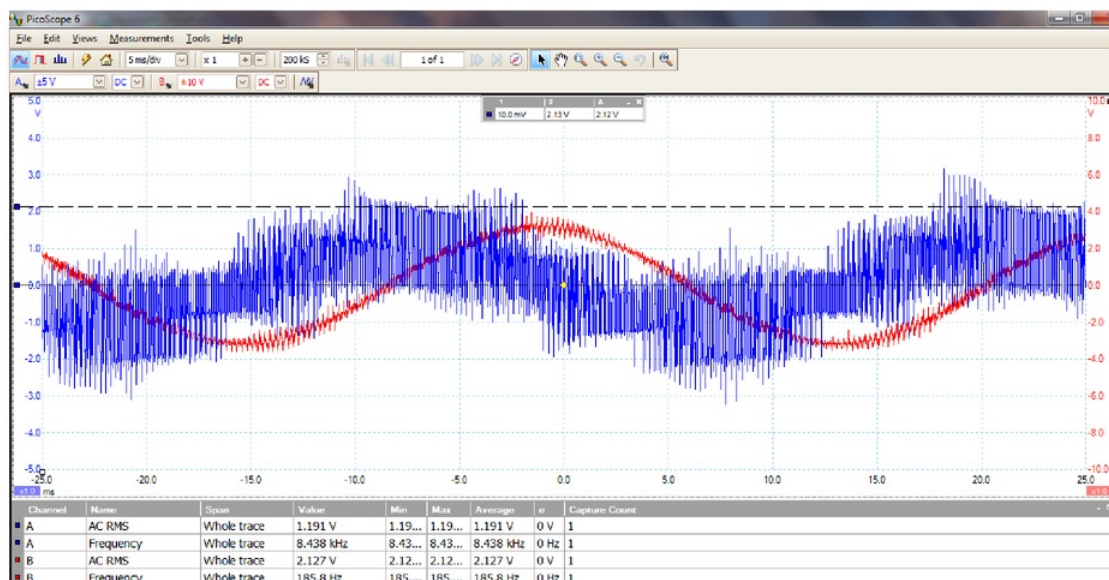


Figure 23 - 35Hz setpoint

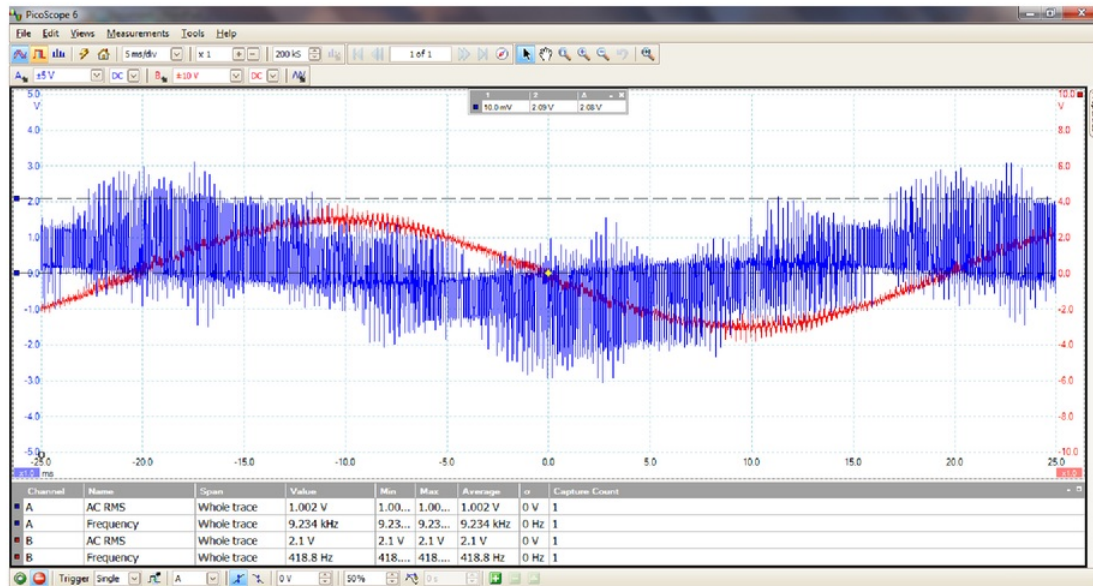


Figure 24- 25Hz setpoint

you could have measured the v/f ratio and commented on the performance of the motor.

Varying load on motor

One interesting observation that can be made from examining the load waveform is how the power factor greatly increases as the motor is loaded. The motor get closer and closer to a unity power factor until the load is too great, and overloading stalls the motor. The speed of the motor also drops when the motor is loaded, which is expected due to the relationship between torque and speed. As the motor has more load to drive, the motor must produce more torque, which in turn causes a slight drop in speed.

The amplitude of the current raises as the amplitude of the voltage remains the same. This is also expected as torque produced by a motor is a product of voltage and current. If the voltage is constant then a greater current will provide extra torque to counteract the load being added.

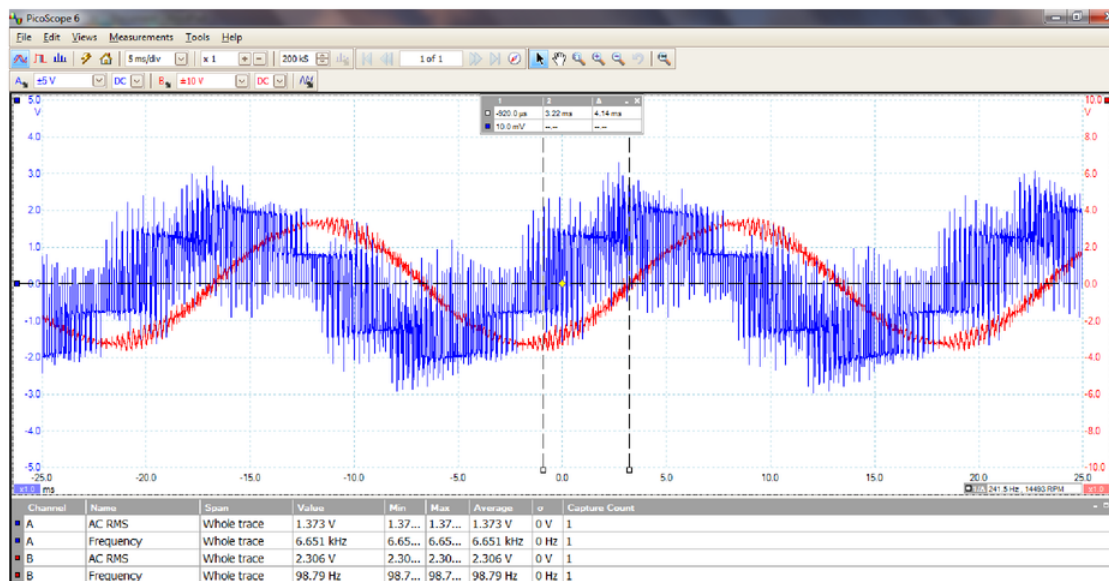


Figure 25- No load 50Hz - PF measurement

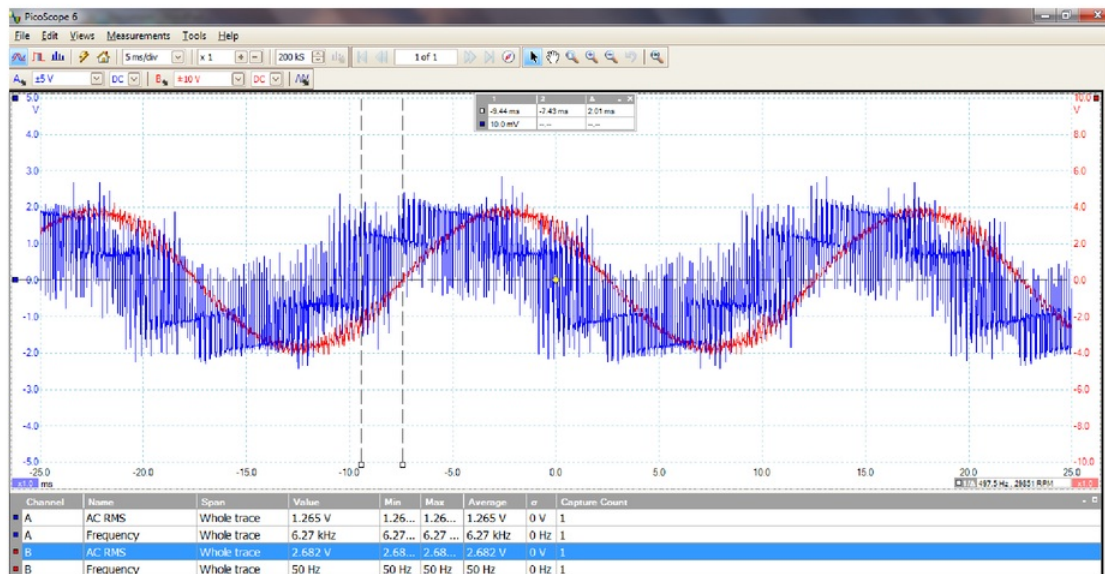


Figure 26 - 50Hz 0.4Nm load - 1450RPM measured

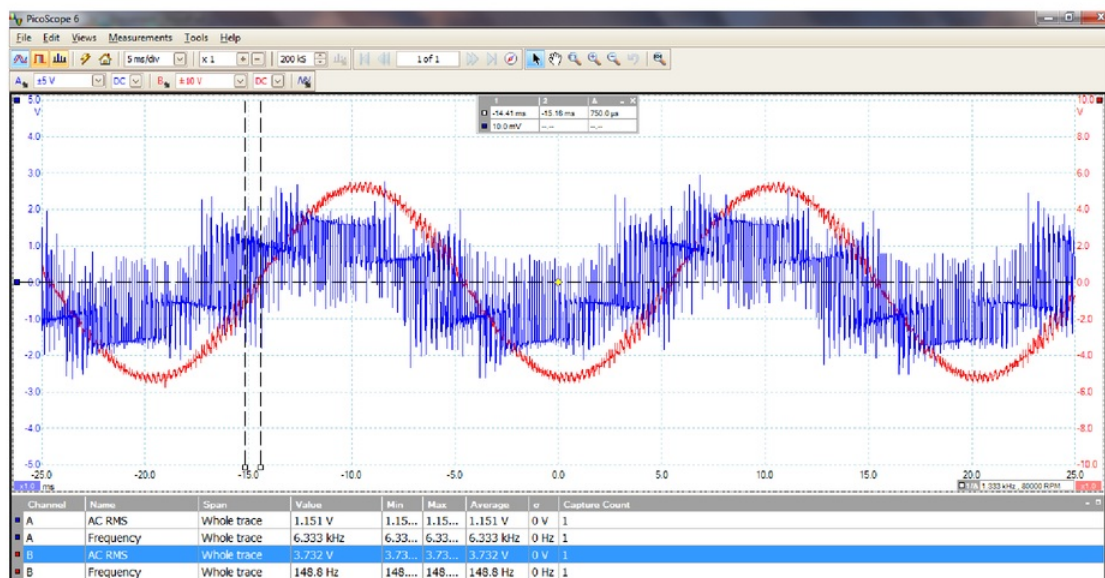


Figure 27 - 50Hz 0.7nm - 1363RPM measured

Spectrum analysis

Notice the number of harmonics that are present in the voltage spectrum in Figure 28, which was expected because of the incredibly messy waveform. Which is one of the detrimental effects high-frequency switching techniques has on this type of circuit. As the load is effectively inductive, the harmonics are much less pronounced in the current waveform, which is why the current waveform was much more sinusoidal than the voltage. The highest amplitude harmonics for the current are: the fundamental frequency at 50Hz, the third, fifth and seventh harmonic. At 150, 250 and 350Hz respectively. The voltage spectrum contains far too many to be listed.

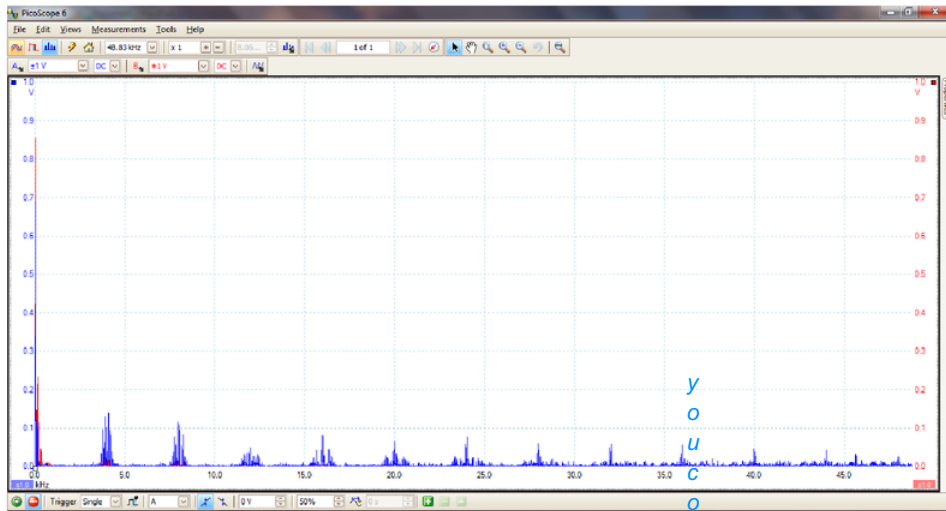


Figure 28- Voltage spectrum @ 50Hz



Figure 29 - Current spectrum @ 50Hz

5. Conclusions and recommendations

Conclusion

The initial research shed light on some of the values that were to be expected in the simulation and practical tests. Mainly, the calculations for the phase and line voltage values, as well as the voltage on the DC link in the PWM inverter. The research matched the expected values, except for the step voltages were not as calculated from $\frac{2V_{max}}{\pi}$. Further research shown that the cause of this could be a capacitor in the DC link, but further testing/investigation would be needed to confirm, as has been mentioned in the recommendation section.

The research also shows some methods of motor speed control and the resulting current and voltage waveforms for the different types of speed controller. The reason why the voltage and current were a particular shape was also discovered. The rapidly high frequency switching in the controllers explained the 'messy' or 'spikey' voltage waveform, and the inductive load acting as a current storage device explaining the relatively smooth current. The simulation and practical experiments confirmed these findings.

Varying the speed setpoint of the Powerflex drive shows how the device chops the voltage at a high frequency, and how the current follows creating a relatively smooth wave. The frequency change of the current waveform can also be clearly seen from the Pico logger output, as well as a slight drop in amplitude at the setpoint was lowered.

Varying the load on the motor shows how the efficiency of the motor increases as the motor is loaded. The power factor for the un-loaded motor was far more inefficient than loading the motor, up until the motor stalls. The amplitude of the current waveform raises to cope with the extra load, which was expected.

Although the voltage is being switched at a high frequency in the drive in both practical experiments, the voltage steps remains the same as was initially calculated. Hence why the amplitude of the current has to change to be able to drive a larger load, and the frequency of the current has to change when the drive wants the motor to run at a slower speed. The spectrum analysis from the practical experiment shows the reason why the voltage and current waveforms are so 'messy' or clean respectively.

Overall the majority of the theory and research tied nicely into the simulations and practical experiments, with all the aims and objectives from the introduction being completed.

Recommendations

During the research section of the report, a simulation was setup to prove that the DC link voltage can go beyond $\frac{2V_{max}}{\pi}$, with the use of a storage capacitor placed across the positive and negative terminals of the DC link. Multisim's limitations did not allow this circuit to run for any length of time without convergence errors, so no useable data was gained. Instead, a theoretical prediction based on knowledge about capacitors was used to arrive at the conclusion that the average DC link voltage can be raised beyond the calculated value, which was confirmed by research. Although when the experiment was being carried out the DC link voltage was above the calculated value, it was not proved in this report with any evidence, a value was only estimated. If time had allowed, it would have been nice to be able to set up a practical experiment to conclusively prove that this is the case.

6. Citation list

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7. Appendices

There are no appendices for this assignment.

Assignment 2 PED

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

65/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

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PAGE 5

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PAGE 6

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PAGE 7

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PAGE 8

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PAGE 9

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PAGE 15

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comparison of ranges, applications etc to assist an engineer in selecting a drive for a particular application

PAGE 16

PAGE 17

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PAGE 20

Text Comment. you could have measured the $1/3$, $2/3$, $-1/3$ and $-2/3$ points to compare with the theory

PAGE 21

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PAGE 25

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PAGE 26

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PAGE 28

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PAGE 29

PAGE 30

PAGE 31

GRADING FORM: CSG-RUBIC

MICHAEL LEWIS**65****RESEARCH-INFORMED LITERATURE**

Section 2: Your research – Good evidence of background reading and research from a wide range of sources. However, some information has been included from a non-published source i.e. from simulation. Keep to published sources that can be referenced in the research section of a report. There are other areas you could have looked at including CSI and VSI drives. (13/20) Section 6 - Wide range of sources correctly cited and listed. However, all image sources should also be cited. (3/5)

16**KNOWLEDGE AND UNDERSTANDING**

Section 1: Introduction – Briefly stated with one error. (3/5) Section 3: Explanation of simulation – Good, clear treatment. (4/5) Section 4: Explanation practical experiment – Very good, shame about the loss of the photos. (4/5)

11**ANALYSIS**

Section 3: Analysis of results from simulation – Very

good but you could have measured more points and compared with theory. (6/10) Section 4: Analysis of results from practical experiment – Generally very good but you could have considered more relationships. (6/10) Section 5: Overall conclusions and recommendations – Generally very good with some useful observations and recommendations. (10/15)

22

PRACTICAL APPLICATION AND DEP.



Section 3: Simulation – Good use of simulation software. Well presented results but more measurements could have been made. (4/5) Section 4: Practical experiment – Good use of equipment with well presented results. (4/5)

8

SKILLS FOR PROFESSIONAL PRAC.



All sections – Well structured and presented. Contains a few spelling errors. (7/10) Section 5: Team role – No comments made and no evidence provided but team working was observed by your tutor. (1/5)

8