

Sam Harries - Power Electronics Assignment Final

by David Harries

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BSc (Hons) Electrical and Electronic Engineering

PSDE6016: Power Electronics and Drives

Assignment - Investigation into DC Drives and Control Methods

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2 - Executive Summary

This report contains research into advanced power electronic circuits, electrical machines and drive systems. The evolution of current drivers and control methods will be researched in addition to the benefits of three-phase drives over single-phase. This can be found in **Section 3**.

A simulation exercise can be found in **Section 4** where a single-phase converter circuit is analysed with two different firing angles; one allowing continuous current, and the other discontinuous current. A three-phase converter circuit will also be analysed for two different firing angles, however these will both be for continuous current.

Finally, a practical exercise will be done to analyse the Parker 514C d.c. drive in **Section 5**. This practical will involve an analysis of four-quadrant operation, regenerative braking, the effect of adding a load, and voltage / current control.

Calculations can be found for both the simulation and practical exercise to link theory to practicality.

3 - Research

3.1 – Evaluation of Current Technologies used in Modern DC Drives and their Evolution

D.c. drives, often named d.c. rectifiers are used as a means to convert or rectify single-phase or three-phase supply into a d.c. voltage of desired magnitude. This desired output voltage is controlled by a bridge of rectifying devices. There are many types of rectifying devices each with advantages and disadvantages such as; diodes, SCRs (Thyristors), GTO thyristors, Triacs, IGBTs, power MOSFETs and transistors. (Lander, 1993). These devices act as switches and can be turned on / off for longer to increase / decrease voltage to the load respectively.

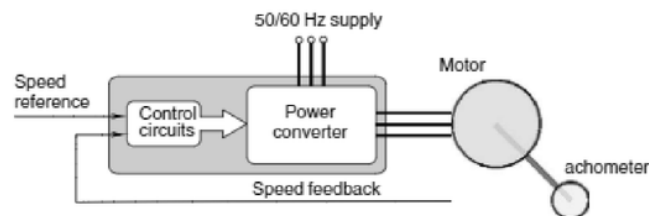


Figure 3.1 – General Arrangement of Speed-Controlled Drive (Hughes, 2006)

A d.c. drive involves a few elements; control circuits, power converter and the closed loop speed feedback. As **Figure 2.1** shows, the power converter draws current from the supply at whatever voltage is required by the motor to run at the desired speed. The magnitude of the voltage sent to the motor is determined by whatever rectifying devices are used within the power converter. These devices are turned on/off by the control circuits which compare the reference / desired speed with the speed feedback. If the speed feedback is lower than the reference speed then the control devices are instructed to increase the voltage by being 'on' for longer. The opposite is true to decrease the speed.

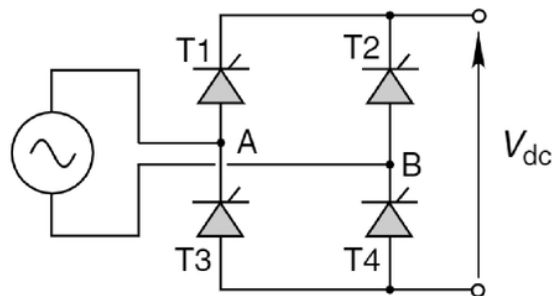


Figure 3.2 – Single-Phase, Full-Wave, Fully-Controlled Rectifier (Hughes, 2006)

In **Figure 2.2** there are four Thyristors being used to control . The thyristors are paired and controlled by altering the firing angle (α). "T1 and T4 are fired together when terminal A of the supply is positive, alternately T2 and T3 are fired simultaneously when B is positive" (Hughes, 2006). The output waveforms are shown in **Figure 3.3**. The waveforms show that as α is increased the average voltage is much lower, therefore lowering the speed of the motor.

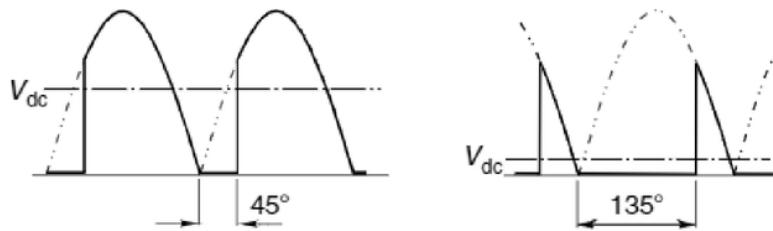


Figure 3.3 – Output Voltage Waveforms for 45° and 135° Firing Angles for Resistive Load (Hughes, 2006)

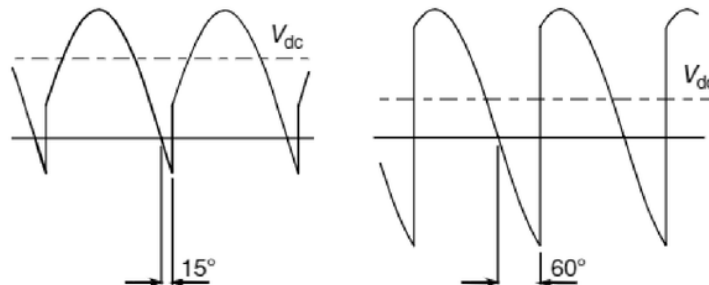


Figure 3.4 – Output Voltage Waveforms for 15° and 60° Firing Angles for Inductive Load (Hughes, 2006)

Due to it being single phase, the output has large ripple and is far from being considered pure d.c. This is fixed by using a three-phase supply and a six-thyristor controller which will be discussed in **Section 3.3**.

3.2 – Configuration and Control Techniques Employed in Commercial DC Drives

3.2.1 – Two Loop Control

Two-loop control is the most common control technique used in industry to control the speed and torque of motors ranging from small low-power drives, to large high-power drives. “This method involves an inner feedback loop to control current (and hence torque), and an outer loop to control speed.” (Hughes, 2006)

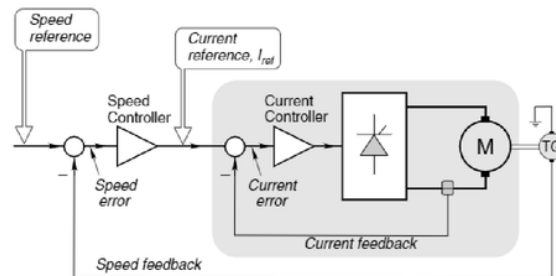


Figure 3.5 – Two-Loop Control Method (Hughes, 2006)

As previously mentioned, the speed feedback is compared to a speed reference which is used to increase / decrease the voltage and therefore the speed. Likewise, a current feedback loop is used to tell the controller that the motor requires more torque and therefore the current is increased.

Block Diagram

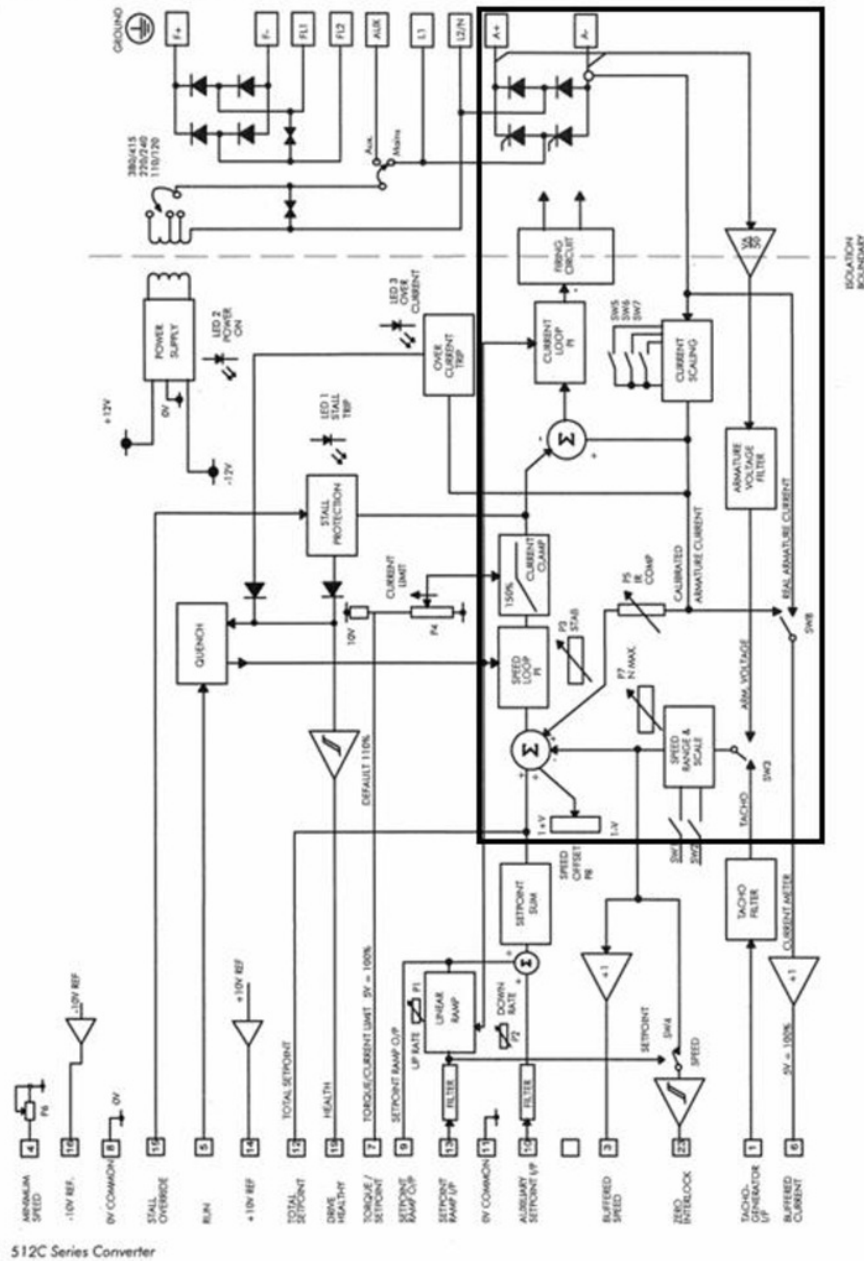


Figure 3.6 – 512C DC Controller Block Diagram (Parker, 2016)

The Parker 512C d.c. drive has a two-loop control system as shown in the highlighted area. This allows the driver to control both speed and torque during the motor's operation.

3.2.2 – Two and Four Quadrant Control

In addition to speed and torque, directional control is commonly required. The four quadrants are determined by whether the voltage (speed) and current (torque) are positive or negative.

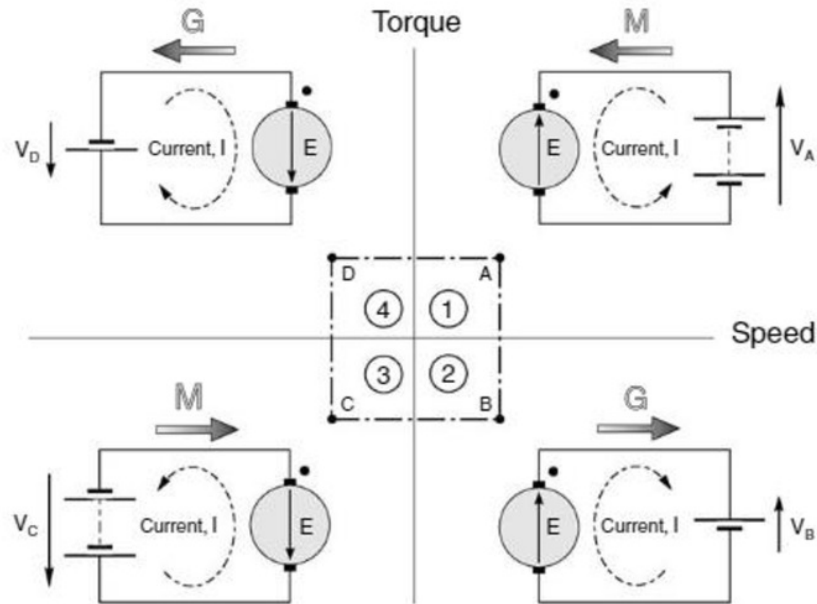


Figure 3.7 – Four Quadrants of Operation (Hughes, 2006)

The circuit configuration in **Figure 3.7** is a two quadrant drive as it can only provide positive current. In Quadrant (1) a supply is fed to the motor meaning voltage and current are both positive. Therefore, the motor turns in the forward direction. In quadrant (1), if the supply is reduced so that the current (torque) becomes negative. The motor is then operating in Quadrant (2). Since the motor still has speed in the forward direction but negative torque, the motor starts regenerative braking, and power is fed to the supply from the motor.

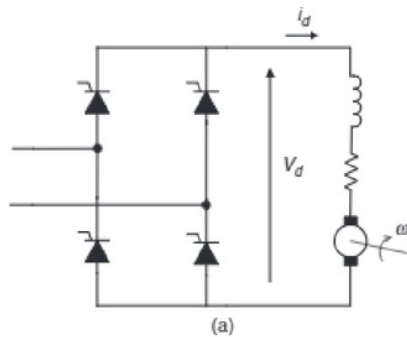


Figure 3.8 – (a) Two-Quadrant Drive (Rashid, 2011)

By adding an additional rectifier circuit connected back to back at the d.c. terminals of the motor, four quadrant operation can be achieved.

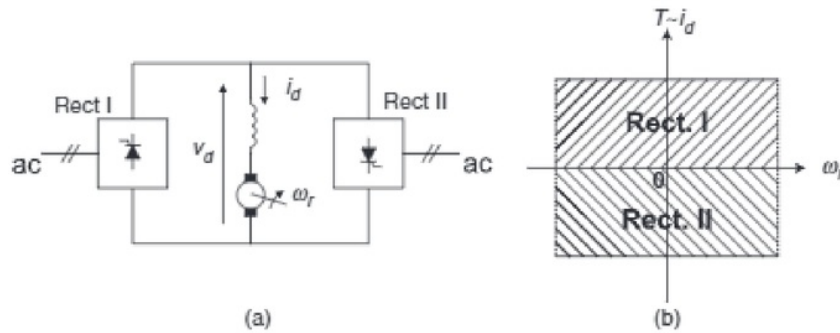


Figure 3.9 – (a) Two Rectifier Circuit Configuration (b) Four Quadrants of Operation (Rashid, 2011)

Quadrant (3) and (4) operate the same as (1) and (2) just in the opposite direction.

“This arrangement, known as a dual converter configuration, allows four-quadrant operation of the drive. Rectifier I provides positive load current, while rectifier II provides negative load current. The motor can work in forward powering, forward braking (regenerating), reverse powering, and reverse braking (regenerating).” (Rashid, 2011, p. 191)

3.2.2.1 – Two-Quadrant Control – Field Reversal

In order to stop a two-quadrant drive from coasting to a lower speed, one method of using Quadrant (2) is to make the motor regeneratively brake. By reversing the field current and reducing the supply the motor will supply current back into the supply and brake. This however is a very slow method of control. (Wildi, 2006)

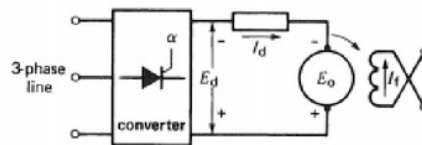


Figure 3.10 – Simplified Field Reversal (Wildi, 2006)

3.2.2.2 – Two-Quadrant Control – Armature Reversal

The time requirement for field reversal is undesirable for some industries, so an alternative is used which is reversing the armature current. This requires very fast switching and high current rated switches. (Wildi, 2006)

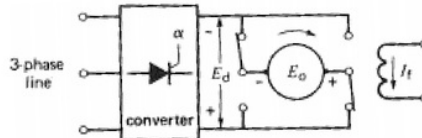


Figure 3.11 – Simplified Armature Reversal (Wildi, 2006)

3.2.3 – Digital Drives

Historically analog drivers have been used to drive motors. However, they have become slowly obsolete with the development of digital controllers. Digital controllers have opened up the possibility of using PWM inverter drives and Matrix converters. Speed control for digital drives can be very accurate with the use of shaft-mounted encoders that compare the speed with a reference frequency. This reference frequency can be made drift free and are much more flexible than analog drivers.

Some digital drivers are programmable allowing ramp-ups / downs, presets such as min / max speeds, and are controllable remotely. This may allow engineers to change speed / torque setpoints from a website, app or computer elsewhere. (Valentine, 1998)

3.3 – Three-Phase DC Drives vs. Single-Phase DC Drives

A three-phase bridge converter is almost identical to that of the single-phase, except it has an extra branch of thyristors. The extra phases and the extra branch of thyristors vastly improves the average voltage, and ripple of the output.

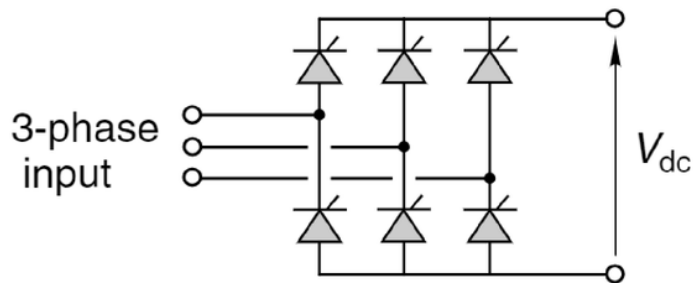


Figure 3.12 – Three-Phase, Fully-Controlled Thyristor Converter (Hughes, 2006)

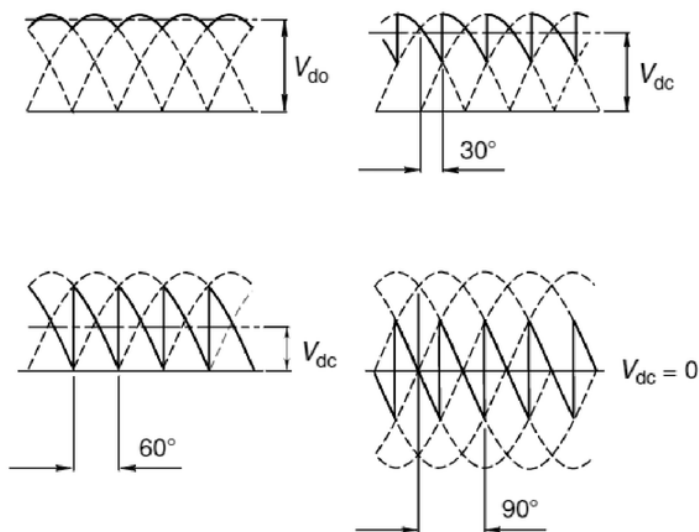


Figure 3.13 – Output Waveforms for Firing Angles 30° , 60° and 90° of an Inductive Load (Hughes, 2006)

As shown in **Figure 3.13** there are six pulses of the output per mains cycle. Just like the single-phase converter the thyristors are fired in pairs and the firing angle controls the output voltage. The use of a three-phase drive also means that the motor is more likely to draw a continuous current. “Under continuous current conditions the torque is constant and the output voltage waveform solely depends on the Firing Angle and not on the actual impedance” of the motor. (Hughes, 2006, p. 60) This makes three-phase d.c. drives much more reliable than single phase.

Three-phase d.c. drives will be able to provide a much higher speed range due to the low ripple and high average voltage. Once the firing angle exceeds 90° the average voltage drops to 0 however, and if it exceeds 90° the average voltage becomes negative. Three-phase d.c. drives also have higher efficiency due to the exact amount of current / voltage being drawn to meet the motor's speed / torque requirements.

The use of a brushless d.c. motor can cut down on maintenance as the absence of brushes means there are less sliding mechanical contacts which will save time and money on maintenance.

4 – Simulation

4.1 – Deriving Formula

The average voltage formula derivation for single / three phase full wave fully controlled circuits with inductive loads can be found below.

$$\alpha = \frac{t_2}{8ms} \times \pi(rad)$$

$$\beta = \frac{t_1}{8ms} \times \pi(rad) \quad (50Hz = 10ms, 60Hz = 8ms)$$

4.2 – Single-Phase Average Voltage Formula

4.2.1 – Continuous Current

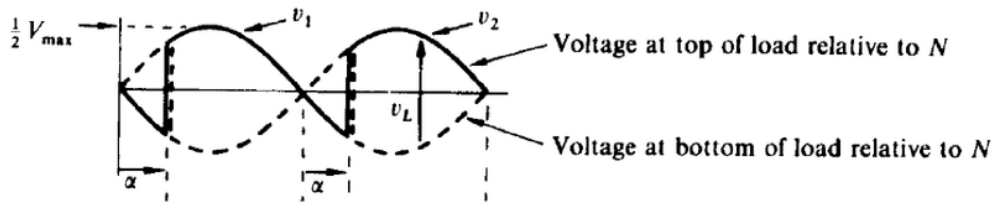


Figure 4.1 – Single-Phase Continuous Current Waveform (Lander, 1993)

To derive the average voltage the area under the curve from α to $\pi + \alpha$ must be found;

$$\begin{aligned} V_{mean} &= \frac{1}{\pi} \int_{\alpha}^{\pi + \alpha} V_{max} \sin(\theta) d\theta \\ &= \frac{1}{\pi} [-V_{max} \cos(\theta)]_{\alpha}^{\pi + \alpha} \\ &= \frac{V_{max}}{\pi} [-\cos(\pi + \alpha) - (-\cos(\alpha))] \\ &\text{Since } \cos(\pi + \alpha) = -\cos(\alpha) \\ \therefore V_{mean} &= \frac{V_{max}}{\pi} = [-(-\cos(\alpha)) + \cos(\alpha)] \\ \therefore V_{mean} &= \frac{2V_{max}}{\pi} \cos(\alpha) \end{aligned}$$

4.2.2 – Discontinuous Current

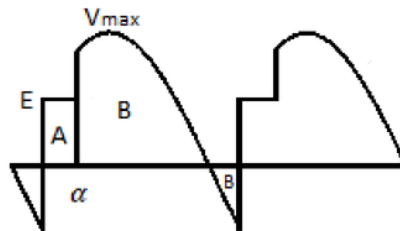


Figure 4.2 – Single-Phase Discontinuous Current Waveform (Kenjo, 1991)

The same must be done here but the back EMF must be accounted for.

$$\begin{aligned}
 \text{Area } A &= E(\alpha - \beta) \\
 \text{Area } B &= \int_{\alpha}^{\pi+\beta} V_{max} \sin(\theta) d\theta \\
 &= V_{max}[-\cos(\theta)]_{\alpha}^{\pi+\beta} = V_{max}[-\cos(\pi + \beta) - -\cos(\alpha)] \\
 &= V_{max}[\cos(\beta) + \cos(\alpha)] \\
 \therefore V_{mean} &= \frac{E(\alpha - \beta) + V_{max}(\cos(\beta) + \cos(\alpha))}{\pi}
 \end{aligned}$$

4.3 – Three-Phase Average Voltage Formula

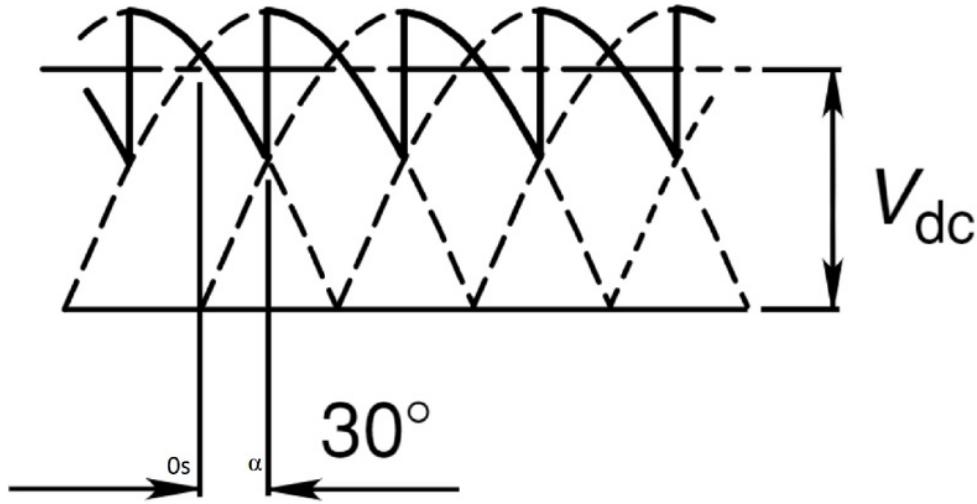


Figure 4.3 – Three-Phase Fully Controlled Waveform (Hughes, 2006)

To find α , time must be measured from when the phases cross over to the first firing angle on the waveform. In order to derive the average voltage formula, between $\frac{\pi}{3} + \alpha$ and $\frac{2\pi}{3} + \alpha$ need to be integrated over an average of $\frac{\pi}{3}$ rads.

$$\begin{aligned}
 V_{mean} &= 1/\left(\frac{\pi}{3}\right) \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} V_{max(line)} \sin(\theta) d\theta \\
 &= \frac{3V_{max(line)}}{\pi} [-\cos(\theta)]_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha}
 \end{aligned}$$

$$\begin{aligned}
&= \frac{3V_{\max(\text{line})}}{\pi} \left[-\cos\left(\frac{2\pi}{3} + \alpha\right) - -\cos\left(\frac{\pi}{3} + \alpha\right) \right] \\
&\cos(A + B) = \cos(A)\cos(B) - \sin(A)\sin(B) \\
&\therefore \cos\left(\frac{\pi}{3} + \alpha\right) = \cos\left(\frac{\pi}{3}\right)\cos(\alpha) - \sin\left(\frac{\pi}{3}\right)\sin(\alpha) \\
&\quad = \frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha) \\
&\text{and; } \cos\left(\frac{2\pi}{3} + \alpha\right) = \cos\left(\frac{2\pi}{3}\right)\cos(\alpha) - \sin\left(\frac{2\pi}{3}\right)\sin(\alpha) \\
&\quad = -\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha) \\
&\therefore V_{\text{mean}} = \frac{3V_{\max(\text{line})}}{\pi} \left[-\left(-\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)\right) + \left(\frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)\right) \right] \\
&\quad 3V_{\max(\text{line})} \left[\frac{1}{2}\cos(\alpha) + \frac{\sqrt{3}}{2}\sin(\alpha) + \frac{1}{2}\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha) \right] \\
&\quad \text{Simplified:} \\
&\quad V_{\text{mean}} = \frac{3V_{\max(\text{line})}}{\pi} \cos(\alpha)
\end{aligned}$$

From this derivation it can be seen that if $\alpha = 90^\circ$, $V_{\text{mean}} = 0V$ and that when $\alpha > 90^\circ$, $V = \text{negative}$. This confirms the theory discussed in **Section 3.3**.

4.4 – Single-Phase, Full Wave, Fully Controlled Simulation

All the simulations have a 240V 60Hz supply and a 100mH inductive load with 10Ω resistance and 100V back EMF.

4.4.1 – Continuous Current Simulation

The firing angle for this simulation was 50° so that the output would have continuous current.

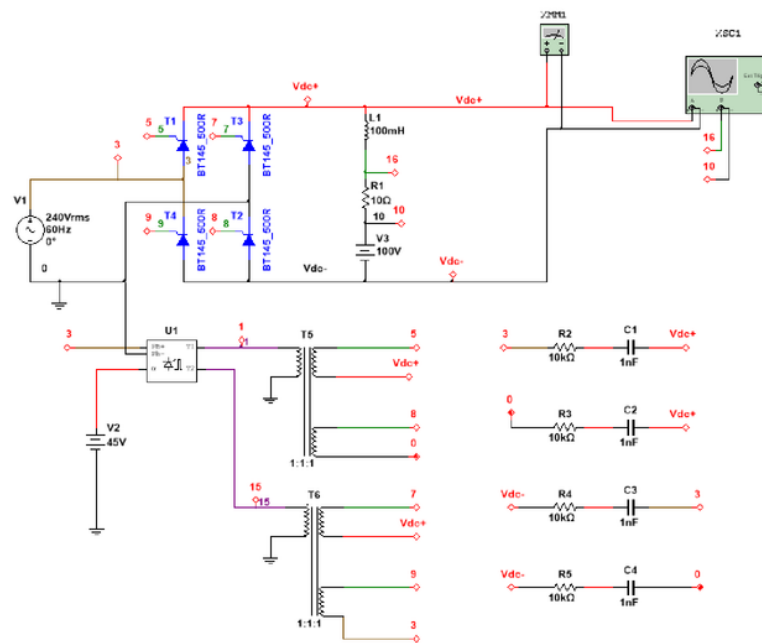


Figure 4.4 – Single-Phase Continuous Current Simulation

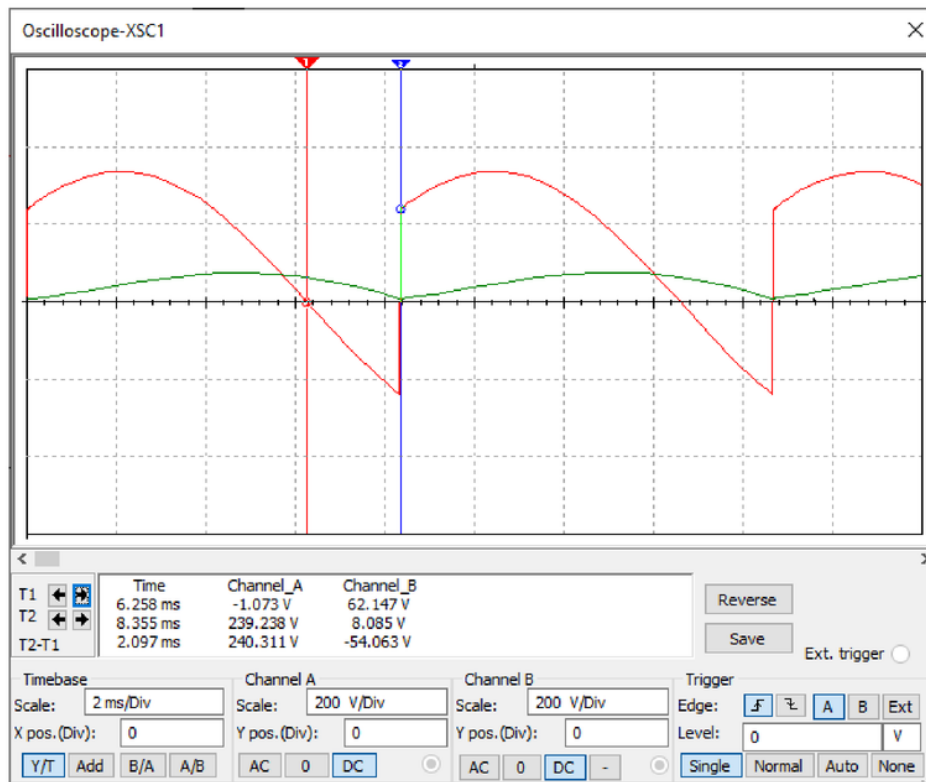


Figure 4.5 – Single-Phase Continuous Current Output Waveform

Firing Angle $\alpha = 50^\circ$

$$\alpha = \frac{2.097}{8} \times \pi = 0.823$$

$$V_{\max} = 337.21V$$

$$\therefore V_{\text{mean}} = \frac{2 \times 337.21}{\pi} \cos(0.823) = 145.99V$$

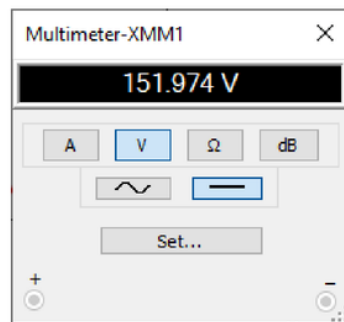


Figure 4.6 – Single-Phase Continuous Current, Average Armature Voltage

4.4.2 – Discontinuous Current Simulation

The firing angle was made 70° for this simulation to have discontinuous current.

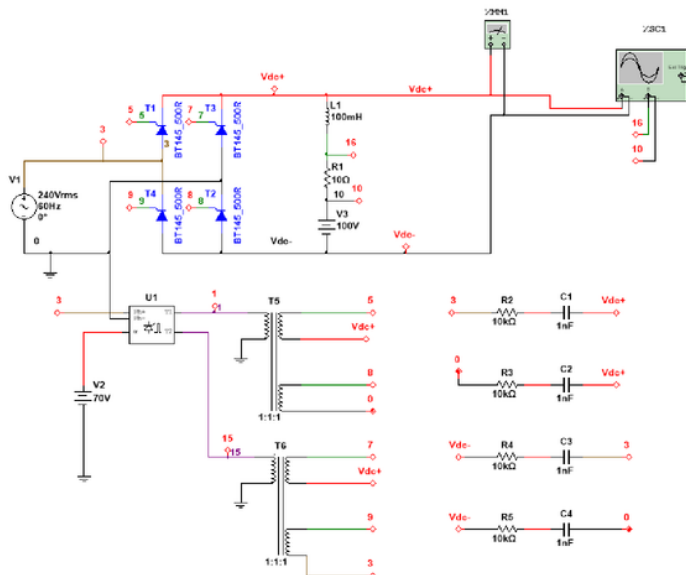


Figure 4.7 – Single-Phase Discontinuous Current Simulation

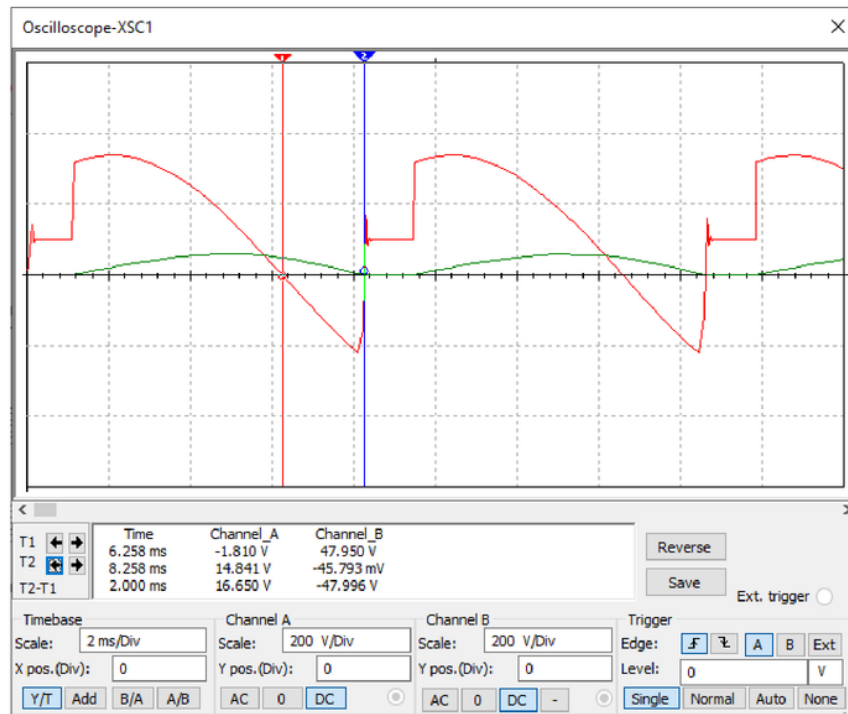


Figure 4.8 – Single-Phase Discontinuous Current Simulation Output Waveform with t_2

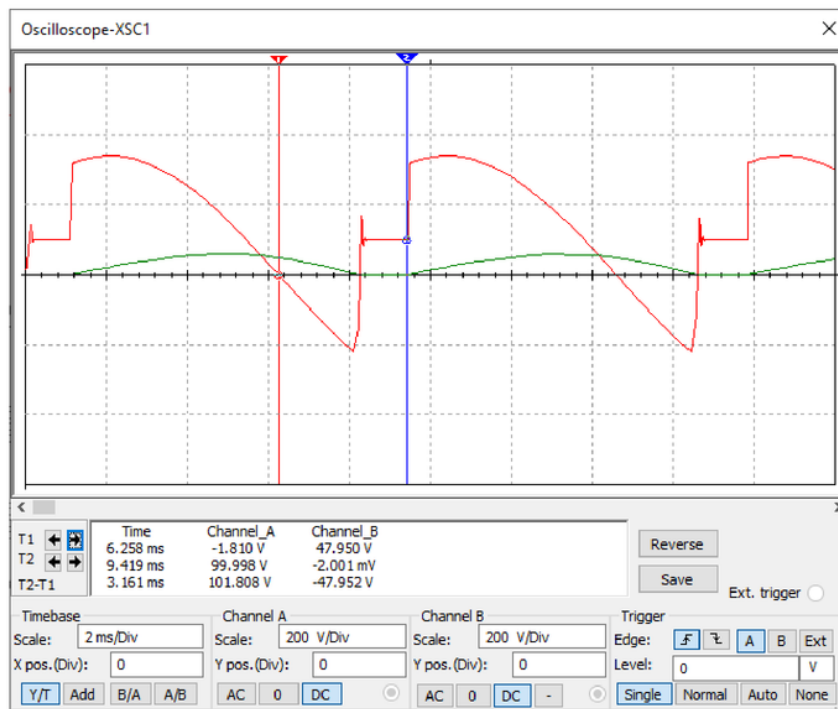


Figure 4.9 – Single-Phase Discontinuous Current Output Waveform

Firing Angle $\alpha = 70^\circ$

$$\alpha = \frac{2}{8} \times \pi = 1.24$$

$$\beta = \frac{3.161}{8} \times \pi = 0.785$$

$$V_{\max} = 339.387V$$

$$V_{\text{mean}} = \frac{100(1.24 - 0.785) + 339.38(\cos(0.785) + \cos(1.24))}{\pi} = 125.99V$$

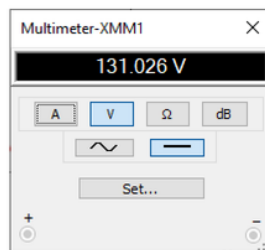


Figure 4.10 – Single-Phase Discontinuous Current, Average Armature Voltage

4.5 – Three-Phase, Full Wave, Fully Controlled Simulation

A Firing angle of 30° was used for this simulation.

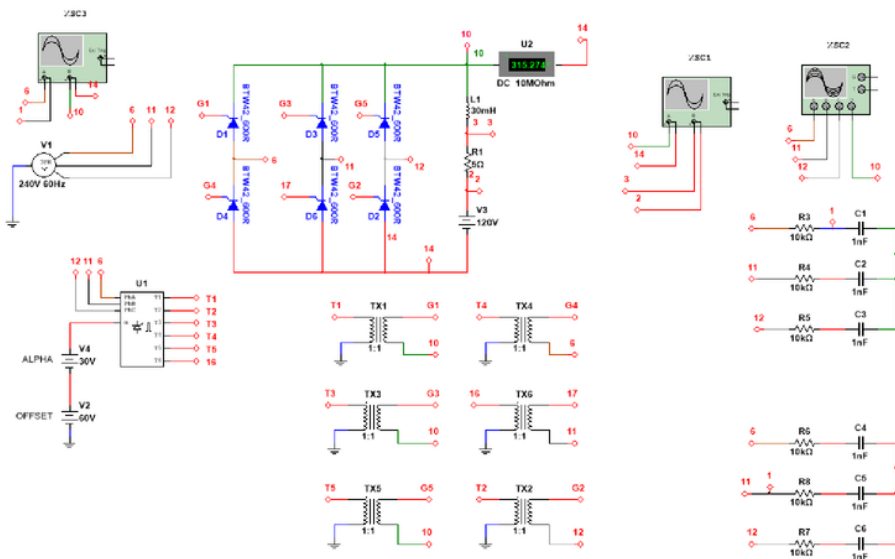


Figure 4.11 – Three-Phase, Full Wave, Fully-Controlled Circuit Simulation with 30° Firing Angle

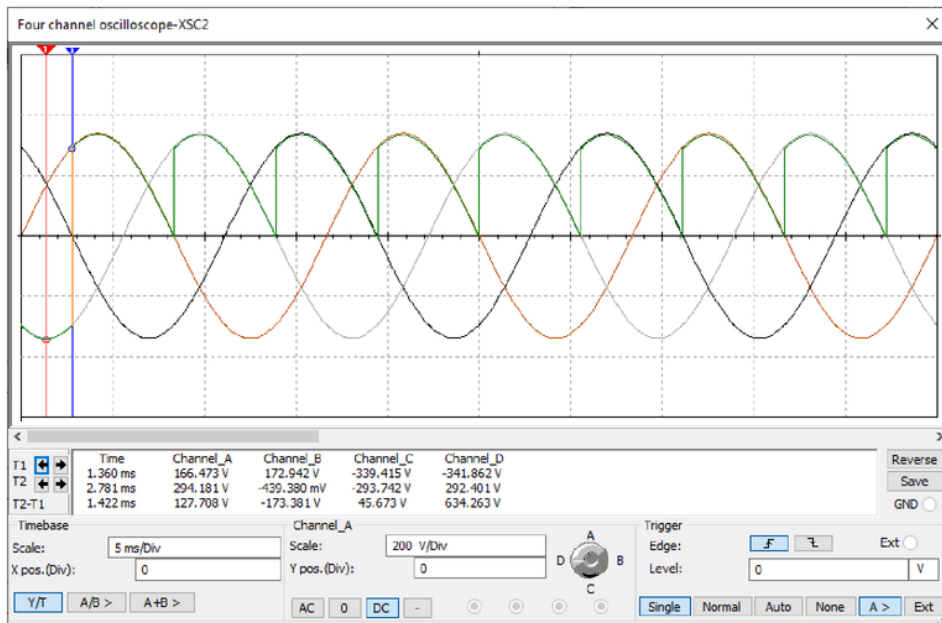


Figure 4.12 – Three-Phase Output Waveform

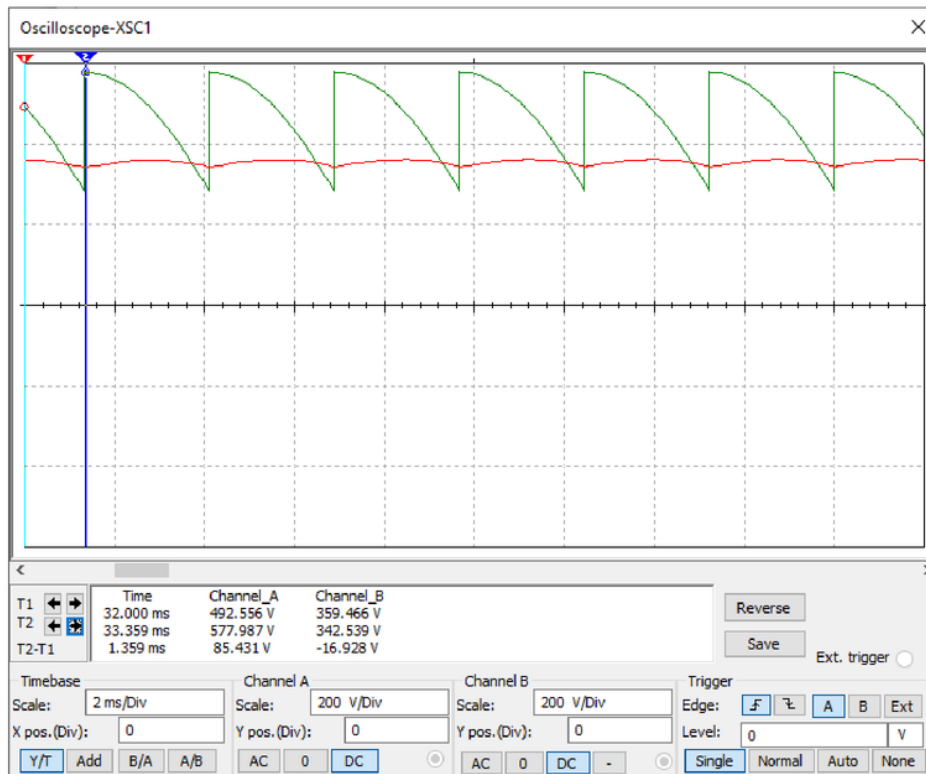


Figure 4.13 – Three-Phase Average Output Voltage Waveform

The firing angle used for this simulation was 30° with an offset of 60°. This is to allow measurement from the phase crossover at 60Hz.

$$\alpha = \frac{1.422}{8} \times \pi = 0.558$$

$$V_{mean} = \frac{3 \times 577.987}{\pi} \cos(0.558) = 468.21V$$

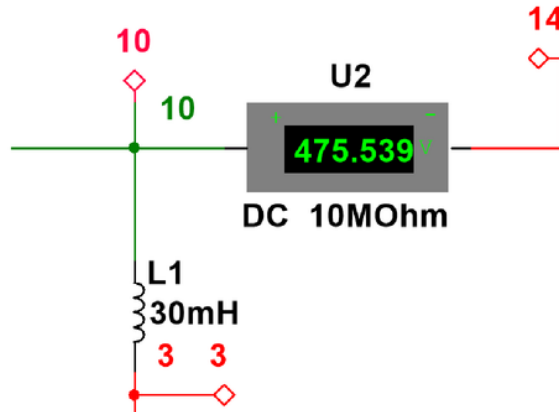


Figure 4.14 – Three-Phase Average Armature Output Voltage for 30° Firing Angle

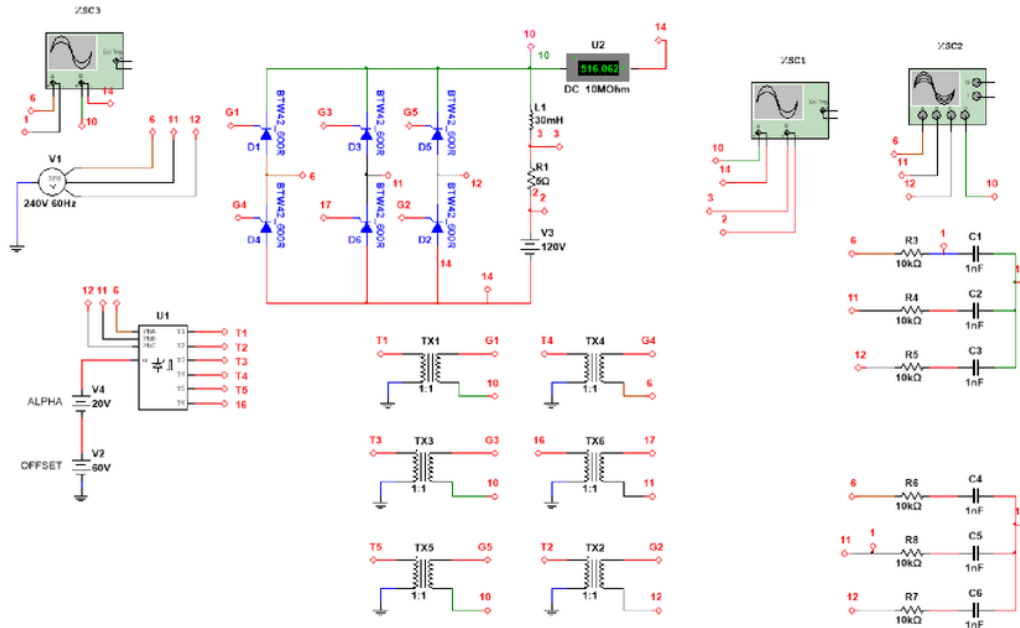


Figure 4.15 – Three-Phase, Full Wave, Fully-Controlled Circuit Simulation with 20° Firing Angle

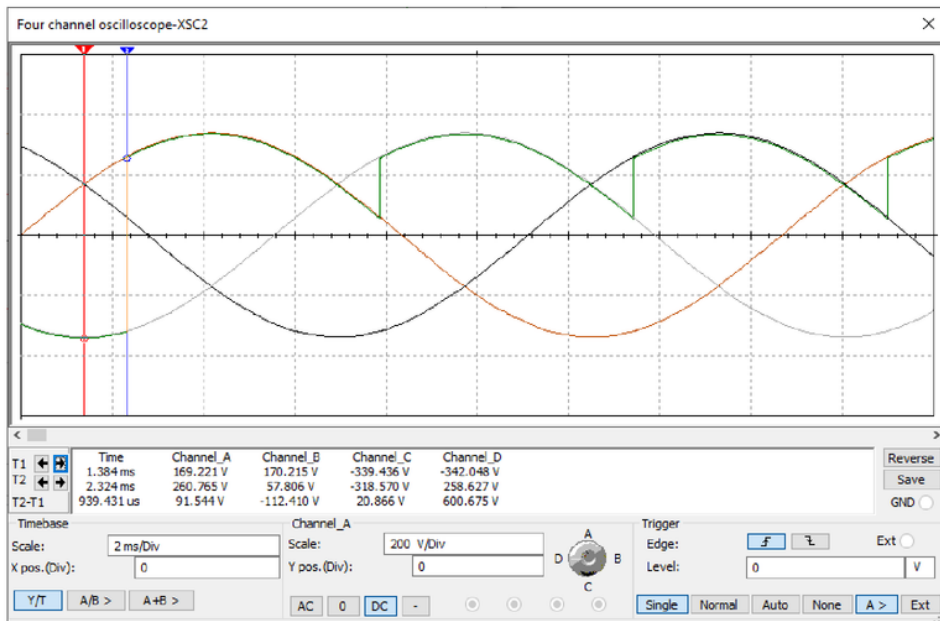


Figure 4.16 – Three-Phase Output Waveform

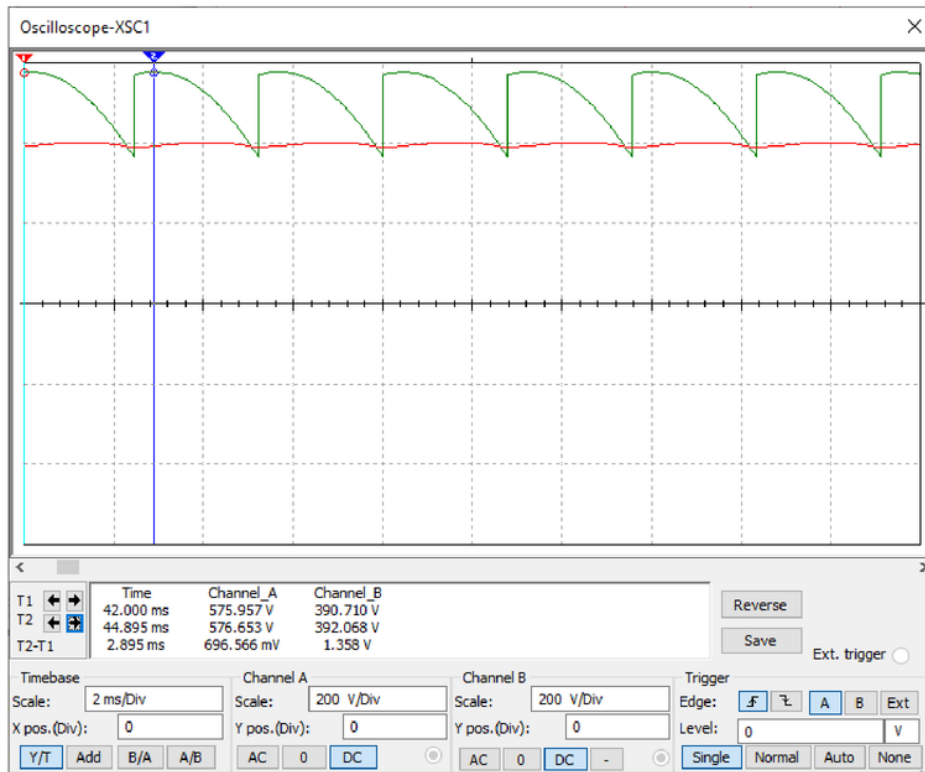


Figure 4.17 – Three-Phase Average Output Voltage Waveform

$$\alpha = \frac{939.431\mu s}{8ms} \times \pi = 0.369$$

$$V_{mean} = \frac{3 \times 576.653}{\pi} \cos(0.369) = 513.597V$$

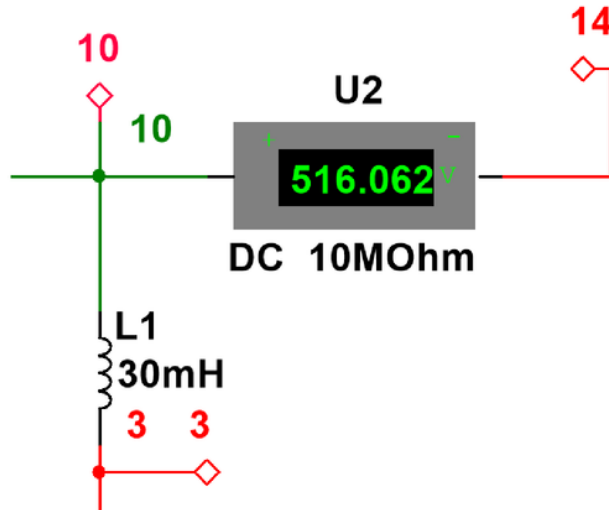


Figure 4.18 – Three-Phase Average Armature Output Voltage for 20° Firing Angle

4.6 – System Comparisons

Firing Angle / Phase	Average Voltage Simulated	Calculated
50° Single-Phase	152V	145.9V
70° Single-Phase	131V	125.9V
30° Three-Phase	475V	468.2V
20° Three-Phase	516V	513.6V

Firstly, when increasing the firing angle of Single-Phase the voltage decreases, and when decreasing the firing angle of Three-Phase the voltage increases. These are both expected results as a larger firing angle means a larger delay before the thyristor is pulsed and turned on to conduct.

The next observation is that the Three-Phase average voltages are significantly higher than that of the Single-Phase. Once again this confirms the research done in **Section 3**. This means that the speeds obtainable by Three-Phase drives are much higher than that of Single-Phase drives.

Additionally, the Three-Phase output waveforms show that the current is a lot more constant and is safely continuous whereas the Single-Phase output waveforms show that there is a danger of the current becoming discontinuous. Even for when the firing angle is at 50° the current is very low and close to reaching 0. This shows that Three-Phase drives are a lot more reliable when it comes to required torque than Single-Phase.

When the current becomes discontinuous in the Single-Phase simulation, it can be seen that the back EMF from the inductor is working in opposition to the supply. The back EMF is shown to appear when the current reaches 0 and disappear when the current returns and the voltage waveform continues. What this means is because the load current (torque) has increased, there is a massive drop in voltage (speed) which results in this torque / speed curve. The dotted lines in **Figure 4.19** indicate the operation of continuous current for comparison.

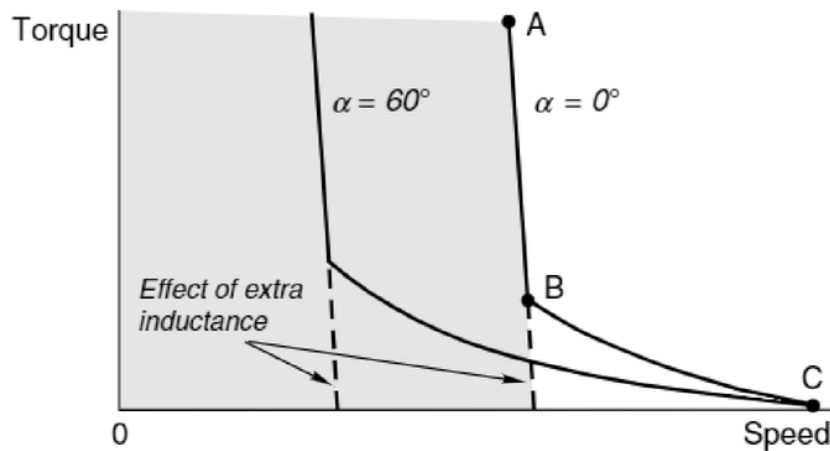


Figure 4.19 – Torque / Speed Curve for DCM (A. Emadi, 2006)

When comparing the calculated results to the simulated results it can be seen that they are all rather close to their simulated counterparts. Therefore, these circuits are accurate representations of how converter circuits operate as the theory backs up the simulated results.

There are however minor discrepancies between the two sets of results. These could be caused by not using the most ‘theoretically perfect’ thyristors in the simulation, rounding errors within calculation or inaccuracy with the cursor measurements as they were done by eye and can only be moved set increments across the x-axis.

5 – Practical Experiments

5.1 – Practical Setup

This practical involves a Parker 514C Driving a d.c. motor in the following setup:

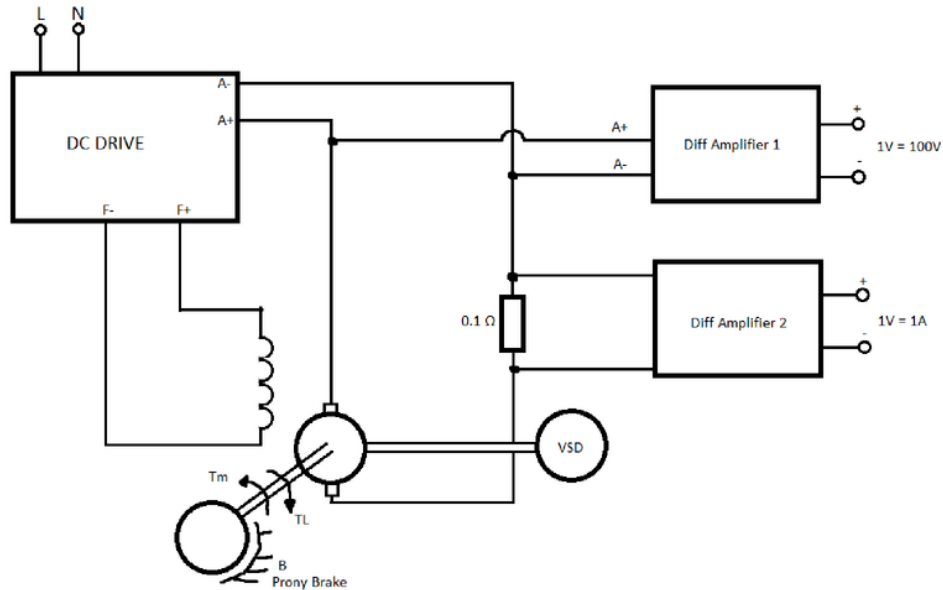


Figure 5.1

The d.c. motor is connected to a feedback VSD drive, a prony brake and measuring instruments. Current and voltage are both measured using a picoscope to display the waveforms on a laptop. In order to do this the current and voltage are both scaled through differential amplifiers which allow the picoscope to read 1V as 100V, and 1V as 1A.

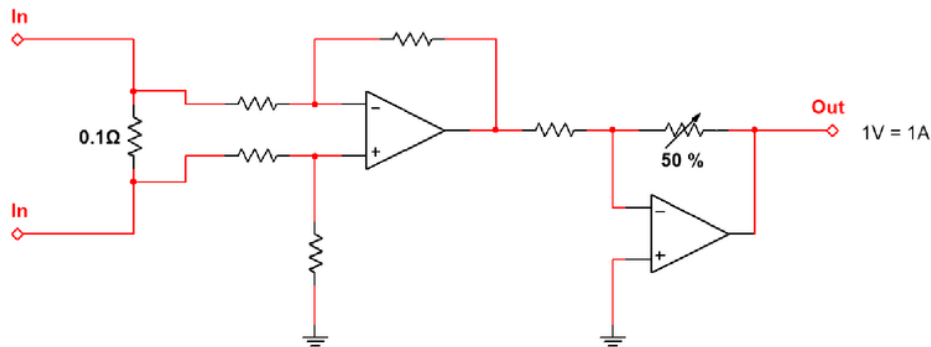


Figure 5.2 – Current Diff Amp

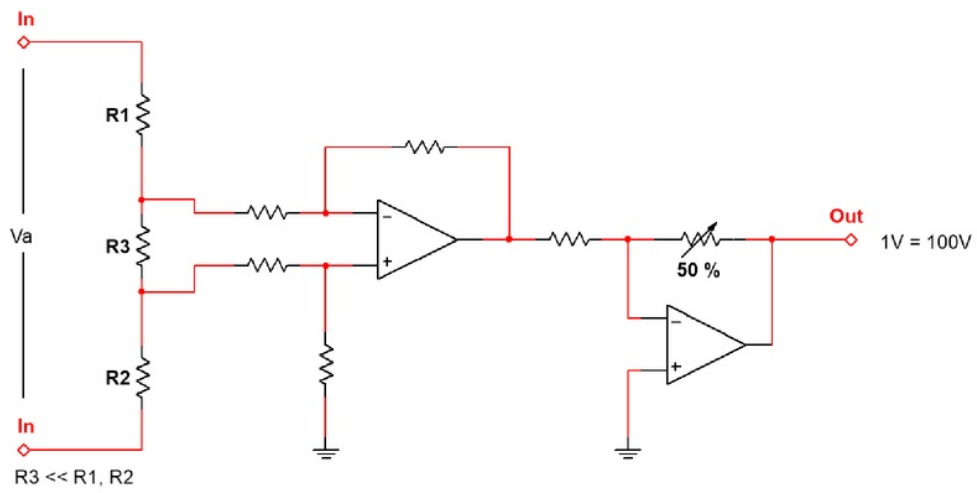


Figure 5.3 – Voltage Diff Amp



Figure 5.4 – Practical Setup

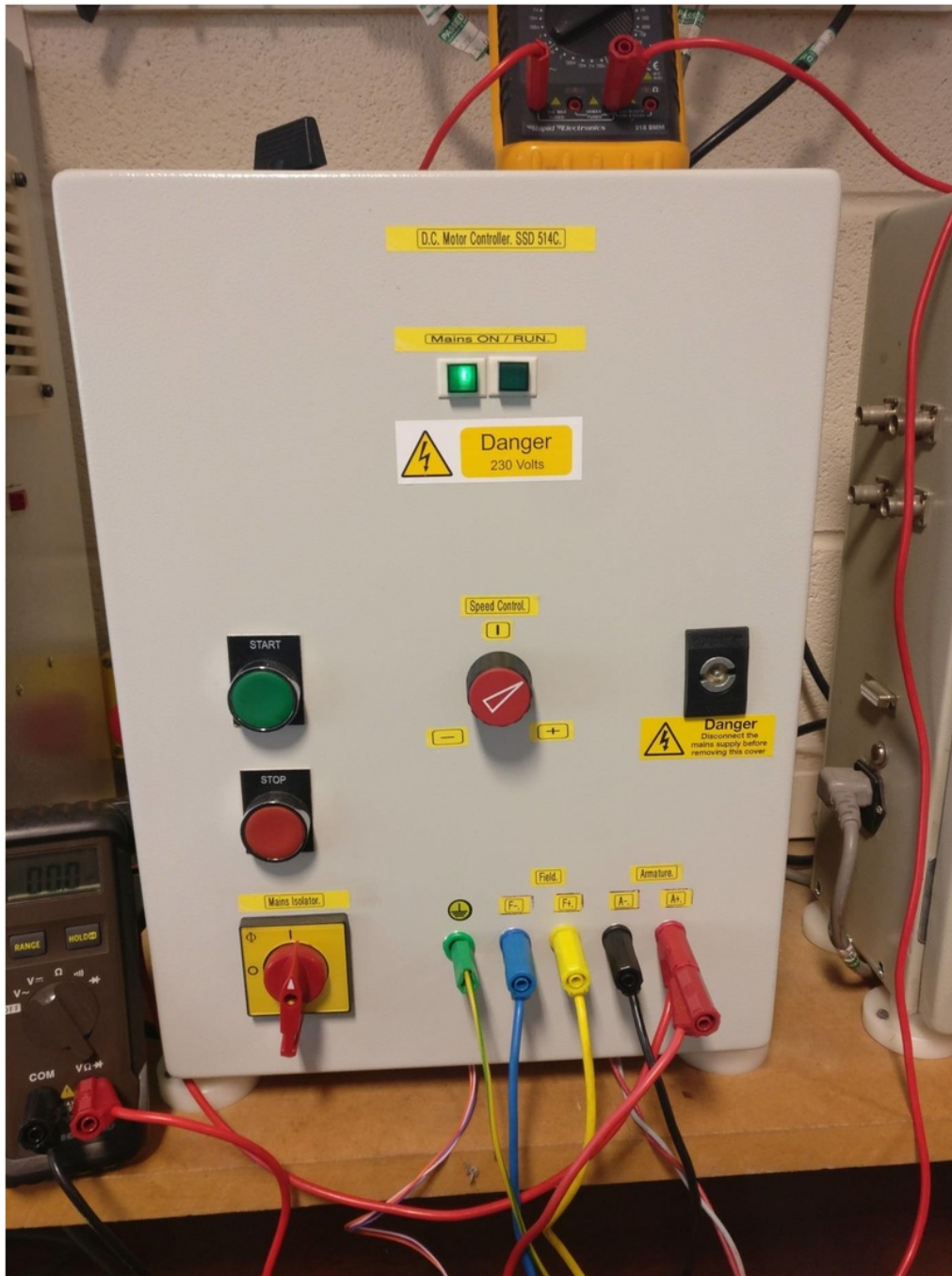


Figure 5.5 – DC Motor Controller 514 Panel



Figure 5.6 – VSD

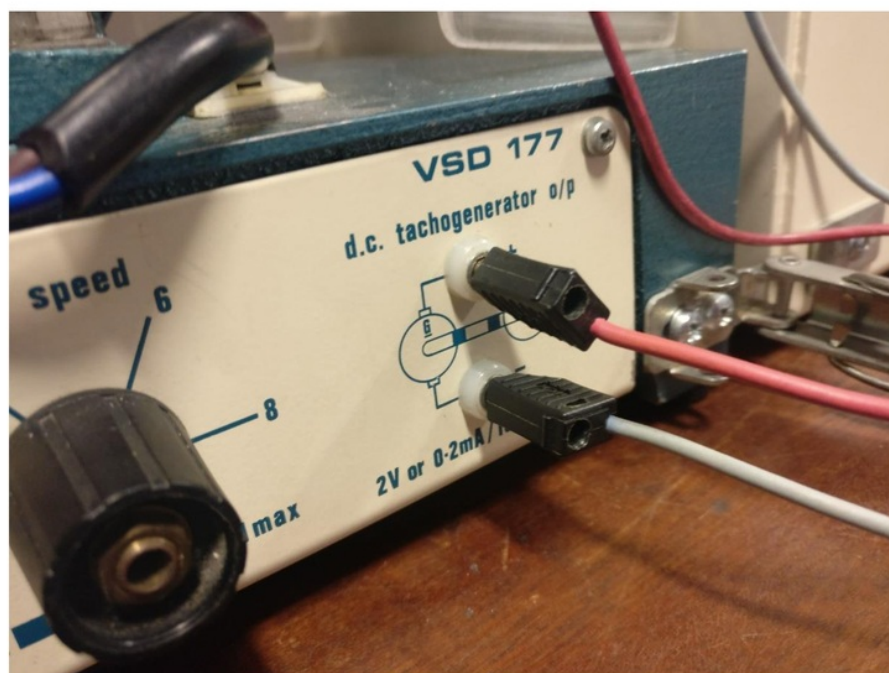


Figure 5.7 – Tachometer Connection

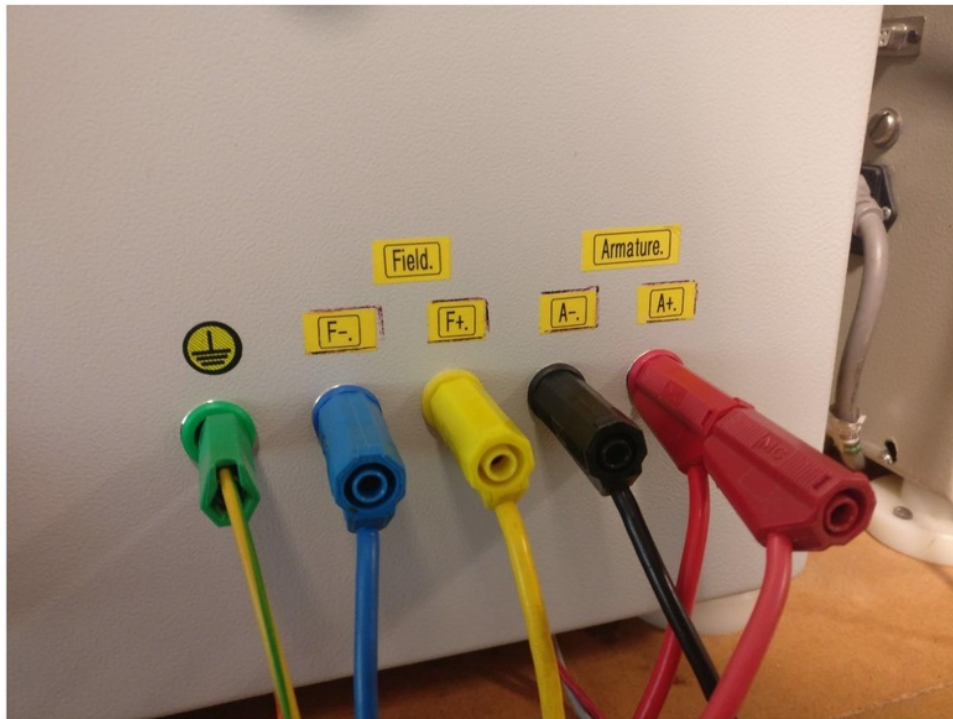


Figure 5.8 – Field and Armature Connections on Panel

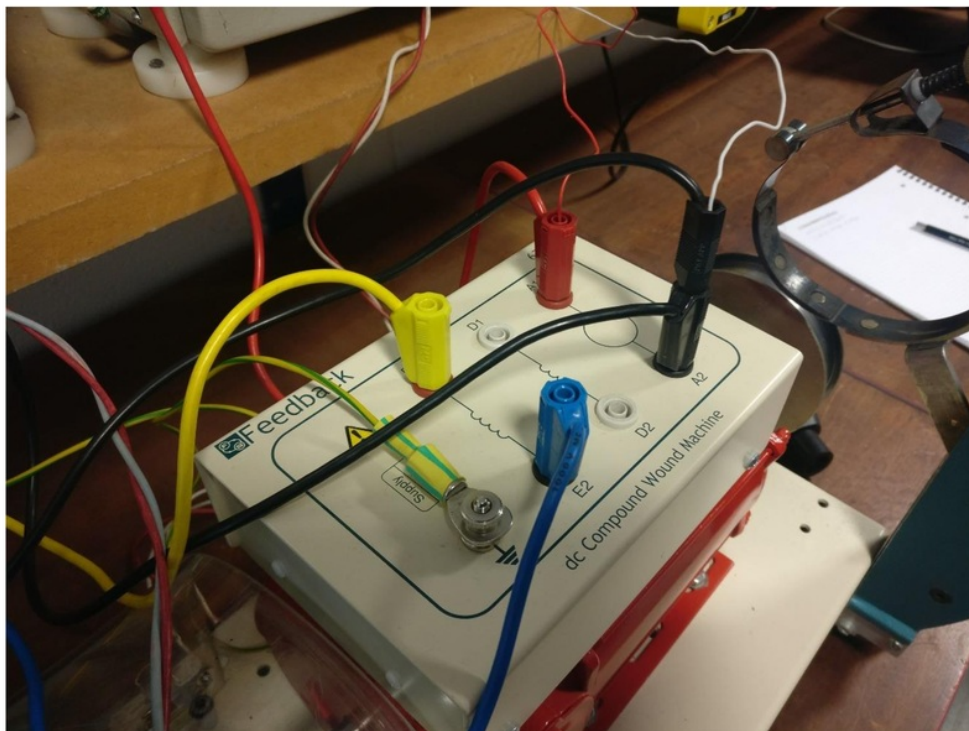


Figure 5.9 – Field and Armature Connections on Motor

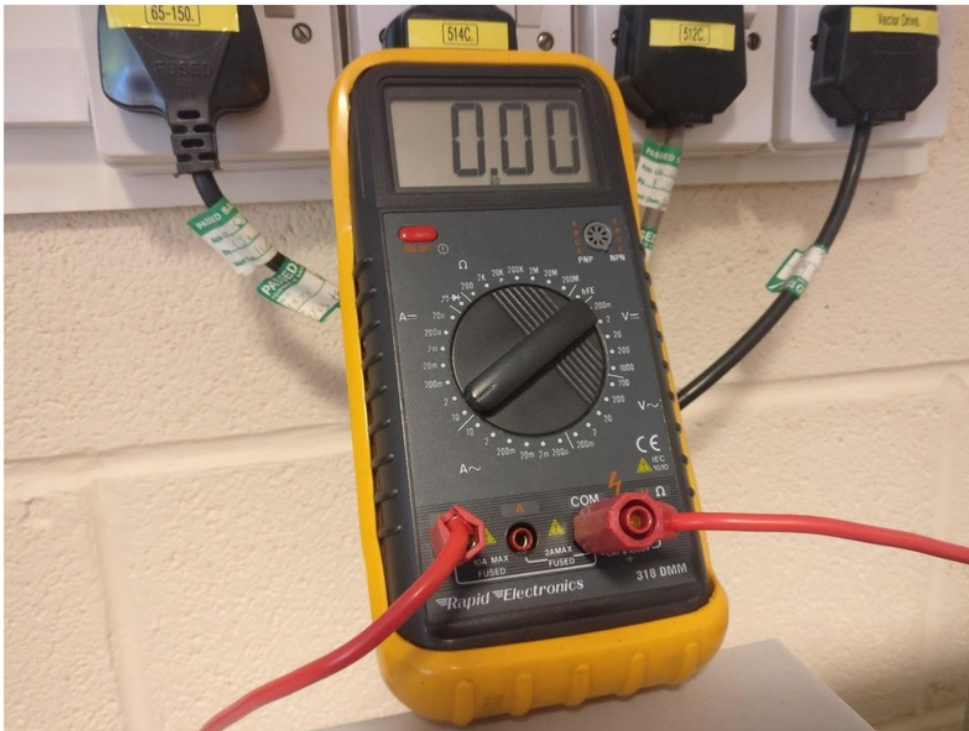


Figure 5.10 – Multimeter Set to Read Current

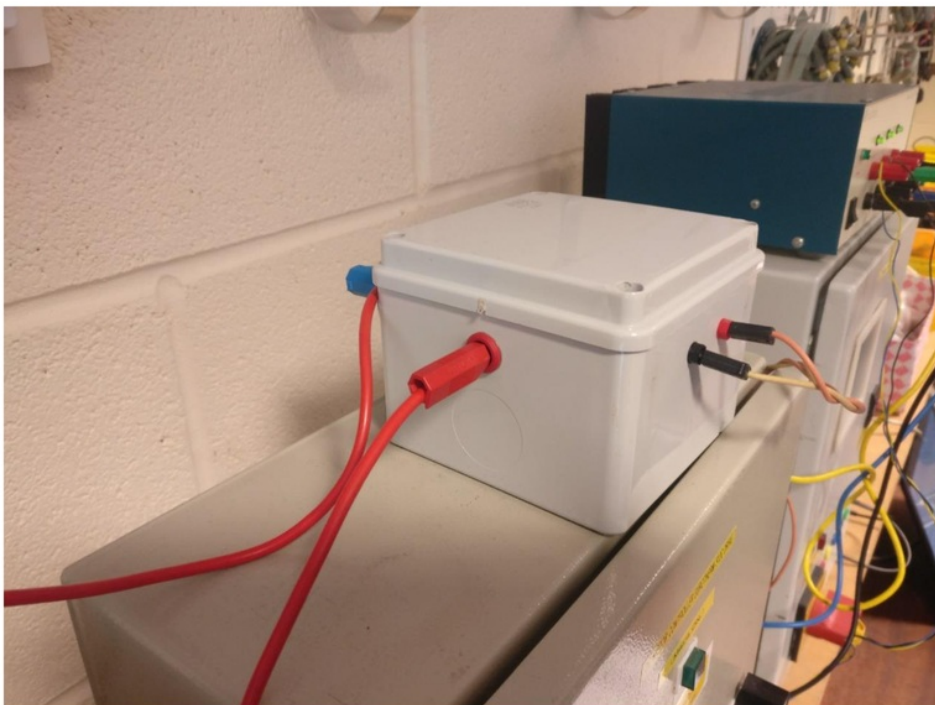


Figure 5.11 – Diff Amp



Figure 5.12 – Multimeter Set to Read Volts



Figure 5.13 – Picoscope

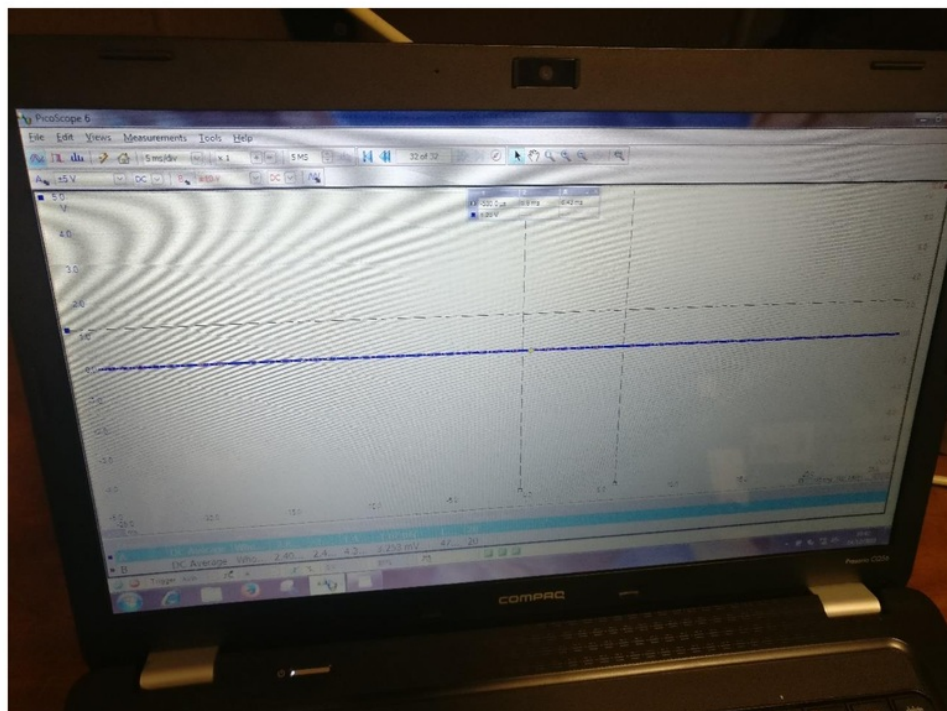


Figure 5.14 – Laptop Picoscope Interface



Figure 5.15 – Digital Tachometer

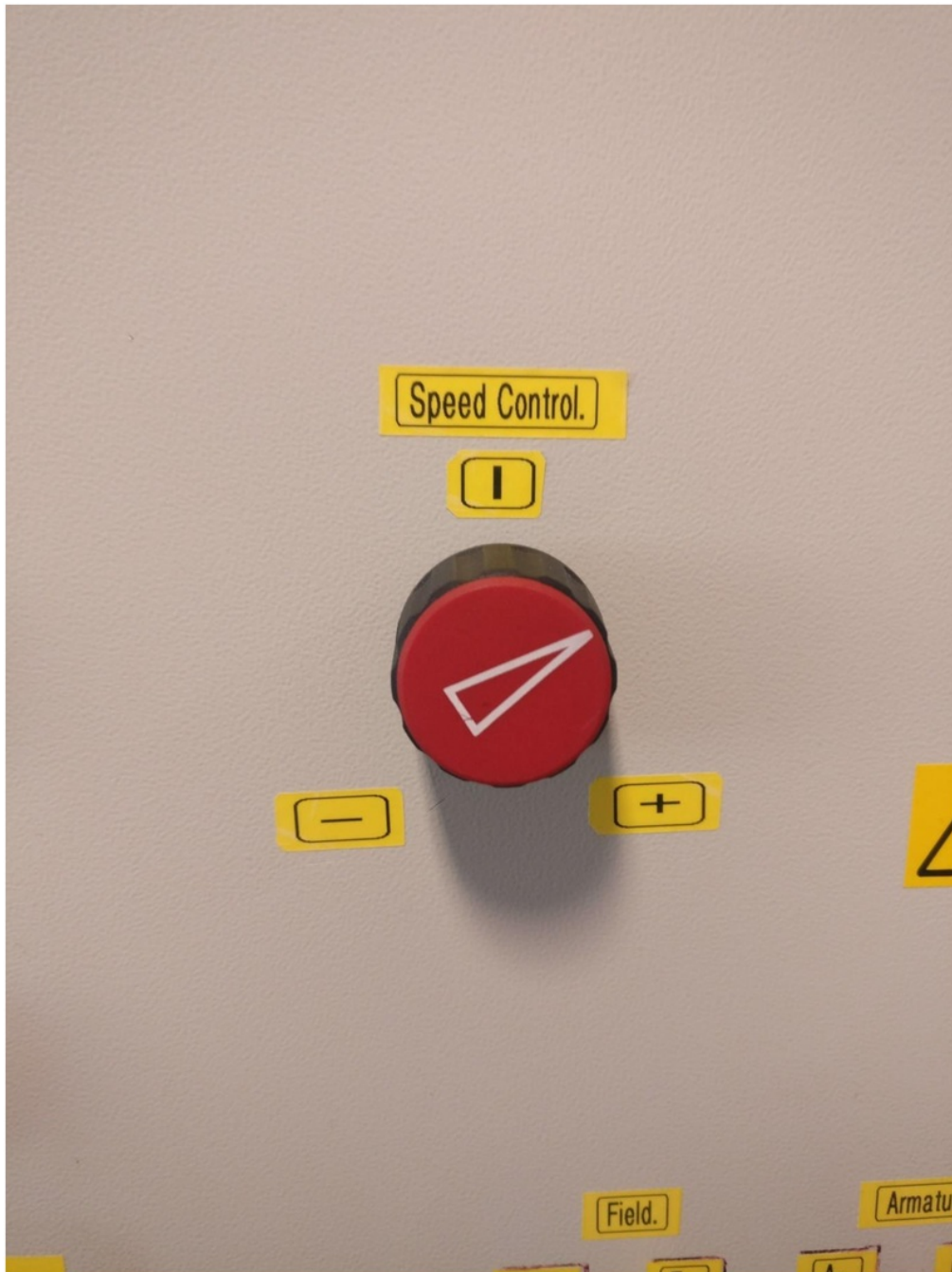


Figure 5.16 – Speed Setpoint Control



Figure 5.17 – Parker 514C Inside Panel

5.2 – Analysis of 514C Drive at Single Setpoint for Both Directions

The first task was to analyse how the motor operated for one speed setpoint showing discontinuous current in the forward direction with the VSD turned off. Measurements were taken of the current and voltage. The same was then be done in the reverse direction. Calculations were then done to compare with the measurements of the motor in the forward direction.

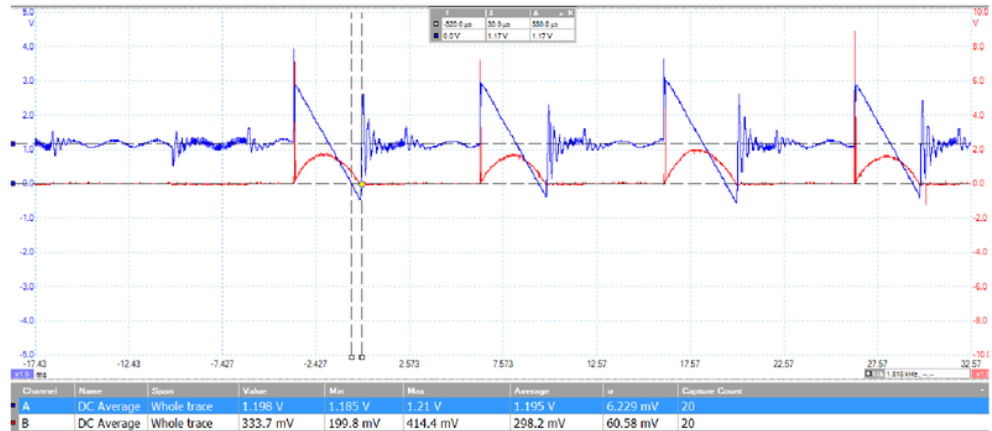


Figure 5.18 - Forward Direction Beta

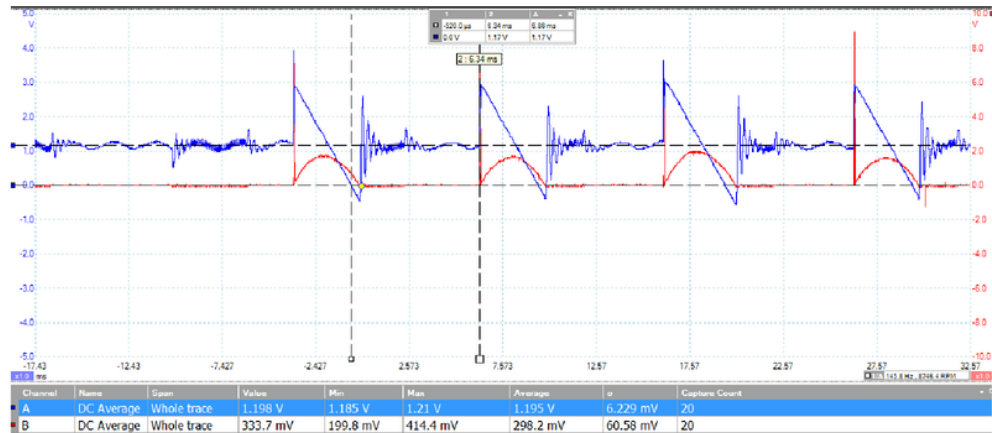


Figure 5.19 – Forward Direction Alpha

E(V)	$t_2(ms)$	$t_1(ms)$	$\beta(rad)$	$\alpha(rad)$	Multimeter (V/mA)		Picoscope (V/mA)		Calculated (V)
115V	6.86	0.550	0.173	2.155	119V	290	119.5	298	119.06

Speed = 1489rpm

$$\beta = \frac{0.55}{10} \times \pi = 0.173$$

$$\alpha = \frac{6.86}{10} \times \pi = 2.155$$

$$\therefore V_{mean} = \frac{115(2.155 - 0.173) + 337(\cos(0.173) + \cos(2.155))}{\pi} = 119.06V$$

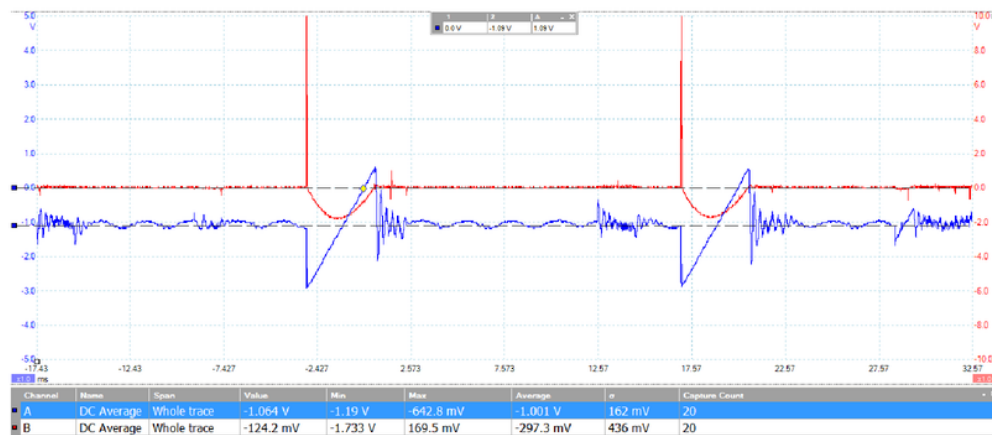


Figure 5.20 – Reverse Waveform

	Multimeter (V)	Picoscope (V)	Multimeter (mA)	Picoscope (mA)
Forward	119V	119.5V	290mA	298mA
Reverse	-101V	-100V	-293mA	-297mA

As shown in both **Figures 5.19** and **5.20**, the shape of the waveforms is identical but mirrored. This is because when the motor is moving in the reverse direction the voltage and current are made negative to produce speed and torque in the negative direction. The magnitude of the reverse voltage however is slightly lower of that of the forward voltage. This may be because of mains variance or the setpoint was changed before taking this reading by the operator. The multimeter readings and picoscope readings both directions correspond with each other which proves accuracy of the results. The calculation is also very close to the picoscope readings which further proves that the waveforms are accurate and follow theory.

The waveforms themselves show that there is discontinuous current in the form of the red line. The current remains at 0 for the majority of each cycle but has a small curve while the armature current is active. Because there is no load there is no requirement for high torque, which therefore means that the speed setpoint is met with a large firing angle. While the thyristors are off and the current is not flowing, the back EMF can be seen in the waveform.

The fact that this motor can operate in forward and reverse means that the 514C is a four-quadrant drive which means it has regenerative braking capabilities.

5.3 – Applying 3 Different Loads to 1 Speed Setpoint

0.6Nm, 1Nm and 1.5Nm loads were applied to the motor using a prony brake.

5.3.1 – 0.6Nm Load

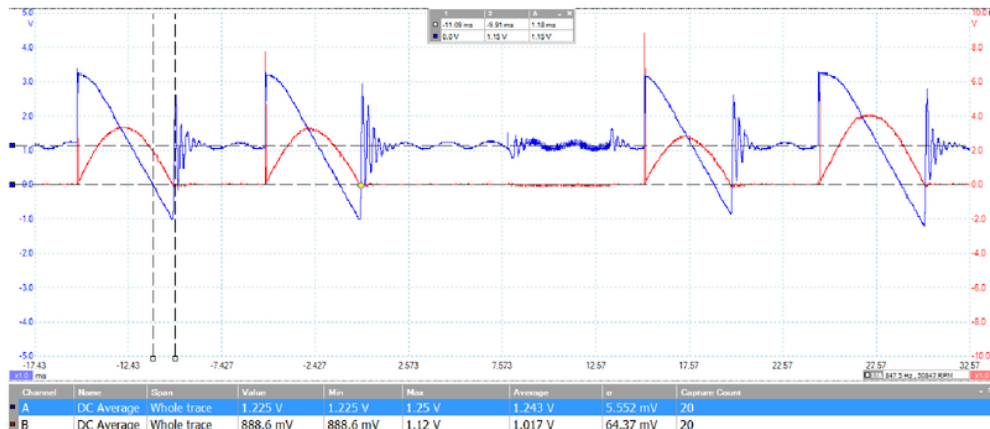


Figure 5.21 – 0.6Nm Load Beta

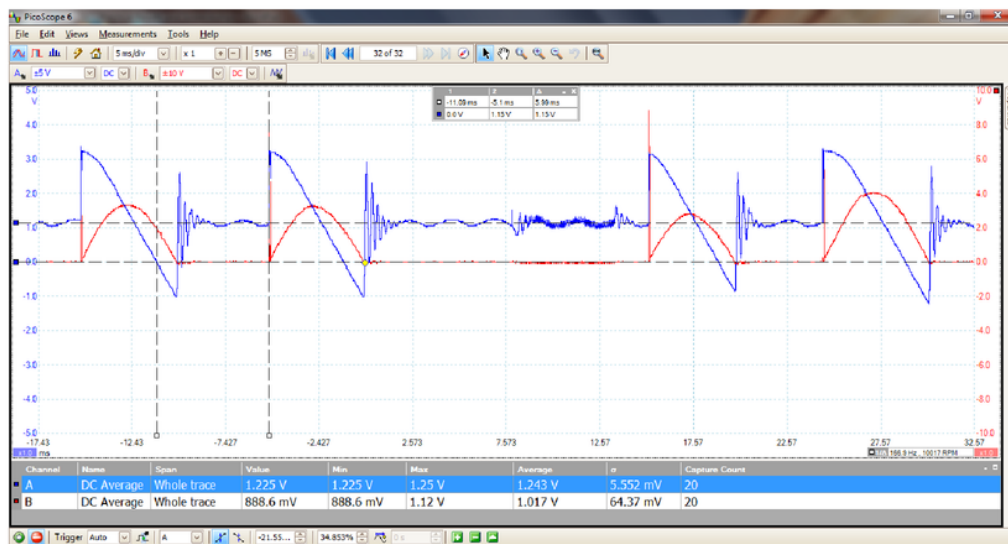


Figure 5.22 – 0.6Nm Load Alpha

5.3.2 – 1Nm Load

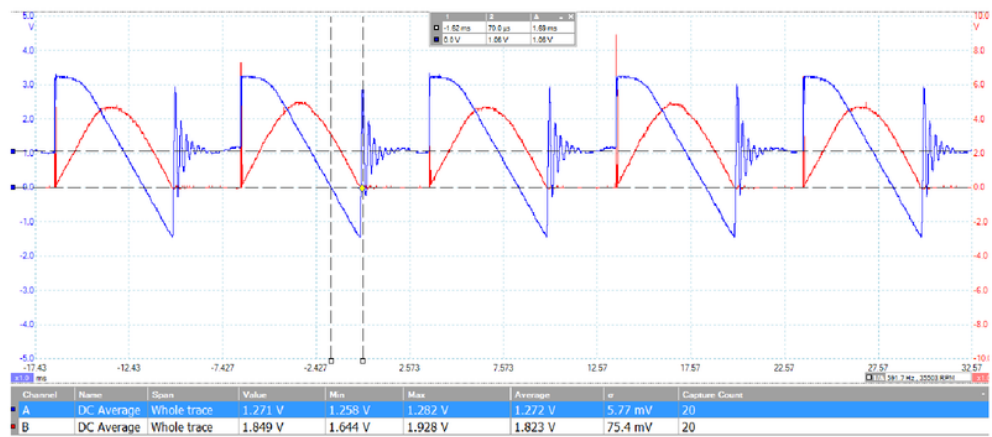


Figure 5.23 – 1Nm Load Beta

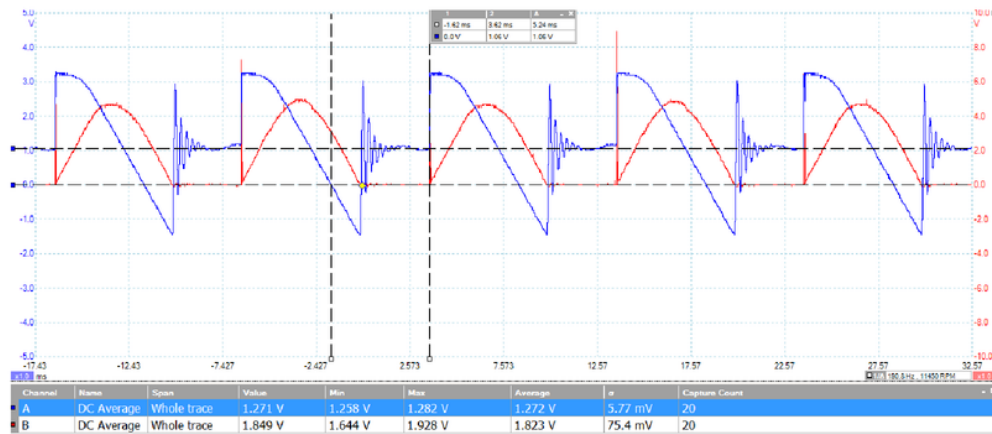


Figure 5.24 – 1Nm Load Alpha

5.3.3 – 1.5Nm Load

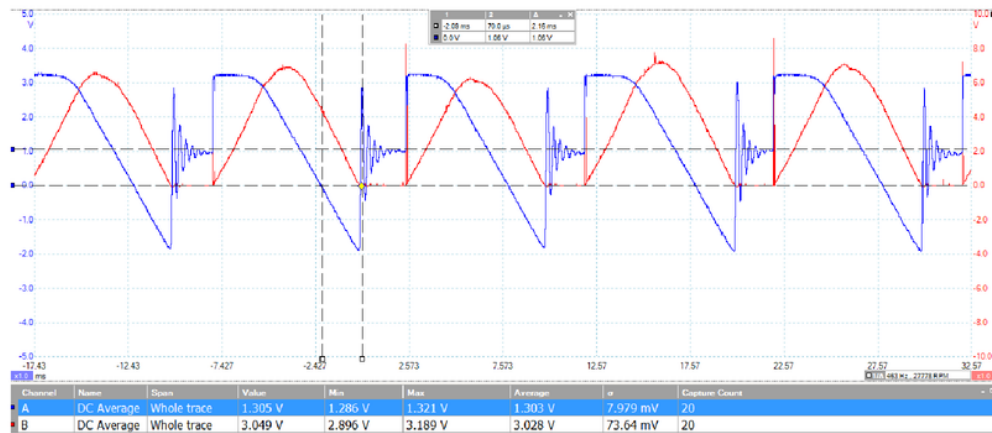


Figure 5.25 – 1.5Nm Load Beta

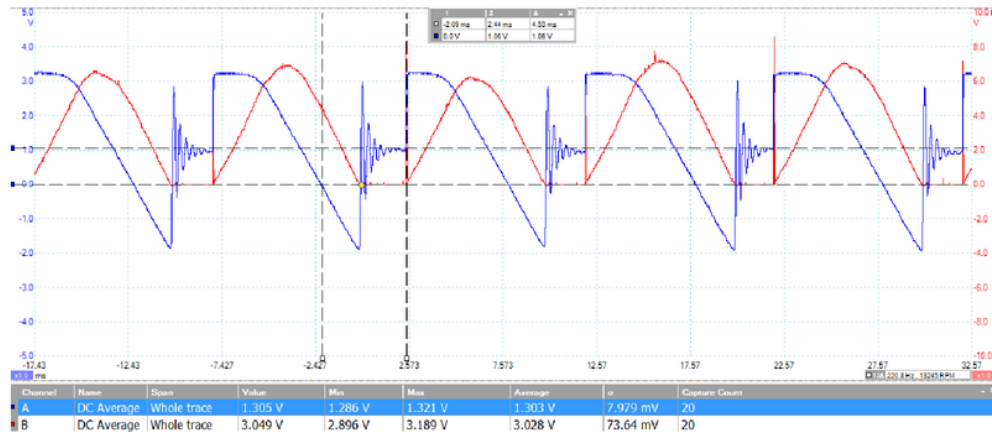


Figure 5.26 – 1.5Nm Load Alpha

Load	t_2 (ms)	t_1 (ms)	β (Rads)	α (Rads)	Multimeter (V)	Picoscope (V)	Multimeter (A)	Picoscope (A)
0.6Nm	1.8	5.99	0.56	1.88	126	124	1.1	1
1Nm	1.69	5.24	0.53	1.65	129	127	2	1.8
1.5Nm	2.16	4.53	0.67	1.42	131	130	3	3

Speed = 1607 rpm, 1603 rpm and 1599 rpm for each load respectively.

The most obvious change when increasing the load was the increase in current from 1A to 3A. This is an expected change as a larger load requires a larger torque to maintain the speed set point. The voltage also slightly increases. This is to compensate for the extra load slowing the motor down. The firing angles of the controller slowly decrease as the load is increased. This is because the controller is detecting a drop in speed and sends more volts to the armature to maintain the 1600 rpm setpoint.

The current however is still discontinuous which means the back EMF is still present. However, the increase in load decreased the amount of time the current was not flowing. By

increasing the load further continuous current could be achieved. This can almost be seen in **Figure 5.27** where the load was increased to 2Nm briefly.

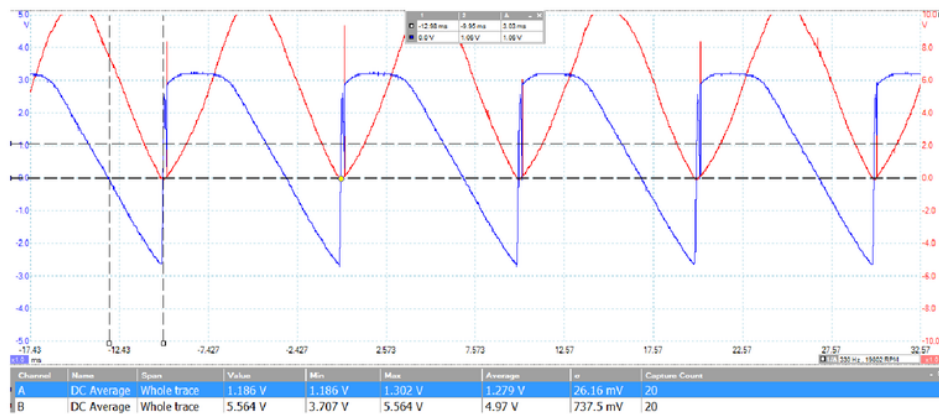


Figure 5.27 – 2Nm Load Continuous Current

Once again, the multimeter and picoscope readings are close and indicate that they are both accurate representations of what is actually happening within the system.

5.4 – VSD and Regenerative Braking

For this the feedback VSD drive is used to drive the d.c. motor in a regenerative braking region.

5.4.1 – VSD Speed Setting = 5

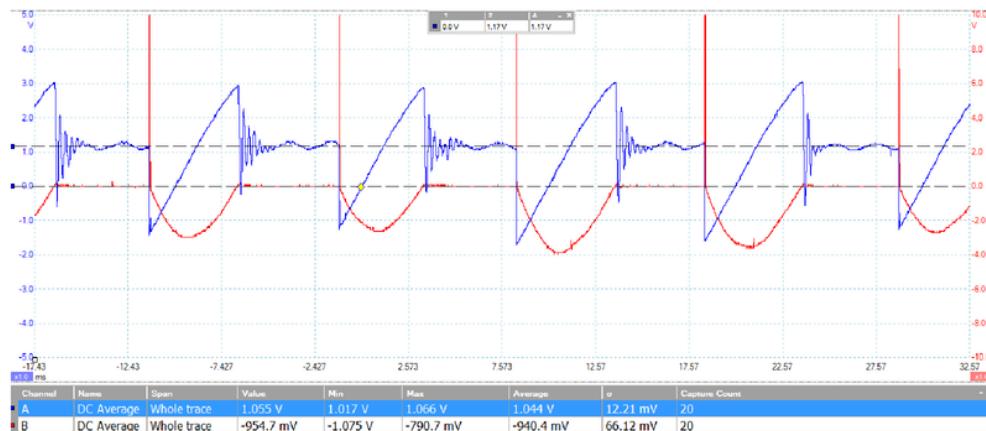


Figure 5.28 – VSD Speed Setting 5 Waveform

5.4.2 – VSD Speed Setting = 6

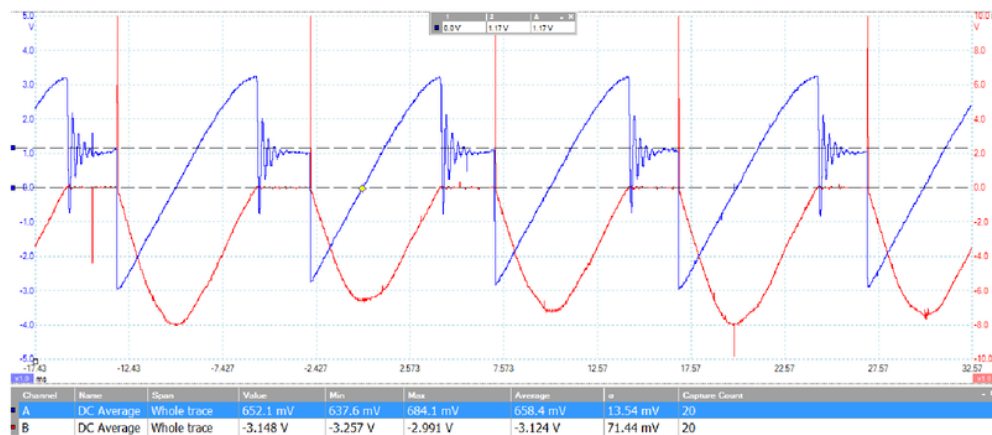


Figure 5.29 – VSD Speed Setting 6 Waveform

5.4.3 – VSD Speed Setting = 7

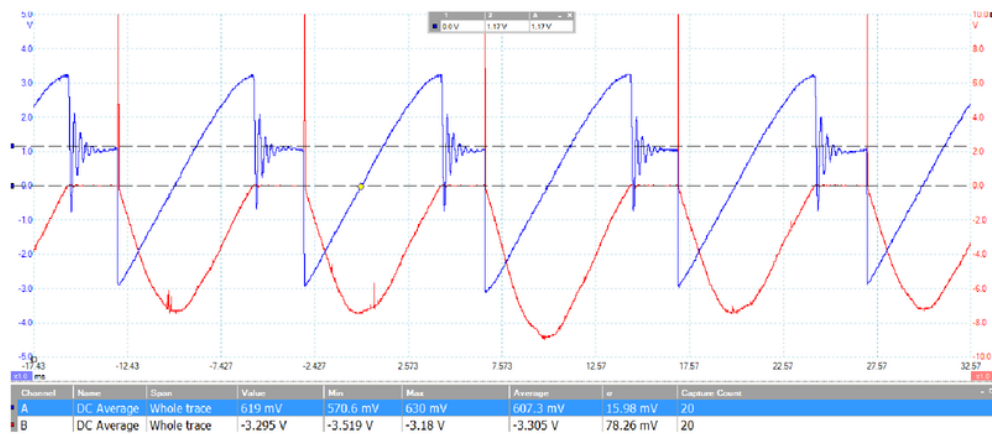


Figure 5.30 – VSD Speed Setting 7 Waveform

As the speed of the VSD is increased, the magnitude of the negative current increases. This can be seen above as the current changes from -9mA to -3.3A. This is because the VSD essentially causes the torque of the d.c. motor to increase in the negative direction. Using **Figure 3.7** it can be deduced that the d.c. motor is operating in Quadrant (2) as it has negative torque (current) and positive speed (voltage). Therefore, the motor is regeneratively braking and feeding current back into the supply.

5.5 – Four-Quadrant Operation

In order to test the four quadrants, the motor speed setpoint will be alternated between forward and reverse motoring.

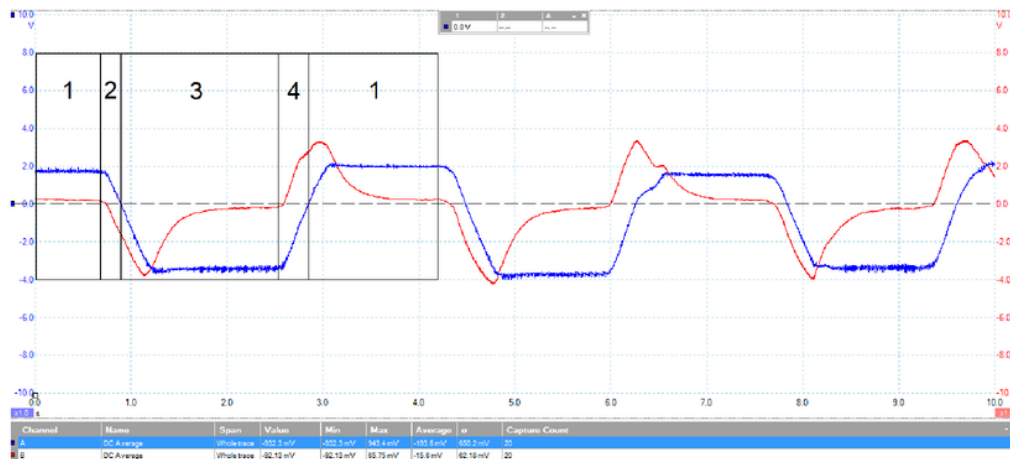


Figure 5.31 – Four-Quadrant Speed / Torque Trace for Forward and Reverse Motoring

5.5.1 – Quadrant 1 – Forward Motoring

The voltage (speed) is represented by the blue line, and current (torque) by the red. The motor starts off motoring in the forward direction. This is seen as the voltage and current are both positive.

5.5.2 – Quadrant 2 – Regenerative Braking (Forward to Reverse)

The instant the setpoint is set to a negative value both the current and voltage start going negative with the current leading the voltage. The current quickly becomes negative and causes the motor to have negative torque, however the voltage takes a bit longer. This is because the motor can't abruptly stop in an instant and therefore takes time to slow down while still moving forward. During this time while the voltage is positive and the current is negative the motor is regeneratively braking.

5.5.3 – Quadrant 3 – Reverse Motoring

In the instant the voltage equals 0, the motor is no longer rotating. However, the current is still flowing negatively which causes the motor to start rotating in the reverse direction with a decreasing negative voltage. As the motor approaches the reverse speed setpoint, the current starts decreasing as it is no longer required to oppose inertia. The voltage then stops increasing as soon as the set point is met. While the motor runs at the reverse setpoint speed, the current tends towards 0.

5.5.4 – Quadrant 4 – Regenerative Braking (Reverse to Forward)

When the setpoint is once again changed to be a forward speed, the current and voltage start increasing. Just like before, the current leads the voltage as the inertia of the motor rotating acts as a load which requires more torque. This continues until the motor stops at 0 volts.

Once the voltage becomes positive the motor starts rotating in the forward direction. As the speed approaches the set point the current peaks then starts to tend back towards 0 as there is no longer any inertia. The motor is once again motoring forward at a constant set speed in Quadrant (1).

This is expected behaviour confirmed by the research done in **Section 3.2** with regards to speed / torque control and four-quadrant control.

5.6 – Analysis of Tuning Parameters

The Parker 514C has an internal PI controller which can be tuned to increase stability at start-up. Both current and voltage will be analysed here.

5.6.1 – Voltage Analysis

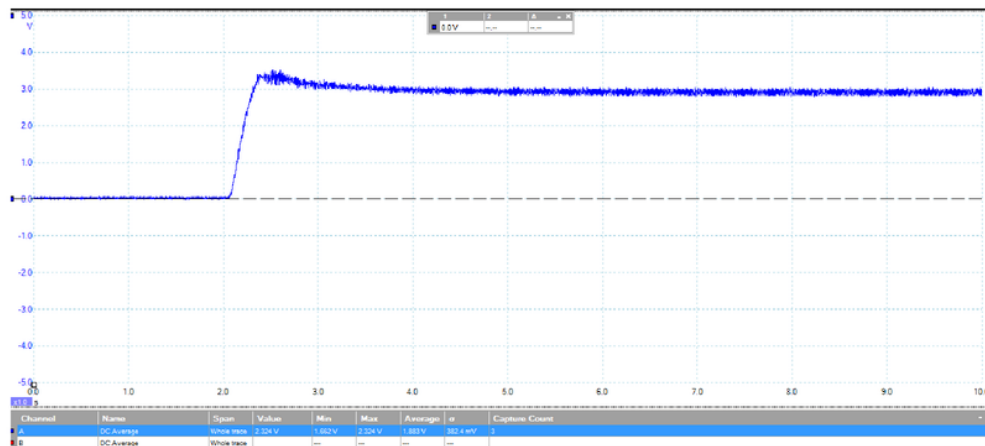


Figure 5.32 – Voltage - $K_p = 0$, $K_i = 0$

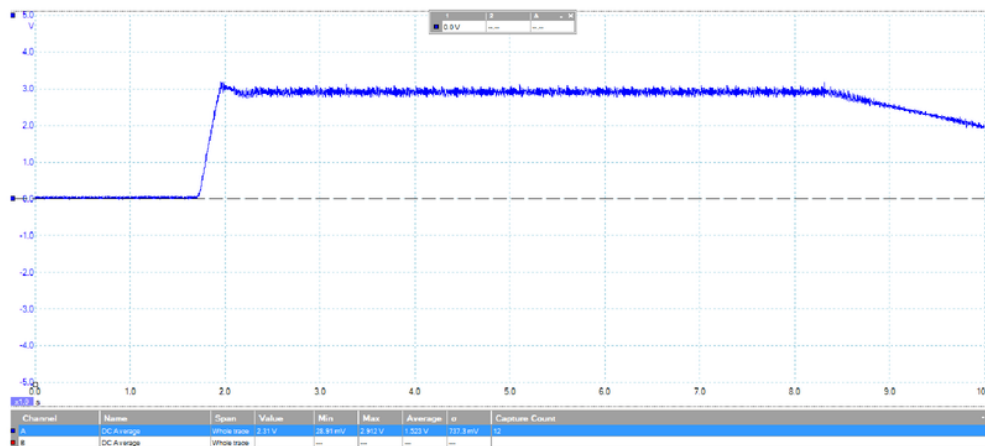


Figure 5.33 – Voltage - $K_p = \text{Max}$, $K_i = 0$

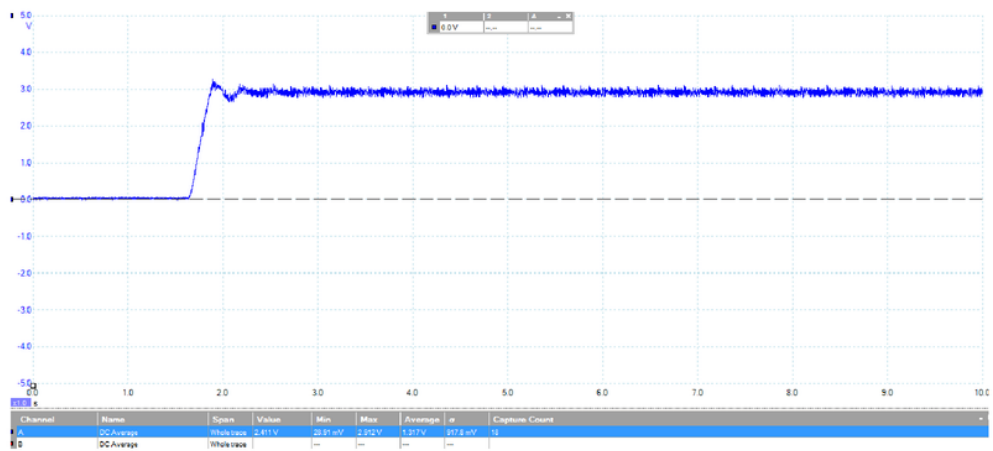


Figure 5.34 – Voltage – $K_p = \text{Max}$, $K_i = \text{Max}$

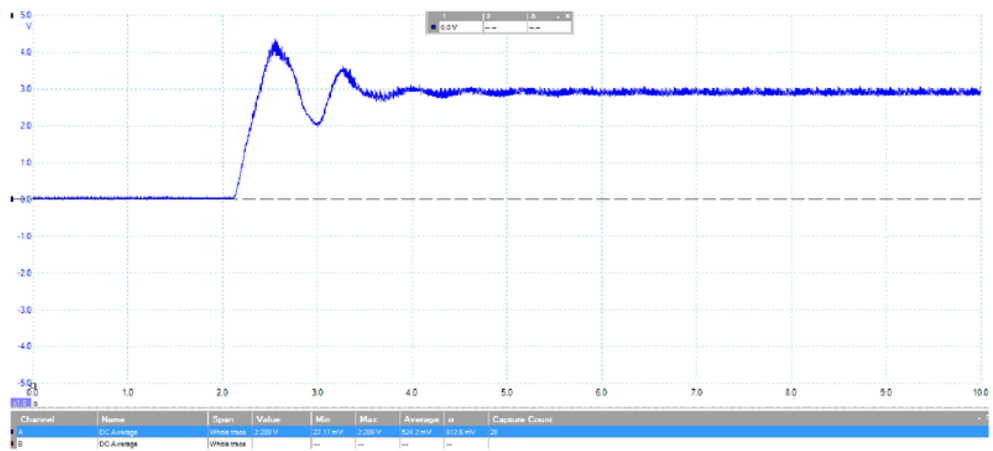


Figure 5.35 – Voltage – $K_p = 0$, $K_i = \text{Max}$

From these waveforms it can be seen that when K_p was tuned to max, the gradient of the rise was slightly higher causing the voltage to peak slightly sooner. It also made the peak sharper causing it to reach steady state faster. By tuning K_i to max a ripple was added and nothing else changed. However, by reducing K_p to 0 while keeping K_i at max a very large ripple was introduced which is undesirable for a stable start up as the speed will vary wildly until it reaches its setpoint. This ripple made the motor take much longer to reach the set point than when K_p was tuned to max.

5.6.2 – Current Analysis

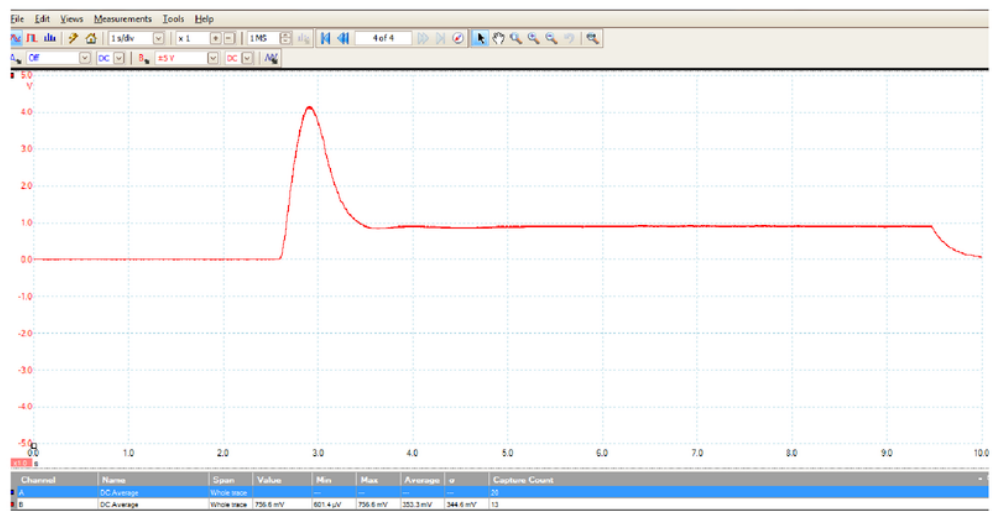


Figure 5.36 – Current – $K_p = 0$, $K_i = 0$

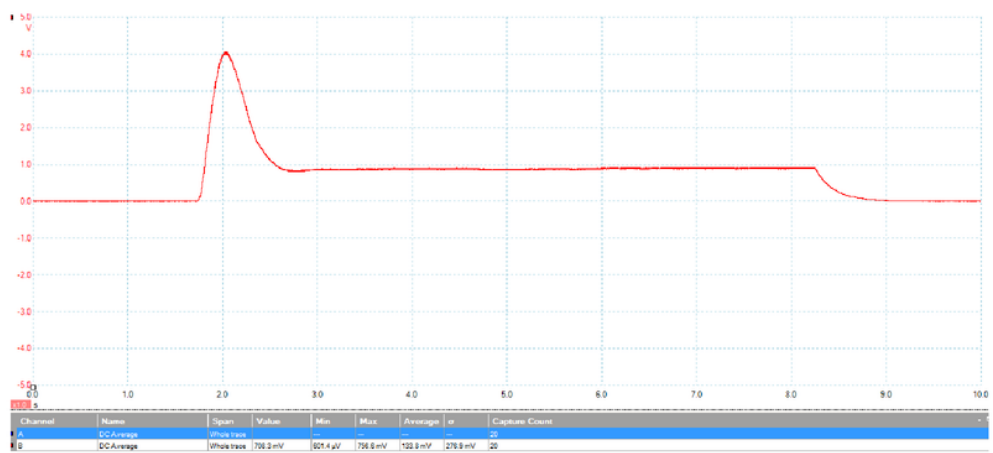


Figure 5.37 – Current – $K_p = \text{Max}$, $K_i = 0$

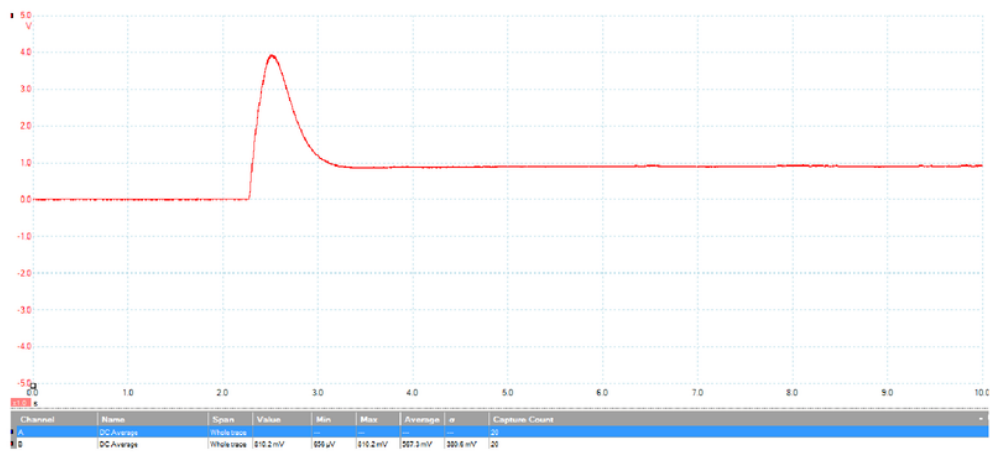


Figure 5.38 – Current – $K_p = \text{Max}$, $K_i = \text{Max}$

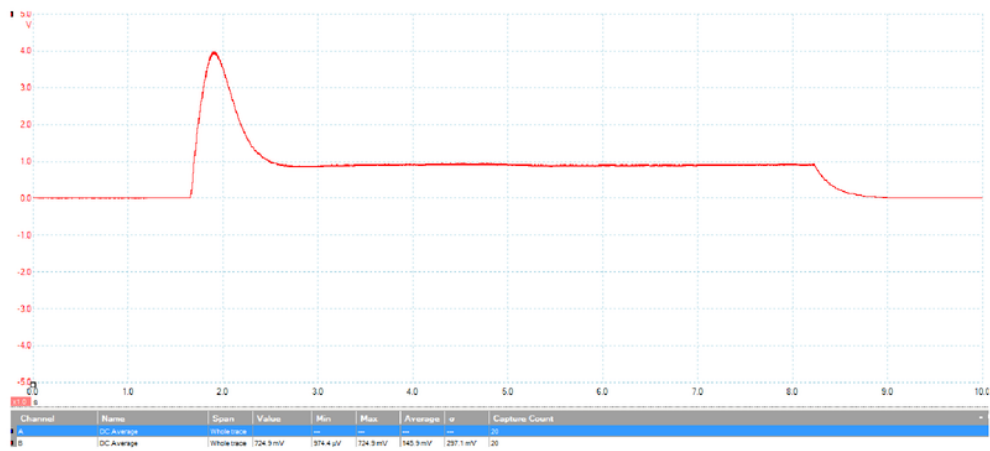


Figure 5.39 – Current – $K_p = 0$, $K_i = \text{Max}$

The effect that K_p and K_i tuning has on current seems to be negligible according to the current traces. This may be because the same amount of current is required to overcome initial inertia as the motor starts and without a load it simply decreases to a steady state which is why no affect is shown.

6 - Conclusions and Recommendations

The results obtained from the simulation task reflected what the theory discussed in *Section 3*, and was then backed up with calculations to prove their authenticity. Despite some minor discrepancies between the calculations and the measured simulated values both sets of values were accurate. These discrepancies were likely caused by rounding errors or component tolerances / ratings. To reduce these errors more calculations for different firing angles could be calculated and compared to simulation to see if the error was consistent or followed a trend. This could lead to finding the reason for the discrepancies. However, these were very minor and the simulated results reflected how a d.c. drive would operate in single-phase with both continuous and discontinuous current, and in three-phase with continuous current. These simulations showed how the firing angle α affected the average output voltage.

The practical exercise also provided excellent results which reflected the theory from *Section 3*, and the simulations from *Section 4*. The first practical showed how the waveform changed when the direction of the motor was reversed. The second provided information on how the load affected the current / torque. The third showed the effect of regenerative braking on the output waveform, and how increasing the speed of the VSD increased the current generated back to the supply. The fifth practical showed how the motor operated in four-quadrant operation by creating a clear trace on the oscilloscope showing how the current and voltage changed as the speed set point was changed from positive to negative. The final practical task showed the effect of changing K_p and K_i on the output voltage and current.

The results obtained from the practical were backed up by calculations and multiple readings from a multimeter, tachometer and oscilloscope. The output waveforms generated were identical to the ones found through research and simulation.

From these exercises and research it is evident that three-phase d.c. drives are much superior to single-phase d.c. drives as they can provide a much larger speed range, while also being much more reliable by maintaining a continuous current. Single-phase d.c. drives are always close to entering discontinuous current mode which is an undesirable trait. The motor used in the practical was always operating in DCM, which would not be the case if it were a three-phase drive. The maintenance cost of a three-phase motor can greatly be reduced by the choice of motor being brushless.

These characteristics of three-phase drives make them an ideal choice for many industrial applications such as lifts, hoists, mills, conveyor belts, presses, pump and many more. Three-phase is much more suited to these applications as it can produce a constant, and higher torque than single-phase.

An improvement to the simulation exercise would be to design and simulate a four-quadrant drive in order to gain a better understanding of how it would operate, and to provide extra waveforms to use in comparison to the practical exercise. Probes could be added in series with the thyristors to help indicate which thyristors are conducting when.

The practical could be improved by doing the same tests on both three-phase and single-phase drives in order to make more comparisons and to see how they'd both compare in real life operation as opposed to theory.

A lot of understanding has been achieved through this assignment including the different rectifier devices and converter circuits, control methods and operation of various drives.

7 - Team Working

My contribution to the team was to monitor the Picoscope generated waveforms on the laptop and to take screenshots of each waveform / reading required for the practical. I had to make sure that the cursors were correctly placed to measure and in addition to timing the screenshots so that they captured valuable information and had clear waveforms.

This was particularly challenging during the four-quadrant operation experiments as the waveform was lagging and only appeared clearly for a split second each cycle.

8 - Citation List

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Sam Harries - Power Electronics Assignment Final

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

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GRADING FORM: NEW CSG-RUBRIC

DAVID HARRIES

60

1. ENGAGEMENT WITH LITERATURE



Engagement with an appropriate range of research-informed literature, including sources retrieved independently. Some over-reliance on texts. Note however, at this level a wider range of sources should have been consulted and the Bibliography should not contain the same sources as the citation list. Much of what has been written is book-work and a number of issues required to be analysed and evaluated have not been considered viz the current technologies of switching devices and their evolution and industrial applications . (8/15)

8

2. KNOWLEDGE AND UNDERSTANDING

- | | | |
|---|---|-----------|
|  | Knowledge is reasonably detailed, accurate with a good systematic understanding of the field of study and to some extent, current research and scholarship. (10/20) | 10 |
|---|---|-----------|

3. COGNITIVE AND INTELLECTUAL

- | | | |
|---|--|-----------|
|  | Sound critical thinking, analysis, synthesis and evaluation demonstrating critical thinking. Ability to devise and sustain persuasive arguments, and to review the reliability, validity and significance of evidence (that may be incomplete) to make mostly appropriate and valid judgments. (20/30) | 20 |
|---|--|-----------|

4. PRACTICAL APPLICATION

- | | | |
|---|--|-----------|
|  | A very good application of a range of methods, materials, tools and/or techniques. Very good consideration of the context of the application, with perceptive insights. Can identify problems and propose appropriate solutions in complex and unpredictable contexts. Evidence of some innovation and creativity. (12/20) | 12 |
|---|--|-----------|

5. TRANSFERABLE SKILLS

- | | | |
|---|--|-----------|
|  | Can communicate well, confidently and consistently in a suitable format. Work is coherent, fluent, well-structured and organised. Can work very well | 10 |
|---|--|-----------|

autonomously and/or as part of a team, with very good contribution to group activities. Demonstrates very good graduate employment skills, with just occasional minor weakness. (10/15)