

1602836

by Daniel Ince

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1. Executive Summary

This assignment evaluates the performance of a DC drive through three methods, theory, practical and simulation. The theory researches features, control methods, applications and viability. The practical experiment is set up to allow the DC motor to switch between all four quadrants and analyse the performance across varying set points. A simulated DC motor circuit allows analysis of performance and modification for four quadrant control. Calculations have been performed to compare the performance of the motor and results compared against theory, showing how the drive allows regenerative braking and motoring in both directions.

2. Research

Four quadrant DC drive

The drive increases control of the motor, giving it the capability of forward and reverse travel, coupled with the ability to motor or generate travel in either direction. As the voltage determines the speed and armature current determines torque, the use of two bridge rectifiers means positive or negative current can be produced to drive the motor in either direction. The firing angle can then be adjusted to provide an average armature voltage that is above or below the back emf. It is stated in *Electric Motors and Drives* that, "The changeover from one converter to another can only take place after the firing pulses have been removed from one converter and the armature current has decayed to zero." (Hughes & Drury, 2013, p. 124) This means that there is a very small 'dead' time in between change over, where no torque is being sent to the motor.

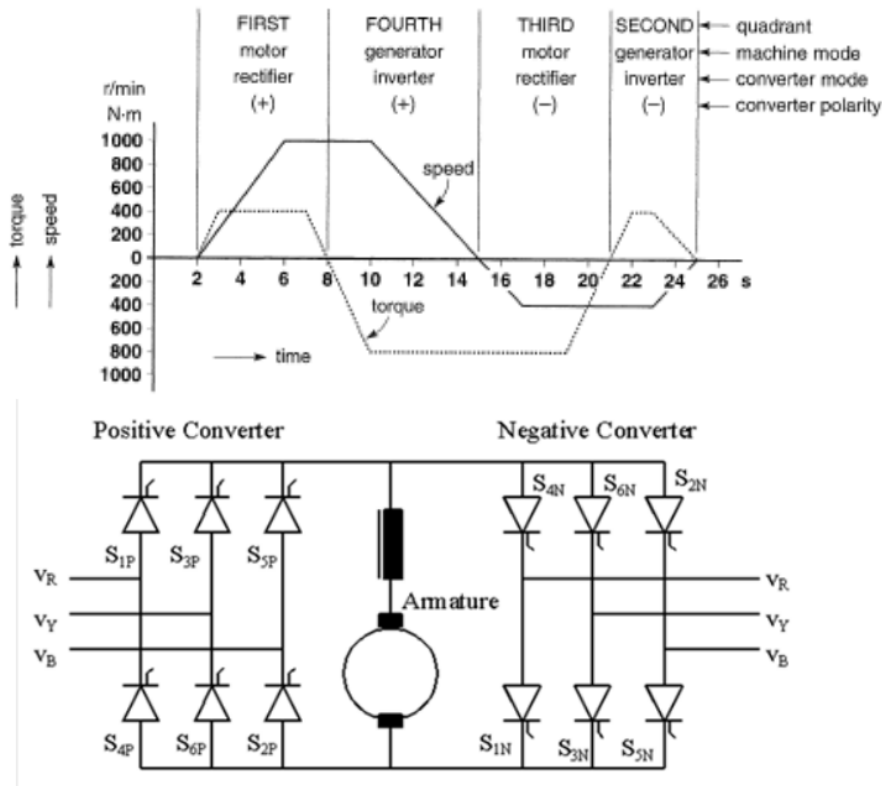
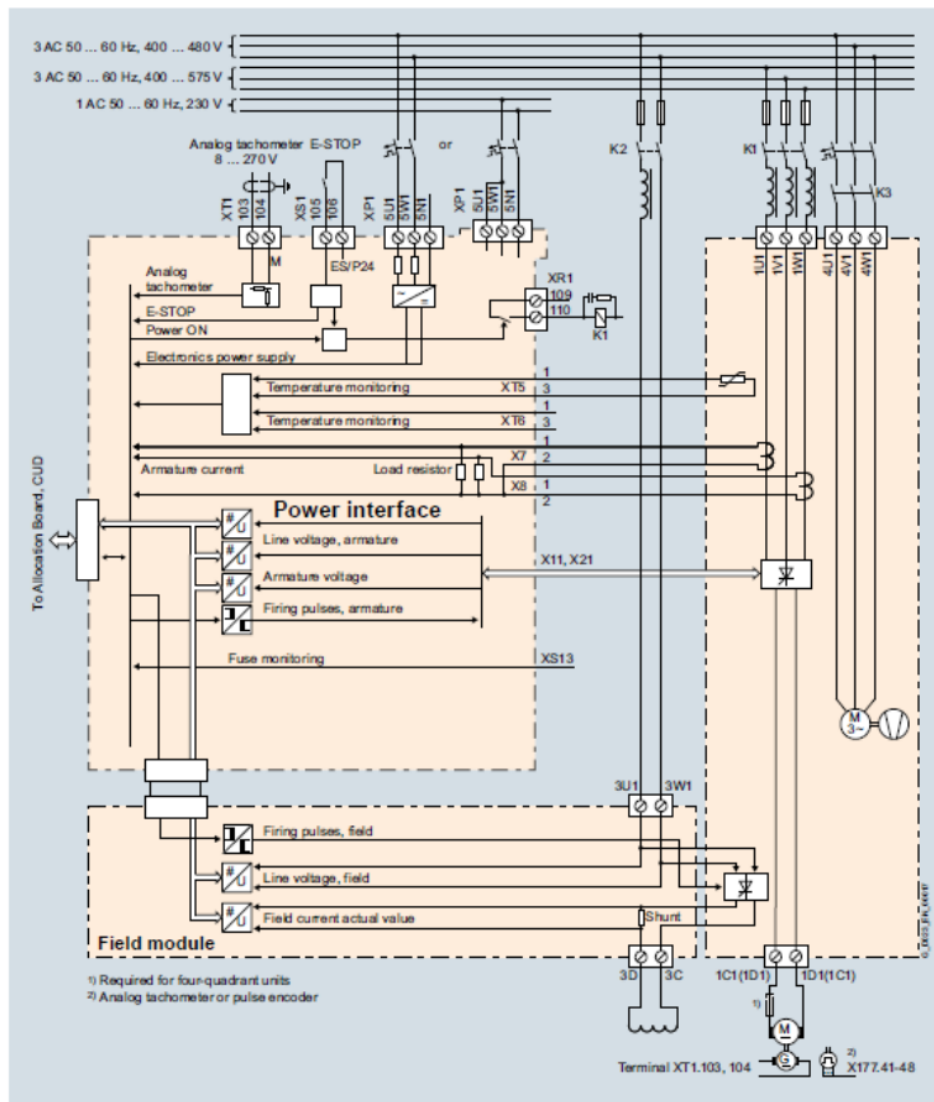


Figure 1: Four quadrants and DC drive circuit (Hajdu, n.d.)

Figure 1 shows the four quadrants in relation to torque and speed. Here we can see how the speed polarity controls the direction of the motor and the torque polarity controls whether it is motoring or generating. Shivaraj explains how the reverse torque that is applied to brake the motor allows the motor to act as a generator when turning forwards or backwards, so long as the torque polarity is

opposite to that of the speed. (2014) This means that when in regenerative braking, the back-EMF becomes higher than the supplied voltage and so flows back with negative current. As explained in the journal *Mathematical Model of Engineering Problems*, the first and third quadrants have speed and torque with the same sign. In the second and fourth quadrants the polarities are opposite, meaning the motor decelerates due to the torque acting against it. (Youssef, 2018, p. 53)

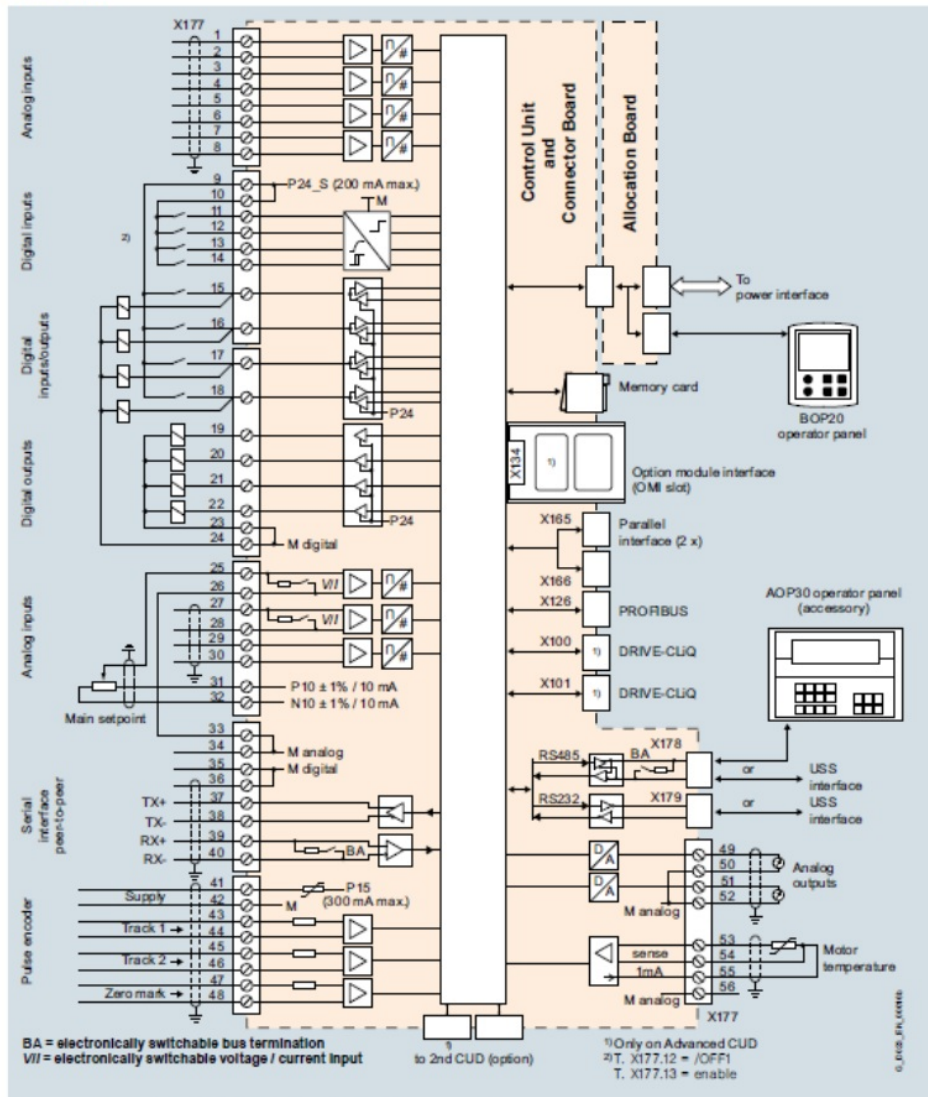
DC Converters



Connection diagram, DC Converters, 400 to 3000 A, electronics power supply 400 V or 230 V, with fan (standard version)

Figure 2: DC converter (Siemens, 2014)

Control Units



Connection diagram, Standard CUD/Advanced CUD with typical connections

Figure 3: DC control module diagram

Figures 2 and 3 display the diagram for the DC converter and control unit respectively. The converter is made up of three modules, the power interface, field module and the rectifier output to the motor. The power interface receives feedback and controls the firing pulses, the field module controls and regulates and pulses sent to the field, and the rectifier block contains both SCR thyristor bridge rectifiers for the armature and field. The control unit in figure 3 contains all analogue and digital I/O to and from the drive, including serial communications such as RS232 and RS485, with memory storage also. This features HMI outputs along with other interface capability to process and transmit data.

The Siemens DCM drive used during this assignment is a three phase four quadrant drive that utilises several techniques to achieve optimum control of the DC motor.



Control blocks for the DC drive are seen in figure 4. The three phase input comes from the top and is regulated by the armature thyristor bridge circuit to provide the DC voltage to the armature. The Siemens website describes some of the control elements. The speed controller looks for deviations between speed and set point and writes a set point to the current controller. *“The speed controller is implemented as PI controller with additional D component that can be selected. Further, a switchable droop function can be parameterized. All of the controller parameters can be adjusted independently of one another.”* (Siemens, 2019) This is also shown in figure 2, where the speed controller feeds the armature current controller once the signal has passed through the current limiter. This feedback loop is taken from the analogue tachometer on the motor itself and fed into the system.

The foremost point of control is the thyristor firing angle as this determines the mean armature voltage and so the speed of the motor. This angle is decided by the various control blocks based on the speed set point. The smaller the angle, the earlier the firing pulse and the more voltage passes through, hence a higher average. Once fired, the thyristors remain switched on until the current

reaches zero. When α is between 90° and 180° , more of the negative portion of the wave is allowed to pass before the current drops to zero, and so the average voltage is negative.

The tachometer voltage output is proportional to the speed measured and so feeds into the speed controller where the error is picked up. It is stated in *Power Electronics*, “any change in motor speed will immediately give rise to excessive motor and thyristor currents which cannot be tolerated; hence means must be employed to limit the current level.” (Lander, 1993, p. 344) This can be seen in figure 2 where the current limiting block comes from the output of the speed controller to help prevent large current spikes when there is a large differential between set point and speed. This drive also features current and EMF sensing so it can provide appropriate field current control and utilise field weakening when applicable.

Applications

There are many uses of a DC drive with four quadrant capabilities, notably applications that require rapid direction changes and regenerative braking.

The application which suffers greatly from large power consumption is the electric car, the extra quadrants allow the vehicle to generate power during braking or coasting. This is especially useful due to the limited range on most electric cars (EC), the regenerative braking increasing the range of the system. As explained by S. Arof, *"However, the EC cost is unaffordable especially for developing and third world countries. DC drive in EC offers better price, nevertheless it requires special research attention to improve DC motors and the converters' performances."* (2017) The regenerative braking allows for extended range and also the opportunity for smaller batteries, meaning lower cost and less maintenance, however as the technology and infrastructure is not quite there, there is still a high cost involved.

Another use of a DC drive is for robotics, part movements in multiple directions and reverse would mean that a four quadrant drive would be needed to allow for the range of movement in the robot.

Industrial tools and equipment such as lathes and CNC machines use DC drives to allow for forward and reverse direction of the chuck or cutting tool. Four quadrants are required as a single thyristor circuit would not be able to pass through current in the reverse direction.

Industry Type	Power	single quadrant	4 quad regen	field weakening	constant torque	single drive	multi drive	Useful information
Metal Industries.								
Rolling Mill	Up to 1000kW	✓		✓	✓		✓	Check for shock loads, and if field weakening is required.
Strip Mill	Up to 100kW	✓	✓	✓	✓	✓		Check if field weakening is required.
Slitters & Perforators	50kW – 150kW	✓	✓	✓	✓	✓		Check constant power range, may need a larger drive and motor.
Wind / Unwind	Up to 200kW		✓	✓	✓		✓	Check reel build up ratio and speed / tension range. Motor/drive needs sizing to suit. Requires Winder card.
Tube Mill	Up to 300kW		✓	✓	✓	✓	✓	May be a pair of drives linked by process, system knowledge on load sharing required.
Cast Tube spinner	20kW – 50kW		✓	✓		✓	✓	Straight forward speed control application.
Machine Tool Spindle	5kW – 150kW		✓	✓	✓	✓		Always four quadrant regenerative drive. Additional signals in/out may be required through add on board.
Machine Tool Table	20kW – 200kW		✓	✓	✓	✓		Straight forward speed control Check if drive requires a position signal.

Figure 5: DC drive uses in industry (Sprint Electric, n.d)

The table in figure 3 was compiled by Sprint Electric and highlights various uses of DC motors in industry. It details industrial applications that will need four quadrant functionalities, which are the majority. Many of these motors are rated for higher power to suit these large industrial machines. (Sprint Electric, n.d) Three phase dual converter drives do have a limit on maximum power, as stated in *Power Electronics and Drives*, "It is a four quadrant drive and limited to applications up to 1500kW". (Muhammed, 2014, p. 719) This information matches that from Sprint Electric as none of the applications detailed are a higher power than 1500kW.

It is stated in *Power Electronics* that, although DC motors are the favourite for variable speed applications, older methods of control are still used in certain applications. When speed control is required only briefly, the power loss through a full semiconductor circuit sometimes outweighs the need and so armature resistance is added instead. An application given is the use of a reeling drive, where there is always tension on the wire and thus always a power requirement of the motor, with a constant force needed at a set speed. (Lander, 1993, p. 359) The patent *Four Quadrant Control Circuit for a Brushless Three-phase D.C. Motor* explains a use of four quadrant DC drive characteristics, "This requires an inherent transition in the operation of the motor-generator between motor and generator operation and vice versa. The motor-generator functions as a motor to retrieve the satellite." (Nola, 1987) Here the motor is being used to control the tethering of a satellite to a space station and achieve stability through use of a reeling drive. The demand from an application such as this would be high due to the operation environment and criticality of the task, therefore the project budget would be high.

Comparison to AC motors

Consumers and companies will compare the need for a DC drive against use of a modern AC drive and which suits the business best overall.

With regards to maintenance, brushes on a DC motor have a finite lifespan as they wear down. ABB document 'DC or AC Drives?' states, "Today, depending on the application involved, the useful lifetime of brushes in DC motors is at approx. 7000 ... 12000 hours (h), thanks to the sophisticated collectors, carbon brushes and optimized field supply units used." (ABB, n.d., p. 6) This shows the technology has improved with DC motors that shortens the gap between DC motors and the high reliability of AC. In *Improving Motor and Drive System Performance* it is stated, "Brush assemblies not only require a larger motor, they can also increase maintenance requirements. As brushes wear, they create a housekeeping problem by generating carbon dust." (US Department of Energy, 2014) This means that DC motors are typically larger than an equivalent AC counterpart. A larger DC motor with increased complexity means

a higher price point. Often it is more favourable to rewind a DC motor and have it refurbished, rather than replace the whole motor, whereas replacing an AC motor is worthwhile due to the lower cost.

Regarding drives, the website *AC Drives vs. DC Drives* describes how the initial cost of a DC drive does not economically exceed the benefit of the low maintenance AC flux vector drive. DC drives have excellent feedback and precise control while being smaller. (Premier Automation, 2018) Some applications would not be suitable for an AC drive, but for those that are AC could be better in the long run.

3. Practical Experiments



Figure 6: Drive cabinet contents

Figure 6 shows the drive enclosure with the Siemens DCM drive in the top right. Below the drive is a Simatic S7-1500 PLC which provides control through I/O and a HMI. To the left of the drive is the Sinamics AC drive. The top left shows the MCB, and below is the filter and three phase inductors used to process and improve the signals.

The readings of voltage and current are taken and processed for the picoscope to read. The voltage waveform is independent of the mains supply and is converted to 100V to 1V drop by a differential amplifier. A multimeter is tied into this reading and can be seen below the PLC. As the picoscope requires voltage, the current reading is also converted to a voltage through a second differential amplifier, there is no delay as this system uses Ohm's law. A laptop is connected to the picoscope to

represent the data in the form of a graph, this laptop was kept separate from ground. The DC drive is independent and uses a floating zero volts to prevent grounding out of the thyristors.

The DC motor under test is set up in speed control, whereas the load induction motor is set up for torque control.



Figure 7: Motor setup

Continuous current

The drive system was first set up so achieve results with a continuous current waveform. In order to analyse the response of the system, the torque was varied between three set points; 5.4, 6.0 and 6.8Nm within quadrant 1. The speed was left constant at 1800rpm for this test, the results are as follows.

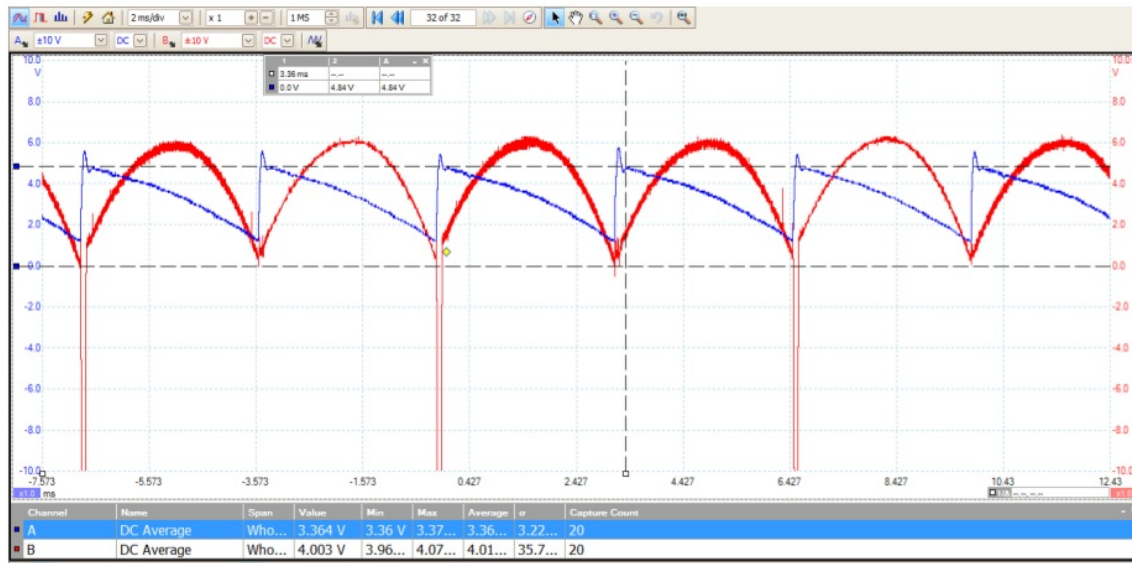


Figure 8: Set point 5.4Nm picoscope

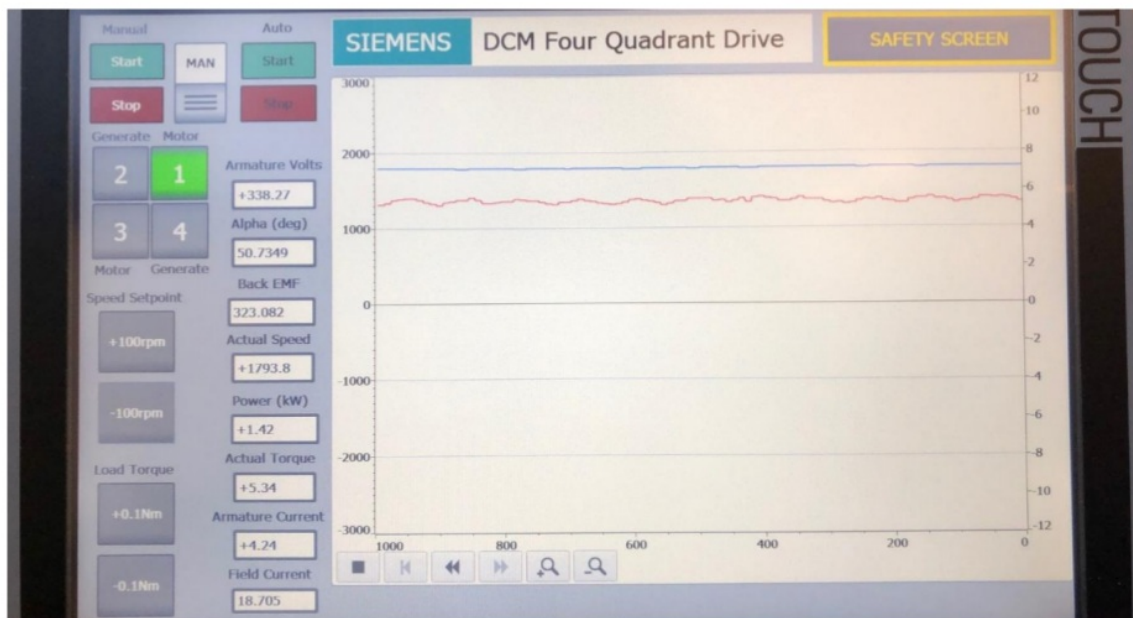


Figure 9: Set point 5.4Nm HMI

Figure 8 shows waveforms with the peak current at 4A. For this first set point, the load is sufficient to just achieve continuous current by driving the armature current high enough that the trough has just lifted off the zero. The max voltage is at 337V and does not manage to decay to zero before the next pulse.

The HMI in figure 9 displays the average values for voltage and current, these loosely tie in with the picoscope values. Small discrepancies such as this are down to the exact timing the photos were taken and fluctuations in the readings. At this point, alpha is at 50.7° .

Figures 10 and 11 display set point 2, both displays show an increase in current. This is due to more load being put on the DC motor so more current is drawn and more torque delivered. Alpha has reduced to 50.3° to provide more of the voltage half cycle. This is only a slight increase and so the average voltage is only a volt higher. The increases ties in with the HMI reading of armature current and of power.

The further increase in torque set point is shown in figures 12 and 13, here the current has increased again to cope with the load and maintain the same speed, this is also indicated by the increase in power. Alpha is dialled back to 49.9° with another small increase in average voltage, the back-EMF has stayed relatively consistent (only visible on the HMI).

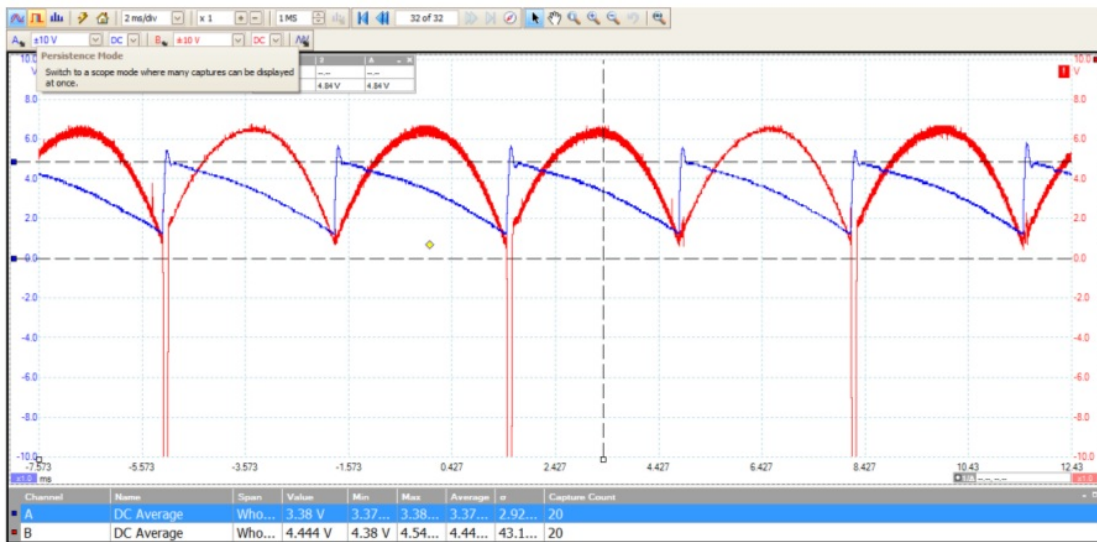


Figure 10: Set point 6.0Nm picoscope

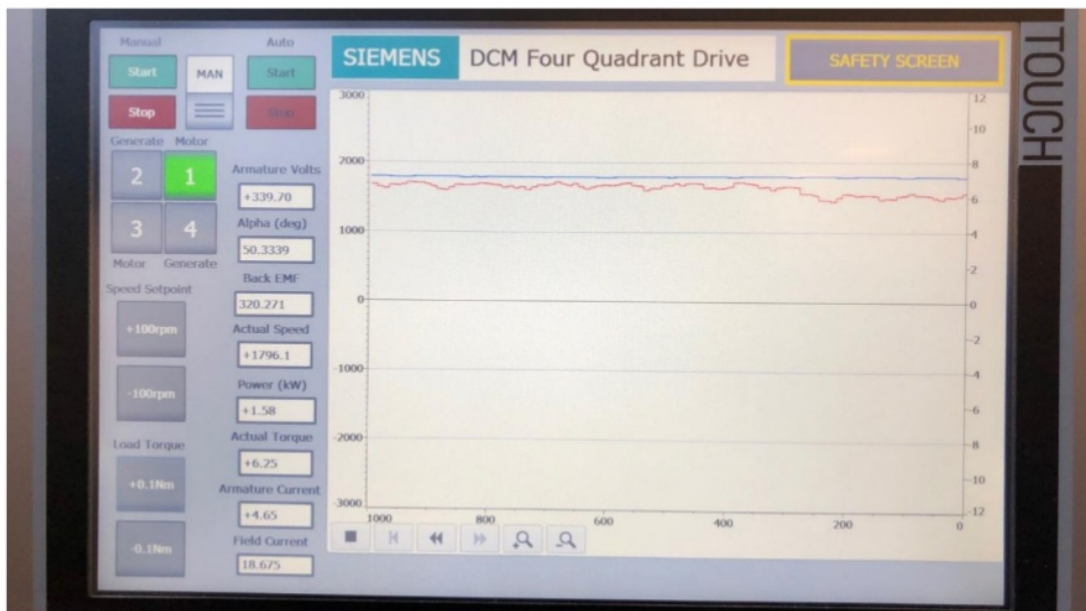


Figure 11: Set point 6.0Nm HMI

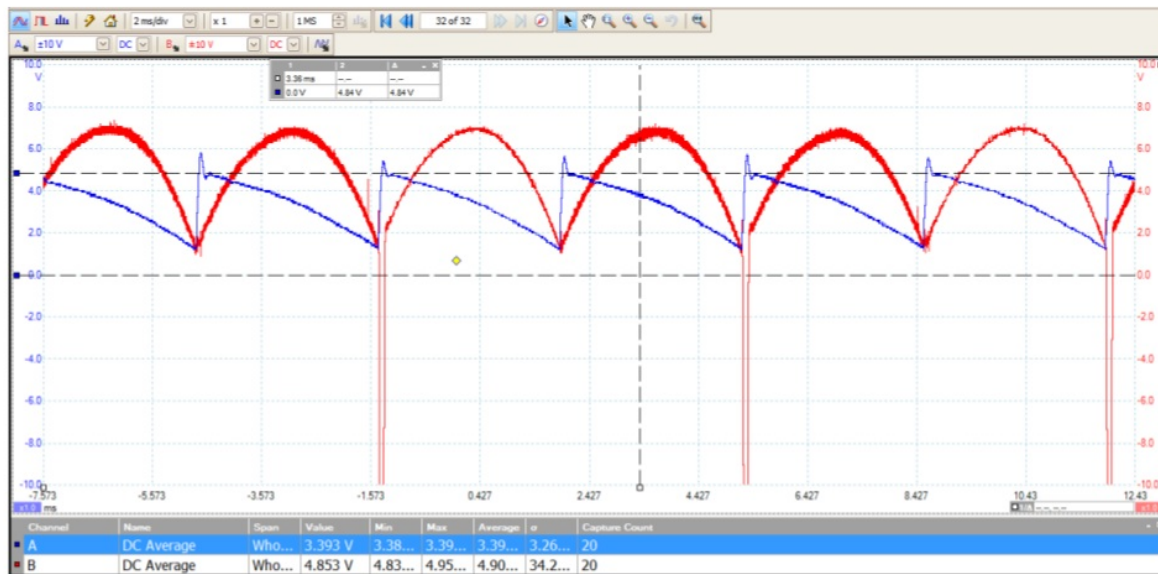


Figure 12: Set point 6.8Nm picoscope

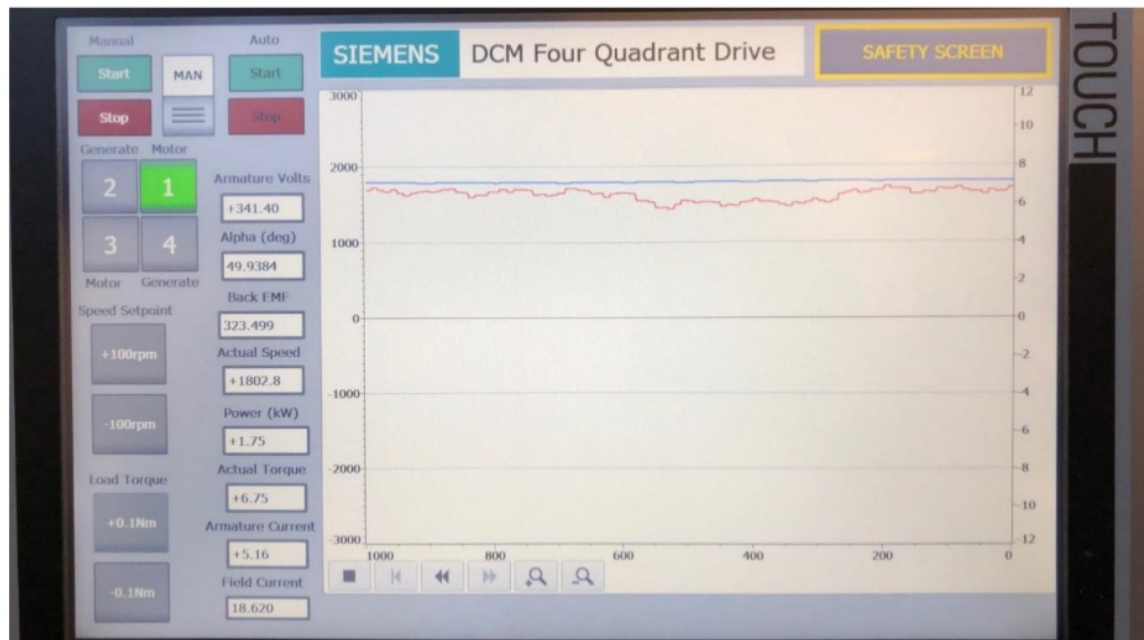


Figure 13: Set point 6.8Nm HMI

Continuous current calculations

To derive the formula for the average armature voltage, the area of one phase peak needs to be calculated.

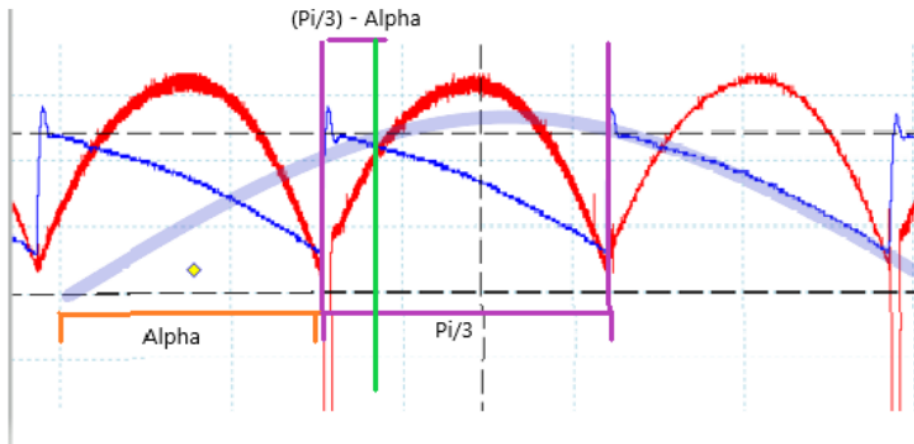


Figure 14: Deriving continuous current

As seen in figure 14, the translucent blue line represents the positive half of one phase. This whole section can be called ' π ', meaning when divided into three to count for the part of the cycle allowed to pass through, it is ' $\pi/3$ ', represented by the purple section. The orange division is alpha and represents the distance between pulses, when taken away from $\pi/3$ we are given the distance between the purple and green line. These figures can now be used to calculate the area of one pulse.

$$area = \int_{\frac{\pi}{3} + \alpha}^{\frac{2\pi}{3} + \alpha} V_{max} \sin \theta \, d\theta$$

$$area = V_{max} [-\cos \theta]_{\frac{\pi}{3} + \alpha}^{\frac{2\pi}{3} + \alpha}$$

When integrating by these limits:

$$area = V_{max} [-\cos(\frac{2\pi}{3} + \alpha) - -\cos(\frac{\pi}{3} + \alpha)]$$

Now as:

$$\cos\left(\frac{\pi}{3} + \alpha\right) = \frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha$$

$$\cos\left(\frac{2\pi}{3} + \alpha\right) = -\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha$$

These can be substituted into the main equation:

$$area = V_{max}\left[-\left(-\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right) + \left(\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right)\right]$$

$$area = V_{max}\left[\frac{1}{2}\cos\alpha + \frac{\sqrt{3}}{2}\sin\alpha + \frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right]$$

Here $\frac{\sqrt{3}}{2}\sin\alpha$ cancels out to leave: $area = V_{max}\cos\alpha$

Therefore for three phases, $V_{mean} = \frac{3V_{max}}{\pi}\cos\alpha$.

Set point 1.

$$\alpha = 50.7^\circ \rightarrow \times \frac{\pi}{180} = 0.8848rad/s$$

$$V_{Max(line)} = \sqrt{2} \times 415 = 587V$$

$$V_{Mean} = \frac{3V_{Max}}{\pi}\cos\alpha$$

$$V_{Mean} = \frac{3 \times 587}{\pi}\cos 0.8848 = 355.07V$$

Set point 2.

$$\alpha = 50.3^\circ \rightarrow \times \frac{\pi}{180} = 0.8779rad/s$$

$$V_{Max(line)} = \sqrt{2} \times 415 = 587V$$

$$V_{Mean} = \frac{3V_{Max}}{\pi}\cos\alpha$$

$$V_{Mean} = \frac{3 \times 587}{\pi}\cos 0.8779 = 358.06V$$

Set point 3.

$$\alpha = 50.08^\circ \rightarrow \times \frac{\pi}{180} = 0.874rad/s$$

$$V_{Max(line)} = \sqrt{2} \times 415 = 587V$$

$$V_{Mean} = \frac{3V_{Max}}{\pi}\cos\alpha$$

$$V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.874 = 359.74V$$

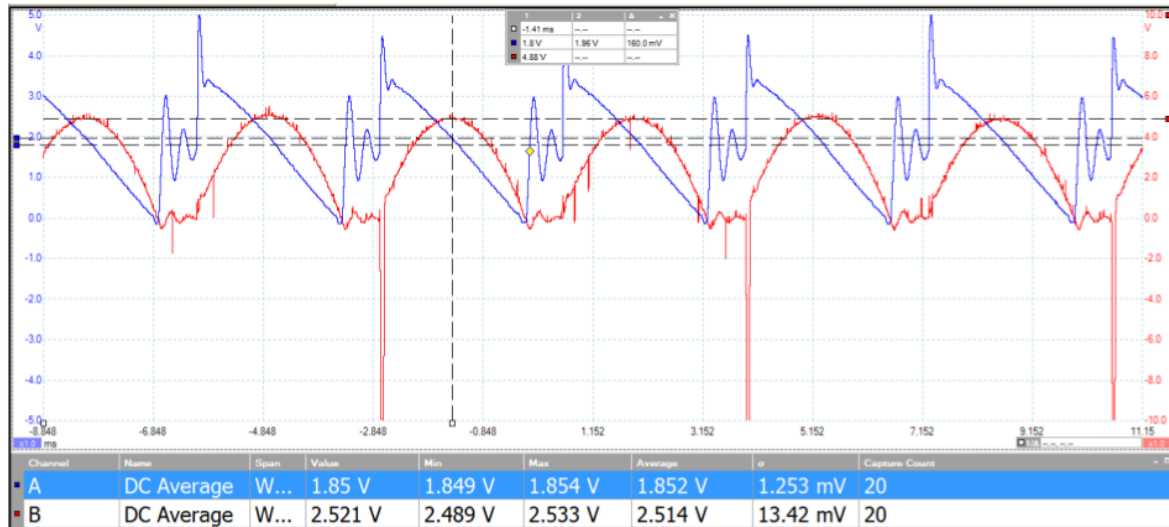


Figure 15: Calculating armature resistance

Figure 15 shows the picoscope of the motor with discontinuous current to make the back-EMF visible for calculating the motor constants.

$$V_a = E_a + I_a R_a + L \frac{dI_a}{dt}$$

At the point of zero gradient current, $L \frac{dI_a}{dt} = 0$ and so can be ignored, so values for V_a and E_a are taken at this point, as shown.

$$V_{arm} = 196V \text{ and } E_{emf} = 180V \rightarrow 196 - 180 = 16V$$

$$\text{Therefore, as } R_a = \frac{V_a - E_a}{I_a}, \text{ armature resistance} = \frac{16}{4.88} = 3.279\Omega$$

$$\text{For continuous current set point 3, } 1802.8\text{rpm} = 188.79\text{rad/s, so; } K_e = \frac{E_a}{\omega_m} \rightarrow \frac{323.5}{188.79} = 1.7135$$

$$K_T = \frac{T_m}{I_a} \rightarrow \frac{6.75}{5.16} = 1.308$$

Overall, there are some notable differences between the calculated, measured and displayed values for average armature voltage.

<i>Continuous</i>							
Measured		Displayed					Calculated
Va(V)	Ia(A)	Va(V)	α°	Back-EMF(V)	Ia(A)	Torque (Nm)	Va(V)
336.4	4.01	338.2	50.7	320	4.2	5.4	355
338	4.44	339.7	50.3	322	4.6	6	358
339.3	4.85	340	50.08	323	5.16	6.8	359.7

Table 1: Results for constant speed and varying torque during continuous current at 1800rpm

As shown in table 1, the measured and displayed average armature voltage (Va) is very similar. Slight differences could be due to rounding errors within the equipment or very small timing changes between the communication of the HMI and drive. The processing time for the picoscope also must be considered, overall these differences are negligible.

Reviewing the outcome of the calculated results shows a greater difference, roughly 20V difference consistently across all three set points. As the drive displayed and measured results are so close, the discrepancy is down to calculation accuracy. These calculations rely on true figures to be accurate, for example V_{max} is calculated at 587V, if the volt drop across the thyristors is considered, this value will drop around 4V and have a large impact on calculations, ultimately reducing the result closer to expected. The theoretical value 415V is used to produce V_{max} , the actual line voltage may be slightly less and would need to be measured to reduce error. The calculation uses alpha taken from the HMI, here a small deviation may be present on the displayed value due to a delay. As small changes on alpha have a large effect, this could produce considerable error.

In general, at a constant speed, the torque increases with current due to the extra load throughout the three set points. The armature voltage slightly increases as alpha is dialled back by a very small amount and the back-EMF increases with the armature voltage.

Discontinuous current

This test involved achieving discontinuous current for three separate speed set points with a constant load torque. The set points are 400, 200 and 600rpm in quadrant 1 and the results are as follows.

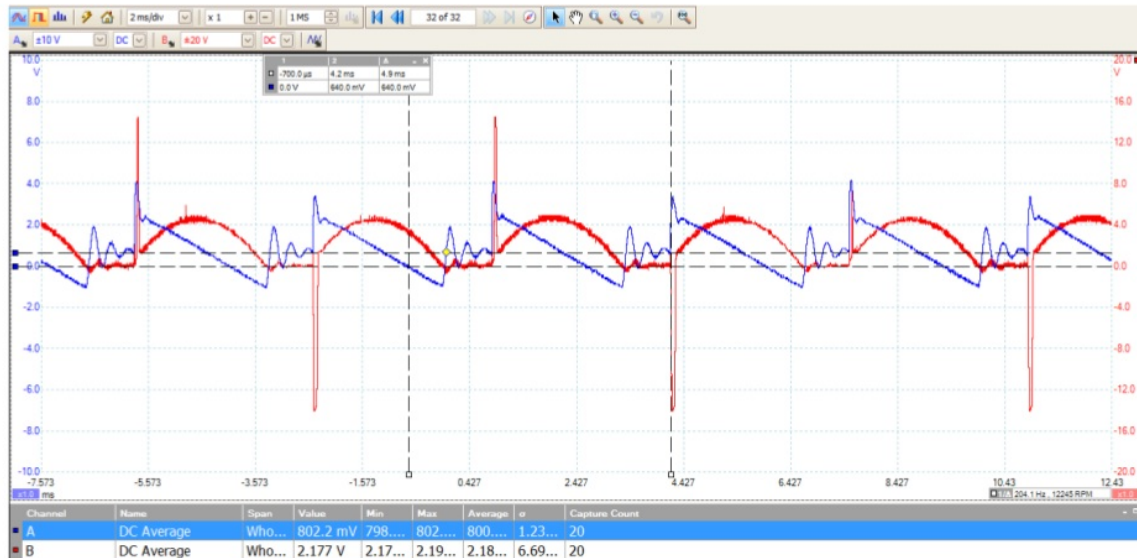


Figure 16: Set point 400rpm picoscope

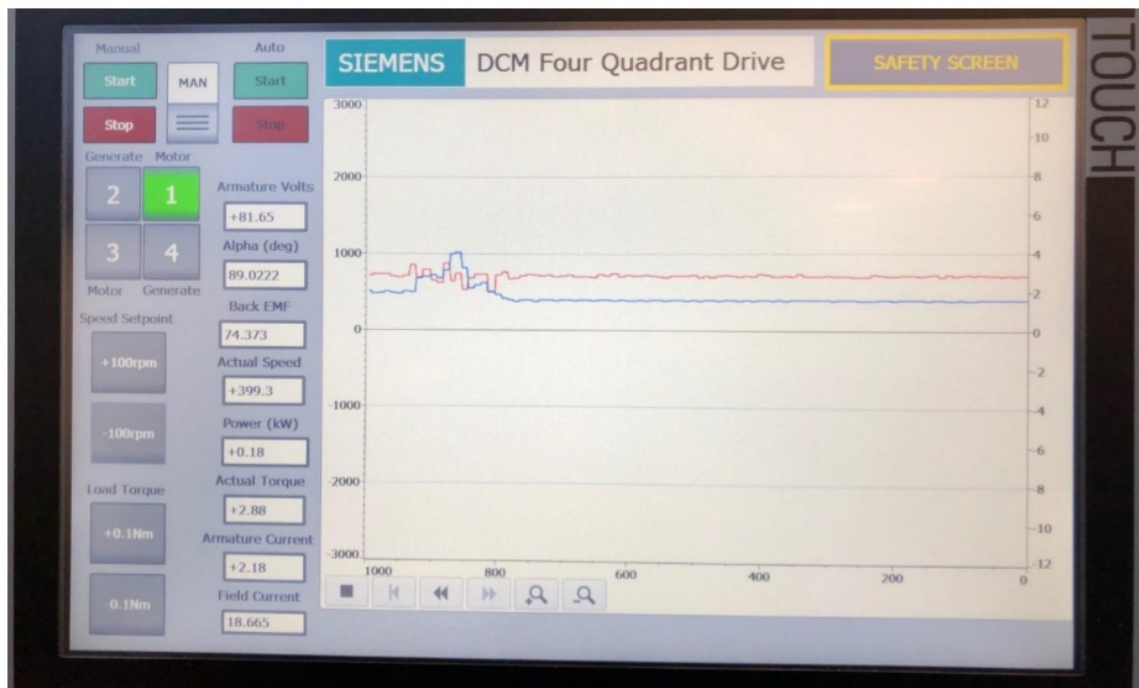


Figure 17: Set point 400rpm HMI

Figures 16 and 17 display the first speed set point on the picoscope and HMI respectively. The current wave form shown on the picoscope is discontinuous as it falls to zero for brief periods, the back-EMF is visible at this time. The average voltage is 80V and is positive overall despite the negative part of the wave. The HMI displays readings that tie into that of the picoscope with only a slight variance.

The 200rpm set point picoscope results are shown in figure 18, here the average voltage has dropped off due to the lower speed set point and the back-EMF has decreased in line with the voltage, almost dropping to zero as the set point is so low. Alpha has increased, seen in figure 19, to pulse less of the half cycle and thus decrease the speed. Despite these changes, the current and torque remain similar to that of the 400rpm set point.

Following on to 600rpm in figures 20 and 21, the voltage increases to 114V and the firing angle decreases to 85° . The back-EMF is 108V and more substantial due to the higher armature voltage and speed. The current and torque have slightly increased, but field current has remained constant throughout all three set points.

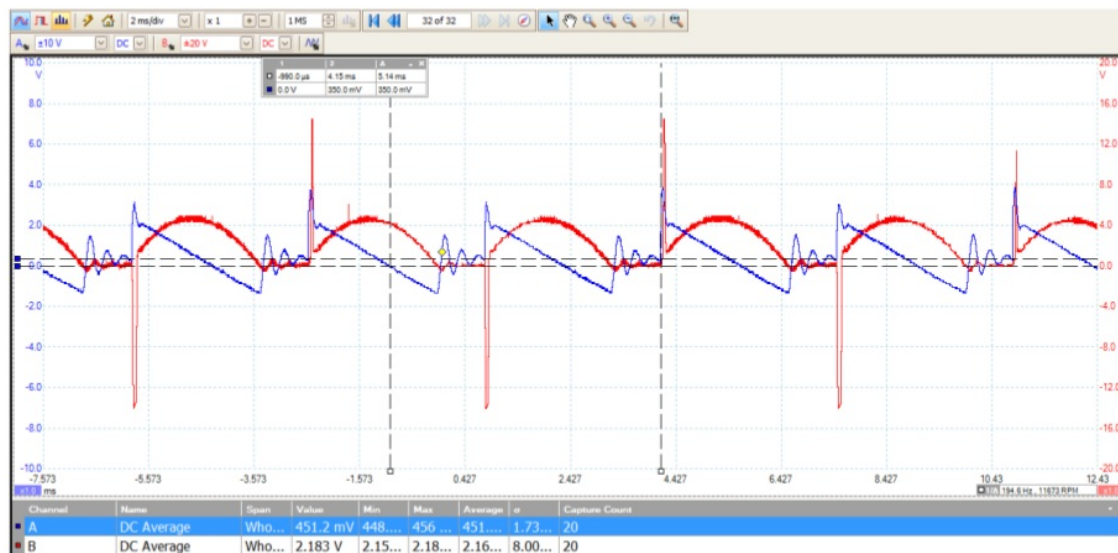


Figure 18: Set point 200rpm picoscope

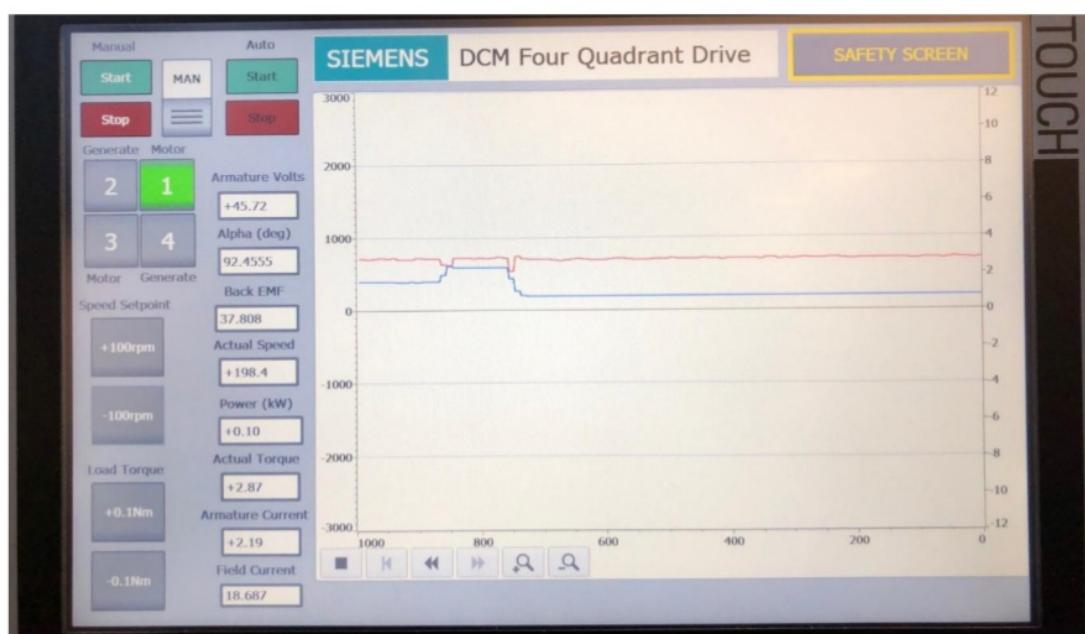


Figure 19: Set point 200rpm HMI

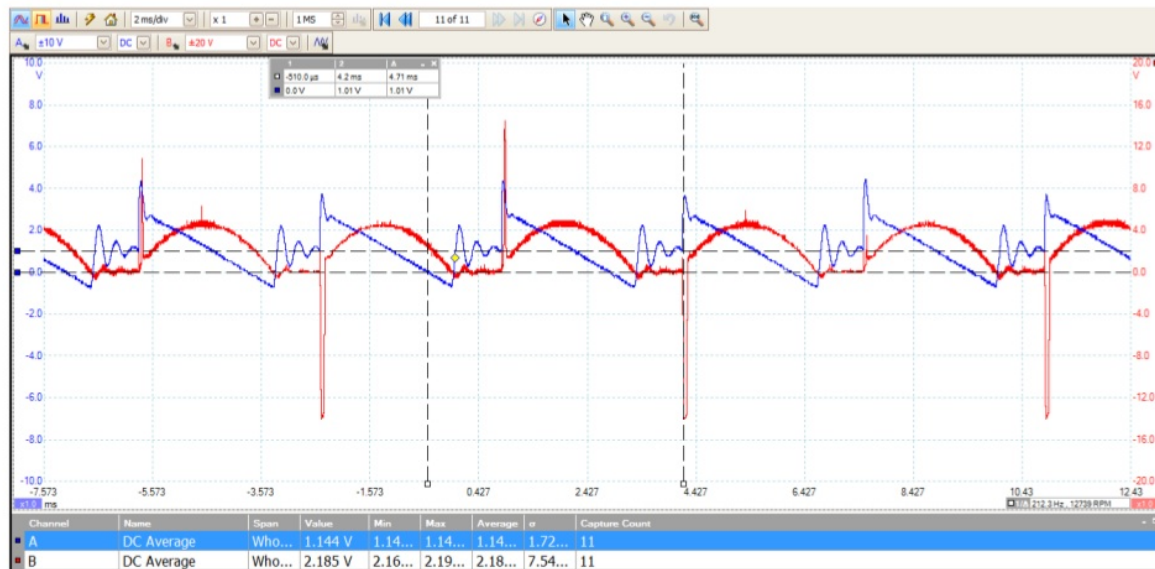


Figure 20: Set point 600rpm picoscope

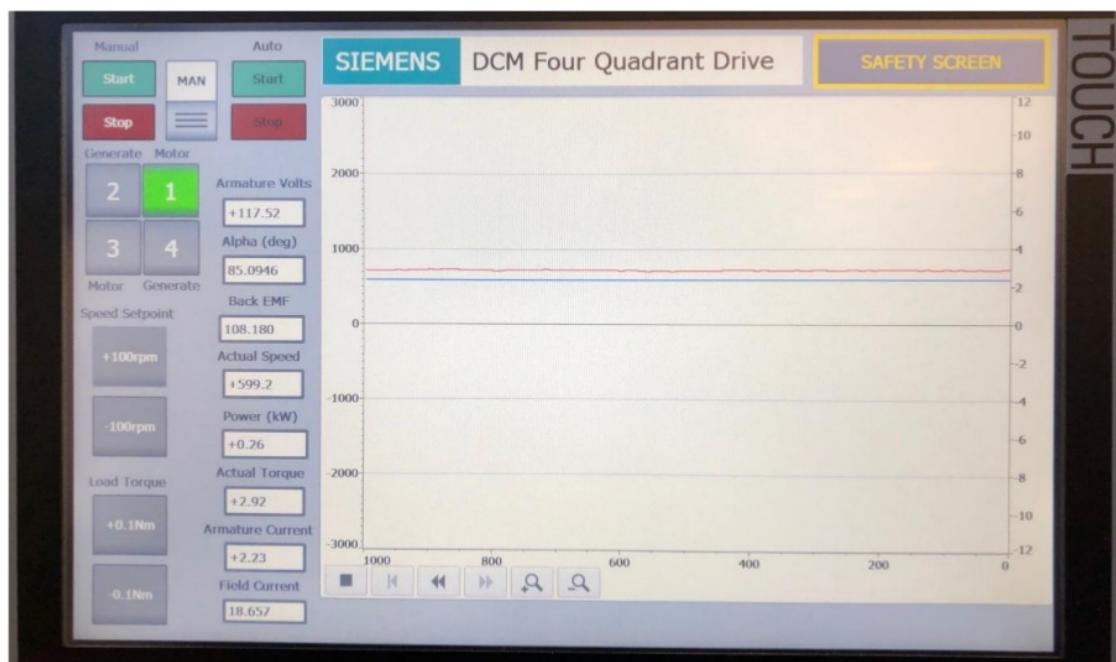


Figure 21: Set point 600rpm HMI

Discontinuous current calculations



Figure 22: Deriving discontinuous current

To derive the formula for discontinuous, the waveform must be split into two areas on the positive part (areas A and B) while also taking the negative Beta into consideration. Area A can be measured as the height of the Back EMF and the width as $\alpha' - \beta$.

$$\text{Therefore Area A} = E(\alpha' - \beta) \rightarrow E(\alpha - \frac{\pi}{3} - \beta)$$

To calculate area B integration between $\pi + \beta$ and $\frac{2\pi}{3} + \alpha'$, as these are the points either side of area B.

$$\text{So, area B} = \int_{\frac{\pi}{3} + \alpha}^{\pi + \beta} V_{\max} \sin \theta \, d\theta$$

$$\text{Now } V_{\text{mean}} = \frac{\text{area A} + \text{area B}}{\frac{\pi}{3}}$$

$$\text{area B} = V_{\max} [-\cos \theta]_{\frac{\pi}{3} + \alpha}^{\pi + \beta}$$

When integrating by these limits:

$$\text{area} = V_{\max} [-\cos(\pi + \beta) - -\cos(\frac{\pi}{3} + \alpha)]$$

$$\text{So } \cos(A + B) = \cos A \cos B - \sin A \sin B \rightarrow \cos(\pi + \beta) = \cos \pi \cos \beta - \sin \pi \sin \beta$$

Now as $\cos \pi = -1$ and $\sin \pi = 0$, the resultant is $-\cos \beta$.

$$\cos(\frac{\pi}{3} + \alpha) = \cos \frac{\pi}{3} \cos \alpha - \sin \frac{\pi}{3} \sin \alpha$$

Now as $\cos \pi/3 = 1/2$ and $\sin \pi/3 = \frac{\sqrt{3}}{2}$, the resultant is, $\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha$

$$\text{Therefore area B} = V_{\max} [-\cos \beta + \frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha] \rightarrow V_{\max} [\cos \beta + \frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha]$$

Finally: $V_{Mean} = \frac{E\left(\alpha - \frac{\pi}{3} - \beta\right) + V_{Max}\left(\cos \beta + \frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha\right)}{\frac{\pi}{3}}$ as the full average voltage formula.

Set point 1.

$$\alpha = \frac{4.9ms}{10} \times 180 = 88.2^\circ \rightarrow \times \frac{\pi}{180} = 1.539rad/s$$

$$\beta = \frac{0.7ms}{10} \times 180 = 12.6^\circ \rightarrow \times \frac{\pi}{180} = 0.22rad/s, \text{ this is taken by measuring the distance on the graph and working out the time per division.}$$

$$E_{measured} = 640mv \rightarrow 64V, \text{ take as } 73.5 \text{ from drive for calculations}$$

$$V_{Mean} = \frac{E\left(\alpha - \frac{\pi}{3} - \beta\right) + V_{Max}\left(\cos \beta + \frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha\right)}{\frac{\pi}{3}}$$

$$V_{Mean} = \frac{73.5\left(1.539 - \frac{\pi}{3} - 0.22\right) + 587\left(\cos 0.22 + \frac{1}{2} \cos 1.539 - \frac{\sqrt{3}}{2} \sin 1.539\right)}{\frac{\pi}{3}} = 89.82V$$

Set point 2.

$$\alpha = \frac{4.15ms}{10} \times 180 = 74.7^\circ \rightarrow \times \frac{\pi}{180} = 1.304rad/s$$

$$\beta = \frac{0.95ms}{10} \times 180 = 17.1^\circ \rightarrow \times \frac{\pi}{180} = 0.298rad/s$$

$$E_{measured} = 350mV \rightarrow 35V$$

$$V_{Mean} = \frac{E\left(\alpha - \frac{\pi}{3} - \beta\right) + V_{Max}\left(\cos \beta + \frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha\right)}{\frac{\pi}{3}}$$

For this equation, Alpha was taken from the drive to provide more accurate results.

$$\alpha(drive) = 92.54^\circ \rightarrow \times \frac{\pi}{180} = 1.6rad/s$$

$$V_{Mean} = \frac{35\left(1.6 - \frac{\pi}{3} - 0.298\right) + 587\left(\cos 0.298 + \frac{1}{2} \cos 1.6 - \frac{\sqrt{3}}{2} \sin 1.6\right)}{\frac{\pi}{3}} = 50.9V$$

Set point 3.

$$\alpha = \frac{4.71ms}{10} \times 180 = 84.78^\circ \rightarrow \times \frac{\pi}{180} = 1.48rad/s$$

$$\beta = \frac{0.475ms}{10} \times 180 = 8.55^\circ \rightarrow \times \frac{\pi}{180} = 0.149rad/s$$

$$E_{measured} = 1.01V \rightarrow 101V$$

$$V_{Mean} = \frac{E\left(\alpha - \frac{\pi}{3} - \beta\right) + V_{Max}\left(\cos\beta + \frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right)}{\frac{\pi}{3}}$$

$$V_{Mean} = \frac{101\left(1.48 - \frac{\pi}{3} - 0.149\right) + 587\left(\cos 0.149 + \frac{1}{2}\cos 1.48 - \frac{\sqrt{3}}{2}\sin 1.48\right)}{\frac{\pi}{3}} = 123.67V$$

Measured					Displayed				Calculated					RPM	Torque(Nm)
Va	t(α)	t(β)	E	Ia	Va	α	E	Ia	Va	α(deg)	α(rad)	β(deg)	β(rad)		
80	4.9ms	0.7ms	64	2.18	82	88.8	73.5	2.2	89.8	88.2	1.539	12.6	0.22	400	2.88
45.1	5.14ms	0.95ms	35	2.16	45.84	92.54	37	2.2	50.9	74.7	1.304	17.1	0.298	200	2.87
114	4.71ms	0.475ms	101	2.18	117	85	107.7	2.18	124	84.78	1.48	8.55	0.149	600	2.92

Table 2: Discontinuous current results for three speed set points

Analysing the results in table 2, there are similarities between measured and displayed. Armature voltage has a small difference, however remains very similar. The calculated values differences can be explained by discrepancies in measuring. As the measuring requires lining up cursors onto the graph, there is some parallax error, meaning timing for alpha and beta is slightly different to actual. As this error is not consistent it can vary depending on the error and this explains why set point 3 calculated value of 124V is 10V off measured. This error coupled with a small deviance in V_{max} or line voltage mentioned earlier affects the result.

The firing angle becomes larger to decrease the speed and vice versa, as this is determined by the voltage. The current affects torque and so stays consistent as extra current is not being drawn. Beta becomes larger the lower the speed as more voltage becomes negative, swaying the average. The back-EMF is visible and varies relative to the voltage.

All four quadrants operation

The system was allowed to run in each quadrant, finally cycling between all four, the results are as follows.

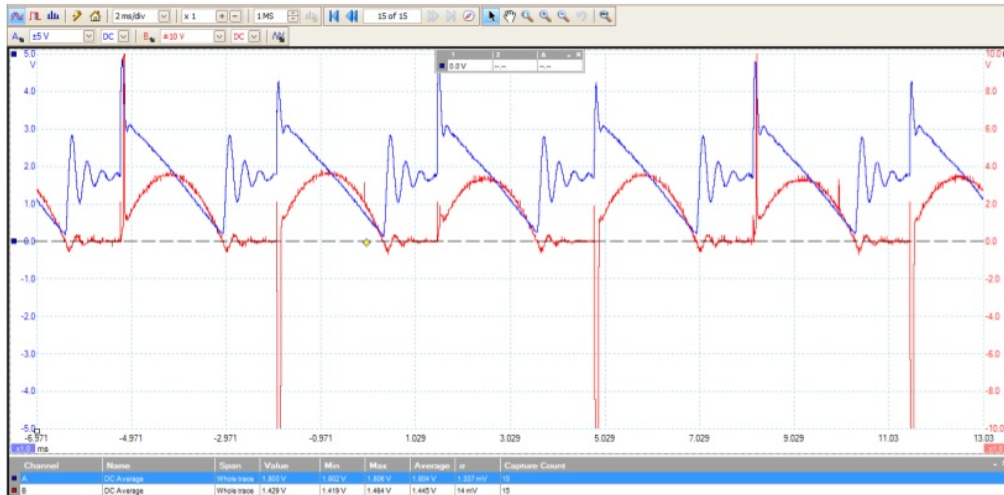


Figure 23: Picoscope Quadrant 1

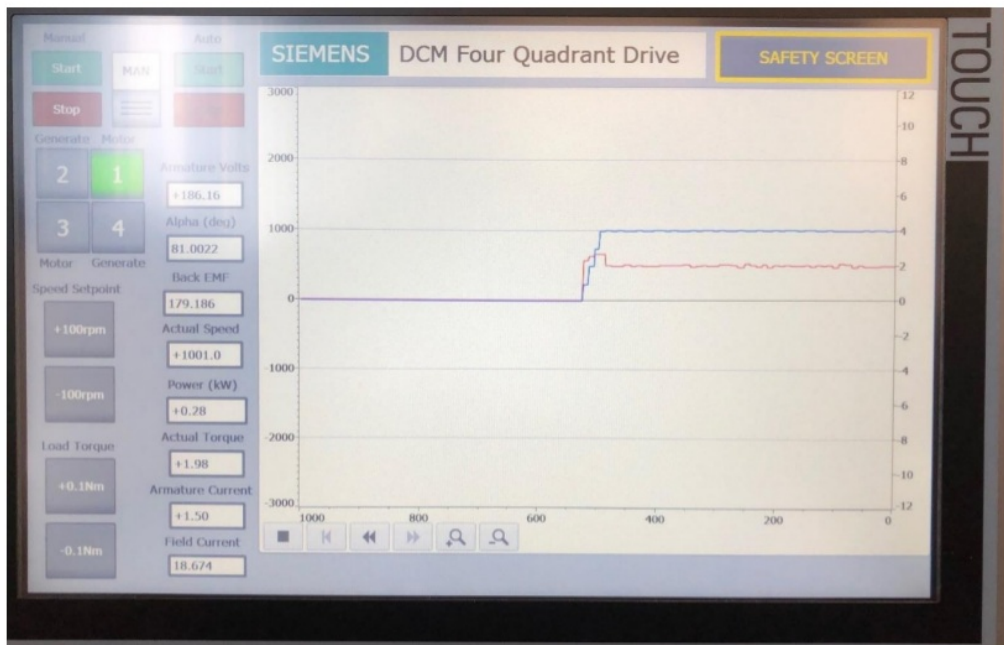


Figure 24: HMI Quadrant 1

The practical results for running quadrant 1 are shown in figures 23 and 24. Unique to this quadrant is positive current and voltage, indicating forward motoring.

Quadrant 2 is displayed in figures 25 and 26, here the voltage can still be seen positive on the picoscope, but current negative. At this point the motor is generating in the forward direction, Alpha is driven past 90° to achieve this, whilst the second bridge rectifier will be in use. The change from quadrant 1 to 2 is visible on figure 26, also the back-EMF can be seen greater than the armature voltage.

To run quadrant 3, the drive dials back alpha to sub 90° and maintains using the second rectifier circuit to motor in reverse with negative current and voltage. Figures 27 and 28 show this, along with the change from two to three. It can be seen that the change is not instant, as the speed drops off until zero before going negative and rotating in the reverse direction.

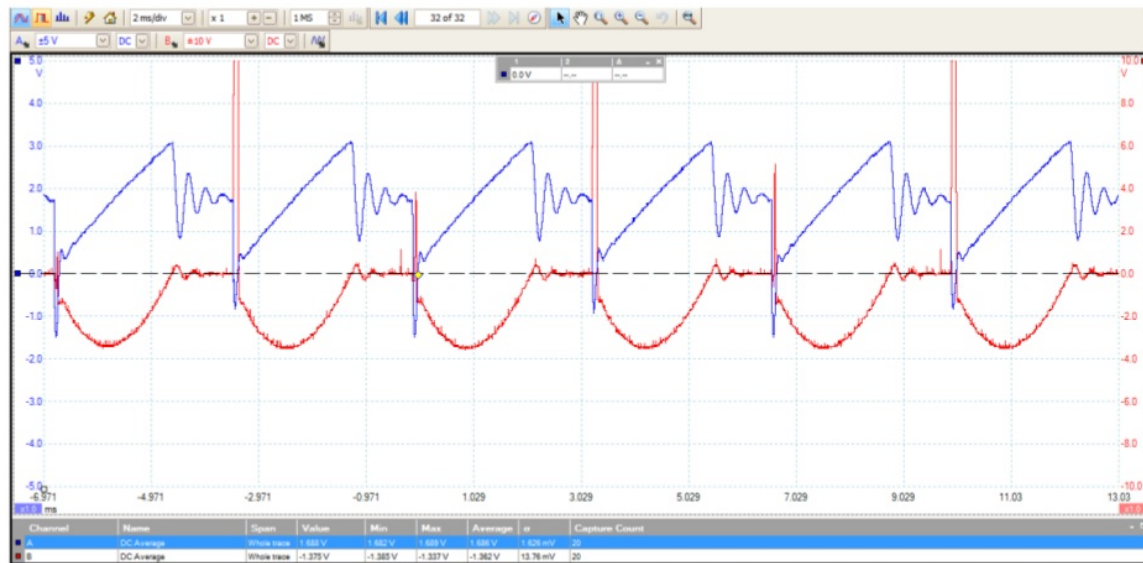


Figure 25: Picoscope Quadrant 2

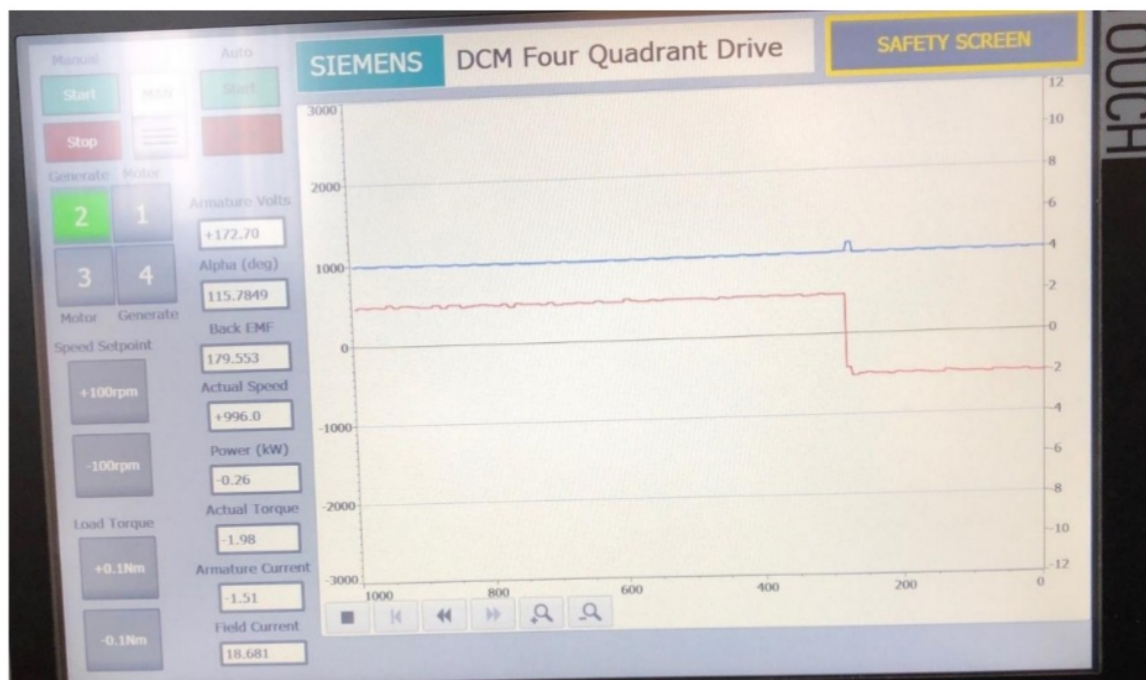


Figure 26: HMI Quadrant 2

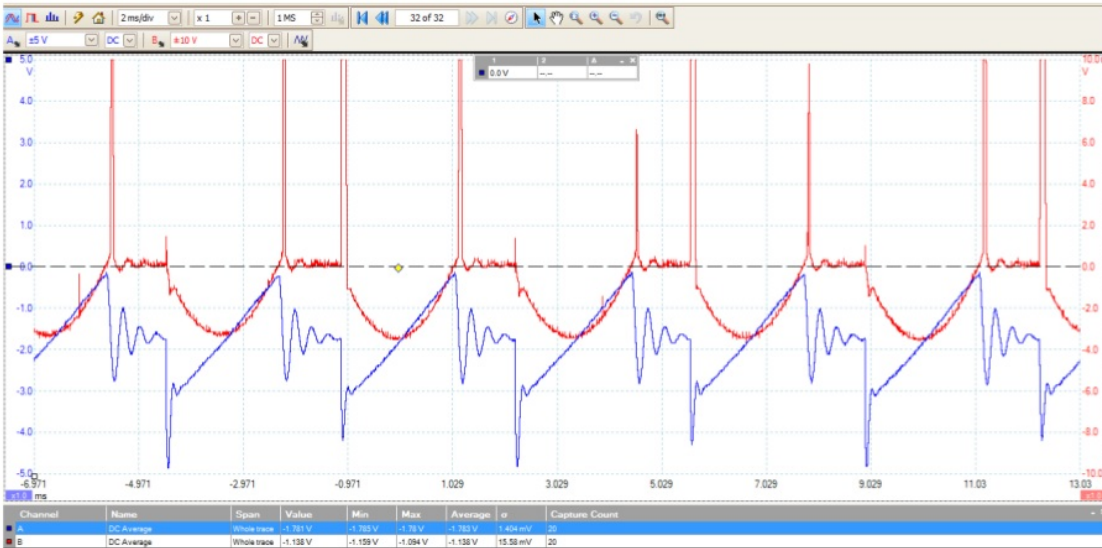


Figure 27: Picoscope Quadrant 3

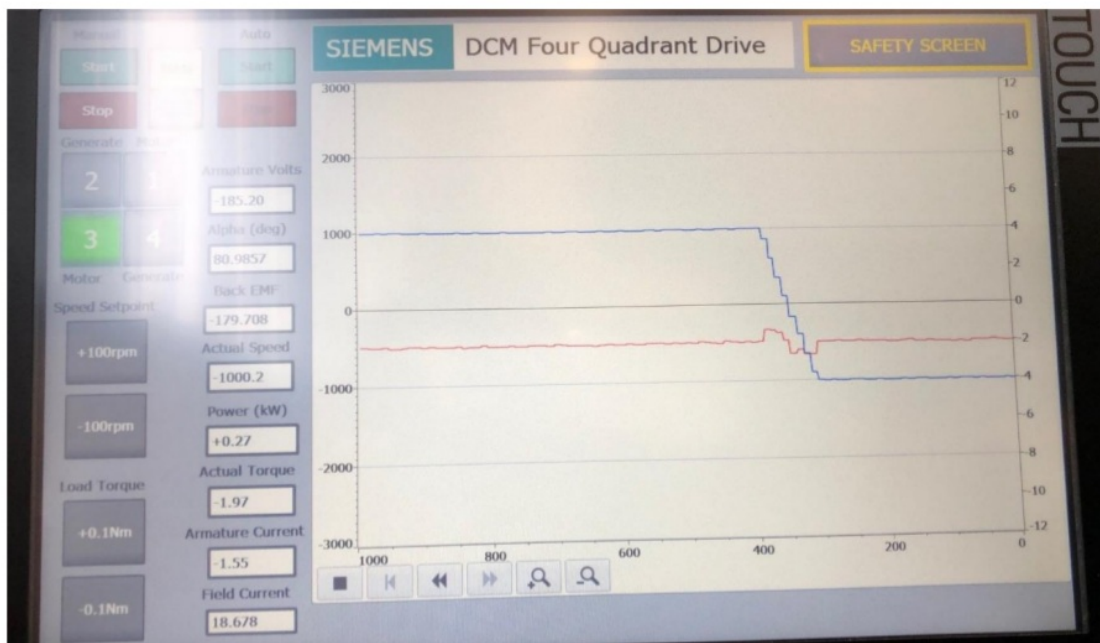


Figure 28: HMI Quadrant 3

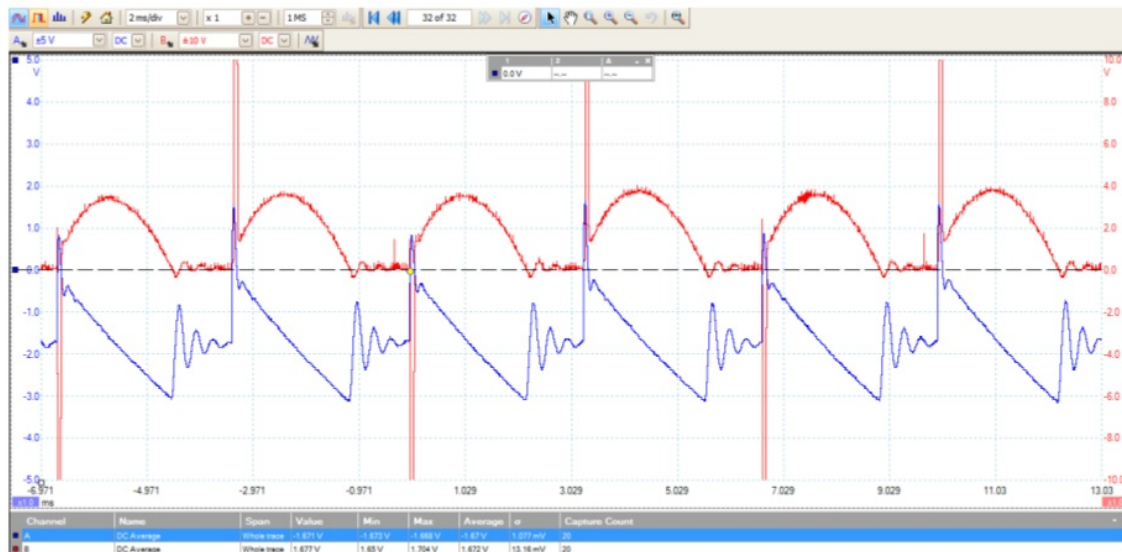


Figure 29: Picoscope Quadrant 4

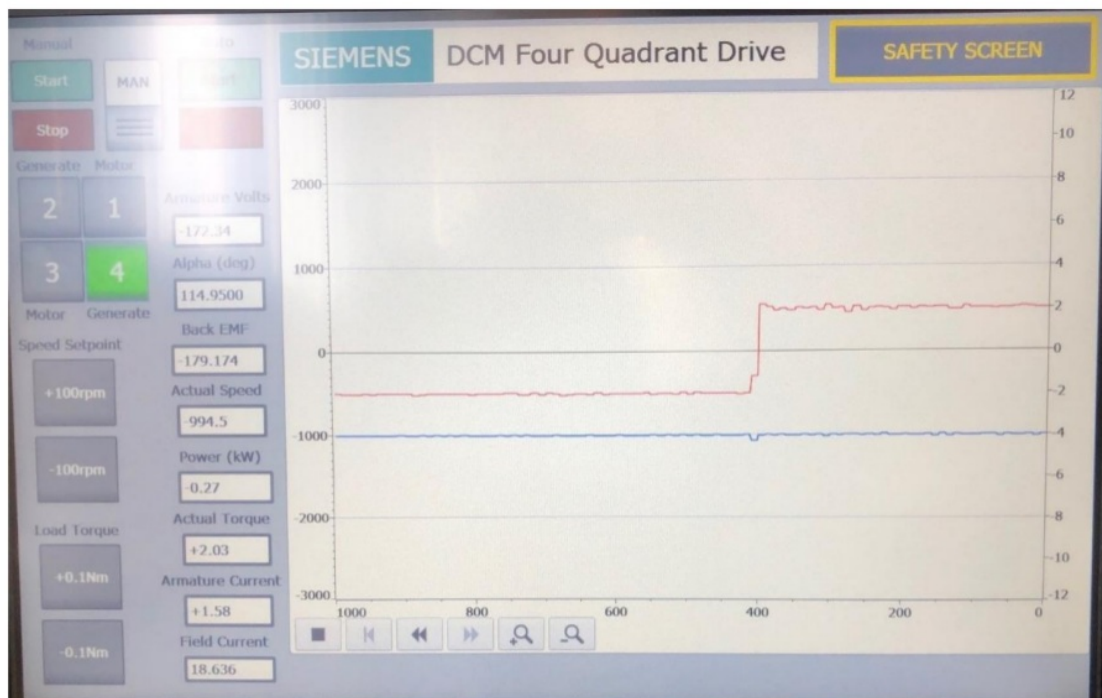


Figure 30: HMI Quadrant 4

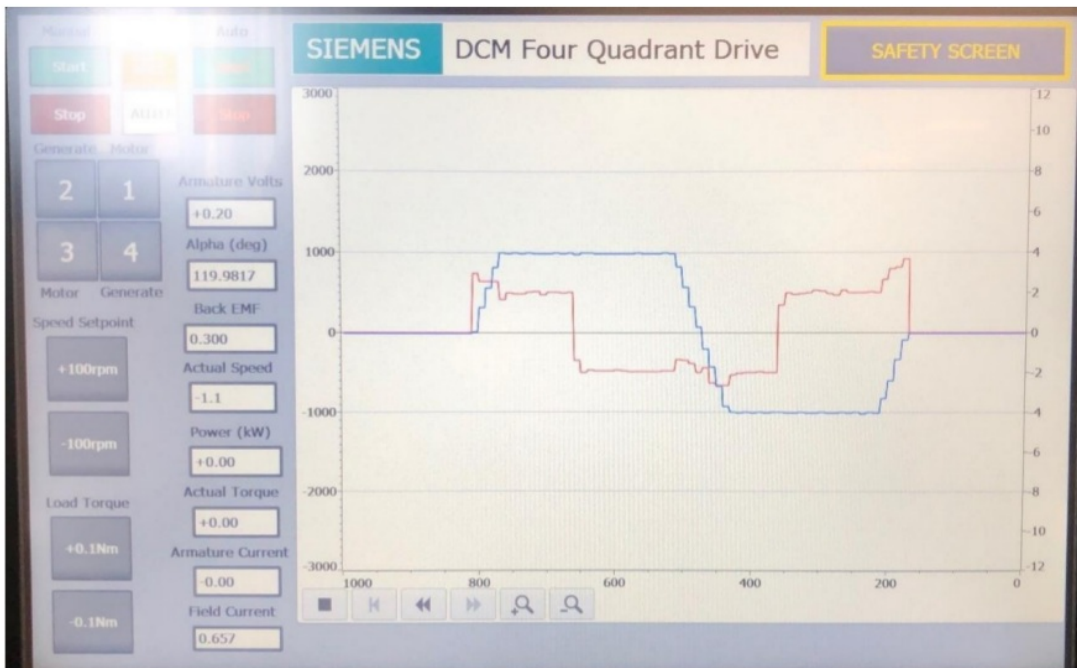


Figure 31: Picoscope four quadrants

Figures 29 and 30 show quadrant 4, reverse generating. This is because the current is now flowing using the positive bridge, however voltage is negative. Once again alpha is greater than 90° but the back-EMF is more negative than the armature voltage, and so the motor is generating.

The motor was run through all four quadrants, figure 31 shows how the drive cycles through the quadrants. The motor torque step changes to the regenerative quadrants with the only delay being bridge change over. The speed takes a while to reverse as the negative voltage begins to slow it down and reverse direction.

4. Simulation and Design Adaption

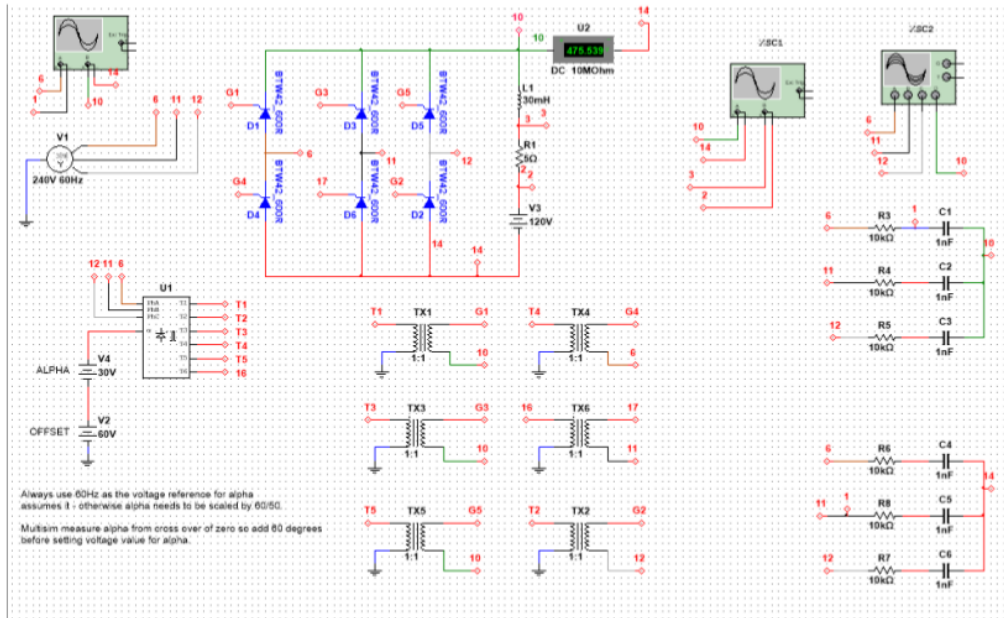


Figure 32: Simulation circuit

A simulation was run using the circuit shown in figure 32, this uses a single thyristor rectifier circuit with the firing angle dictated by the voltage on the left. As multisim uses a separate timing point (cross over) for measuring alpha, an offset of 60 is used. An array of transformers is used to boost the output to the thyristors. The inductor, resistor and voltage represent the armature with scopes on to measure the voltage and current waveforms. The transformers are used to separate power to the gate when firing to prevent interference. A three phase 240V 50Hz source in delta configuration is used to deliver power, while the inductor and resistor are used to represent the armature. A multimeter is tied in to read the average voltage.

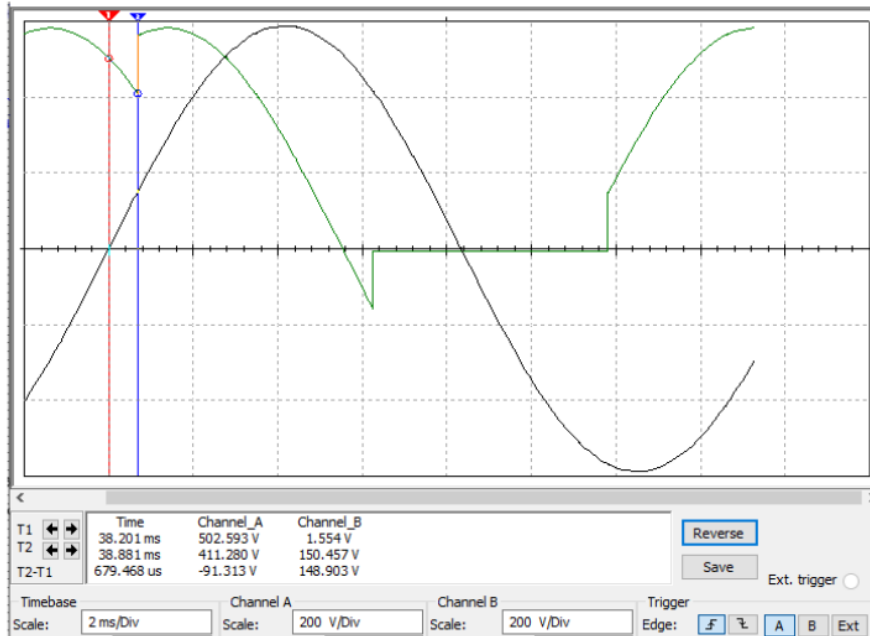
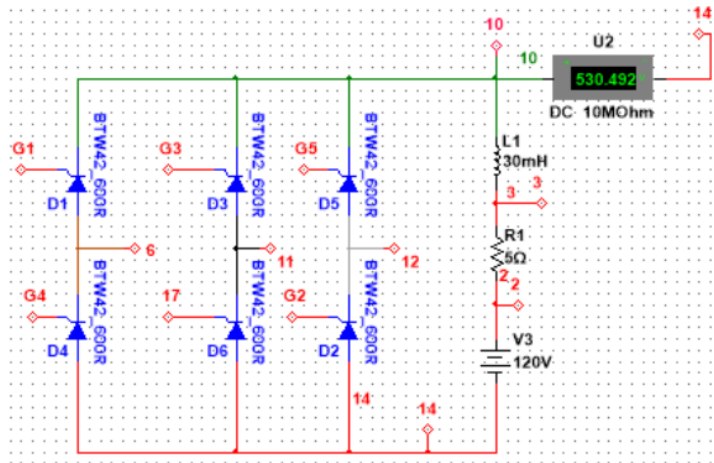


Figure 33: Alpha of 15 degrees



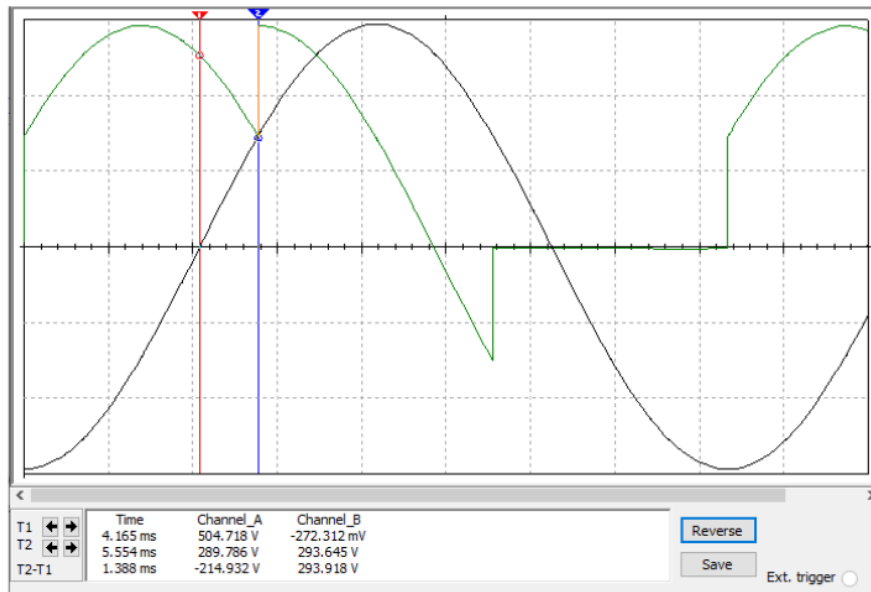
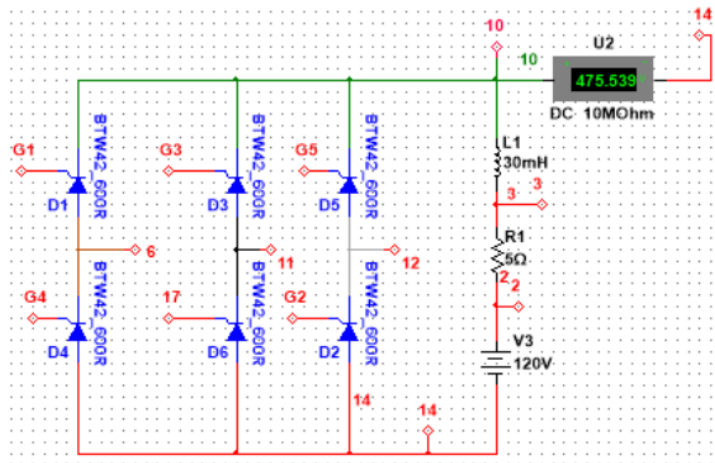


Figure 34: Alpha of 30 degrees



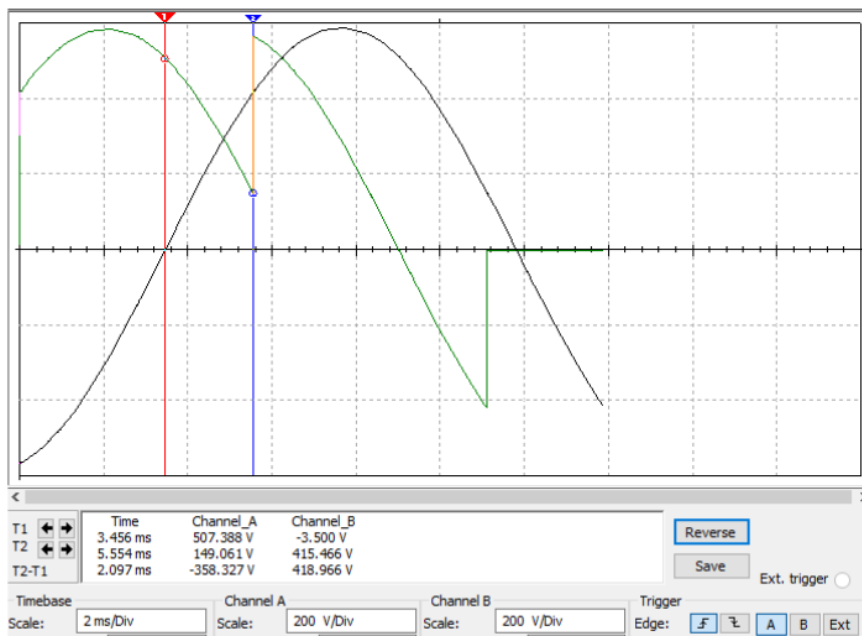
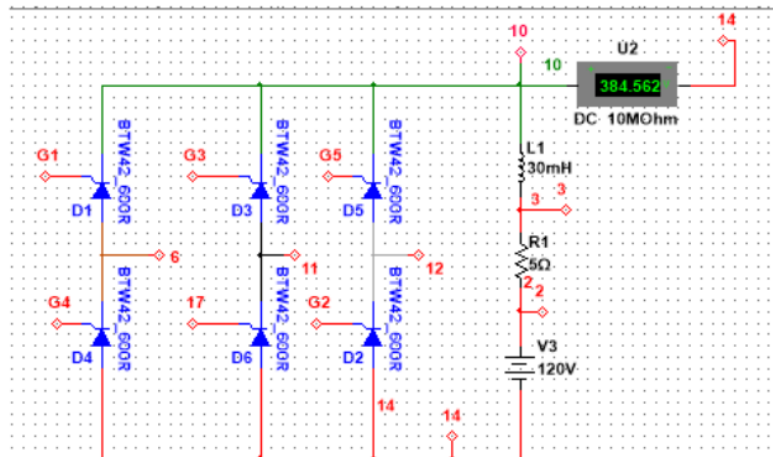


Figure 35: Alpha of 45 degrees



Figures 33 to 35 show how the time for alpha becomes larger as the average voltage drops.

Simulation calculations

Set point of 15° Measured $V_{Mean} = 530.2V$

$$\alpha_{measured} = \frac{0.679ms}{10} \times 180 = 12.22^\circ \rightarrow \times \frac{\pi}{180} = 0.213rad/s$$

$$\alpha_{simulated} = 15^\circ \rightarrow \times \frac{\pi}{180} = 0.2618rad/s$$

$$V_{Max(line)} = \sqrt{2} \times 415 = 587V \quad V_{Mean} = \frac{3V_{Max}}{\pi} \cos \alpha$$

$$Using \text{ measured } \alpha; V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.213 = 547.87V$$

$$Using \text{ simulated } \alpha; V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.2618 = 541V$$

Set point of 30° Measured $V_{Mean} = 475.54V$

$$\alpha_{measured} = \frac{1.388ms}{10} \times 180 = 24.984^\circ \rightarrow \times \frac{\pi}{180} = 0.436rad/s$$

$$\alpha_{simulated} = 30^\circ \rightarrow \times \frac{\pi}{180} = 0.5236rad/s$$

$$V_{Max(line)} = \sqrt{2} \times 415 = 587V \quad V_{Mean} = \frac{3V_{Max}}{\pi} \cos \alpha$$

$$Using \text{ measured } \alpha; V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.436 = 508.1V$$

$$Using \text{ simulated } \alpha; V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.5236 = 485.44V$$

Set point of 45° Measured $V_{Mean} = 384.562$

$$\alpha_{measured} = \frac{2.097ms}{10} \times 180 = 37.746^\circ \rightarrow \times \frac{\pi}{180} = 0.6588rad/s$$

$$\alpha_{simulated} = 30^\circ \rightarrow \times \frac{\pi}{180} = 0.7854rad/s$$

$$V_{Max(line)} = \sqrt{2} \times 415 = 587V \quad V_{Mean} = \frac{3V_{Max}}{\pi} \cos \alpha$$

$$Using \text{ measured } \alpha; V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.6588 = 443.24V$$

$$Using \text{ simulated } \alpha; V_{Mean} = \frac{3 \times 587}{\pi} \cos 0.7854 = 396.36V$$

Table 3 displays the simulated versus calculated values for armature voltage.

α°	Simulation V_a	Calculated V_a using measured α	Calculated V_a using sim α
15	530.2	547.9	541
30	475.5	508.1	485.44
45	384.56	443.24	396.36

Table 3: Simulated and calculated average armature voltage

Comparing the simulation armature voltage with the two calculated values shows some differences. When using the measured alpha, the accuracy varies for each set point. This is down to variance in the measurements, using the cursor by eye means there will always be some difference. As the time for alpha is so small, these differences have a large outcome on calculating the angle. Comparing to the simulation V_a , there is a notable difference of at least 15V. When the raw alpha value is used for calculations, the results are more accurate. Here the parallax error is eliminated and so the results come within a reasonable tolerance. The remaining error is down to a difference with V_{max} as the volt drop across the thyristors is not accounted for.

Four quadrant simulation

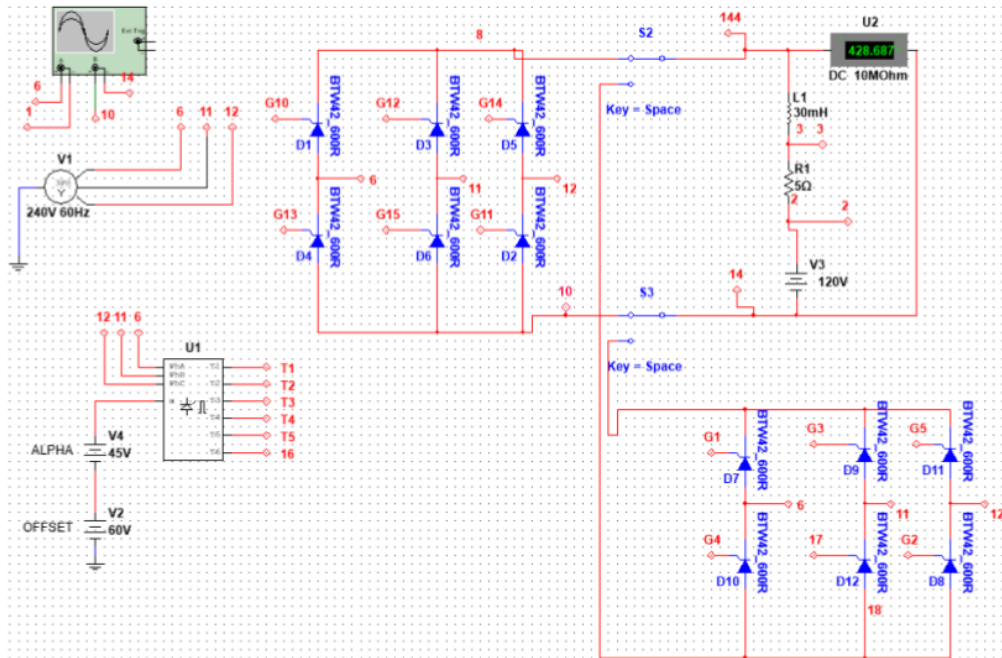


Figure 36: Four quadrant modified circuit.

Figure 36 shows the circuit having been modified for four quadrant operation. This is done by adding an extra thyristor bridge in the opposite direction. The bridges are switchable to allow the motor to alternate between allowing positive or negative current. Operating this switch also changes over firing to the correct thyristors.

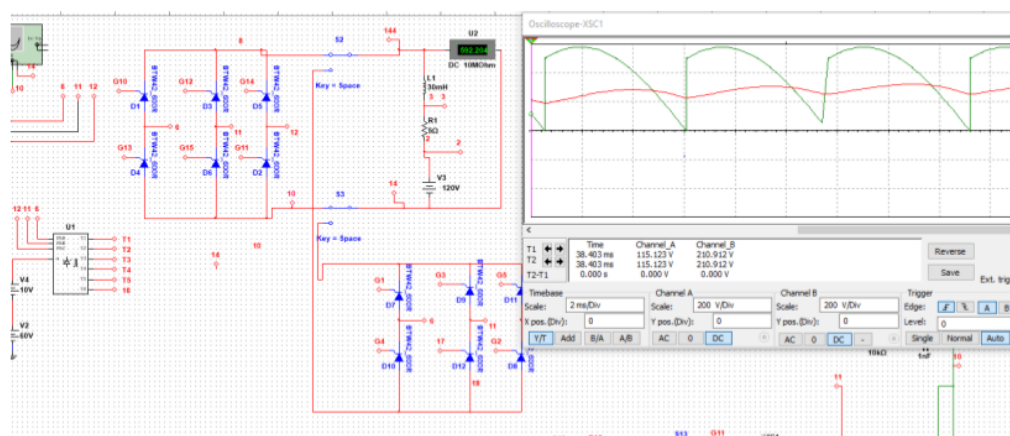


Figure 37: Quadrant 1 operation

Figure 37 displays quadrant 1 with positive current and voltage seen at the armature. The first positive thyristor bridge is selected for use and alpha is below 90° .

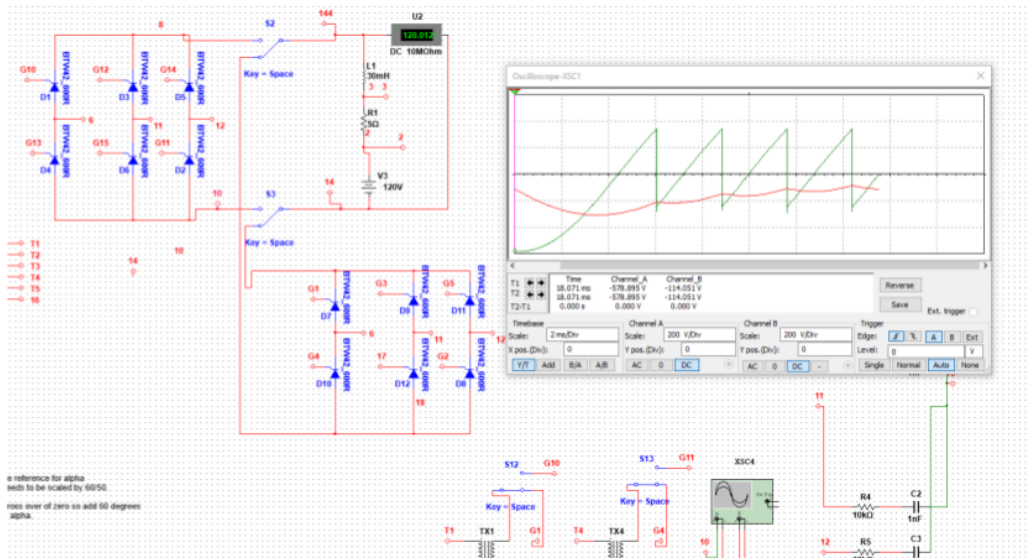


Figure 38: Quadrant 2 operation

Quadrant 2 is shown in figure 38 with negative current but positive voltage. Here alpha remains below 90° but the negative bridge rectifier is used, simulating regenerative braking.

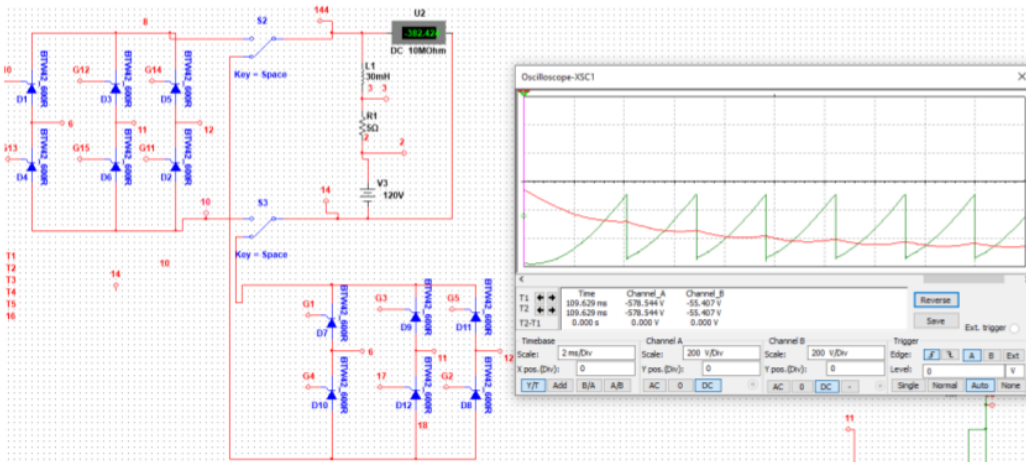


Figure 39: Quadrant 3 operation

Negative current and voltage is shown in figure 39 as the simulation is in quadrant 3. The average armature voltage is negative with alpha greater than 90° and second bridge rectifier selected for reverse motoring.

Difficulties with the multisim simulation meant that errors occurred when attempting to simulate quadrant 4. The scope would have displayed positive current using the first bridge rectifier, but negative voltage and an alpha above 90° .

5. Conclusions and Recommendations

To summarise the research, it was found that DC motors are more maintenance heavy than AC, potentially causing reliability and cost issues. However, their versatility can outweigh this as they have excellent control of speed and torque and are used in a variety of applications that AC motors could also be used for. The advancement of modern AC motors means they can be cheaper in the long run whilst achieving almost the same performance as a DC drive. Larger upfront costs for the drive and additional control are balanced by reliability. Therefore, AC motors may slowly replace DC in many applications that can suit both, but for niche control requirements, and regenerative applications, the DC motor will remain the most suitable.

From the simulation results, the value for average voltage decreases as alpha increases. To improve accuracy the measured value for alpha should be used in calculations. With the addition of the second thyristor bridge, the drive can perform all four quadrants by allowing current to flow forward and back to the supply. The current builds before settling out due to the nature of the inductance. Overall, finer tuning will be needed to get better performance out of the drive and reduce losses through manual switching in this design.

Analysing the results of the practical, there are differences between the results versus calculated. For continuous current, a value for alpha cannot be measured and so has to be taken from the drive. This means the difference between the armature voltage calculations must be down to the value for maximum voltage. To correct this, V_{line} should be measured and V_{max} will need to be adjusted to compensate for the volt drop across the thyristors. Recalculating these figures will then bring the results closer to an acceptable level. Measured values for alpha and beta used in discontinuous should not be hand measured and the raw values used instead. Small changes in these measurements have a large effect on the result.

Overall the drive successfully controlled the motor all four quadrants in the practical. The simulation and practical results show how opposite polarities of current and voltage mean regenerative and the same polarities equate to motoring. The voltage controls the speed and direction, whereas the current determines the direction of flow and torque, the theory backs this up. DC motors, although potentially costly, are still a viable method of control in many applications.

6. Team Working

The team working allowed a combination of knowledge and skills from different industry backgrounds to be applied to carrying out the experiment. The team was split up into setting up, monitoring and recording data from the picoscope, while the other member adjusted and monitored the HMI. Sticking to a role each enabled the members to work efficiently while co-operating, without overwhelming any task with all members at once.

7. Citation List

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8. Appendix List

FINAL GRADE

GENERAL COMMENTS

Instructor

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GRADING FORM: NEW CSG-RUBRIC

**DANIEL
INCE**

65

1. ENGAGEMENT WITH LITERATURE



Engagement with a wide range of research-informed literature, including sources retrieved independently. Selection of relevant and credible sources. Correct method of listing sources using Harvard but many of your citations use an incorrect method. You have focused in your research on AC motors rather than AC drives. (13/20)

13

2. KNOWLEDGE AND UNDERSTANDING



Knowledge is reasonably extensive coherent and detailed. Exhibits very good understanding of the breadth and depth of established views, and the work is, at least in part, well-informed by current

12

research and scholarship. (12/20)

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. (14/20)

14

4. PRACTICAL APPLICATION

 An advanced application of a range of methods, materials, tools and/or techniques. The context of the application is well considered, and insightful. Application and deployment extend beyond established conventions. Can identify complex problems and propose excellent solutions. Innovation and creativity evident. (16/20)

16

5. TRANSFERABLE SKILLS

 Can communicate professionally confidently and consistently in a suitable format. Work is coherent, very fluent and is presented professionally. Can work autonomously with initiative. Where relevant can work professionally within a team, showing leadership skills as appropriate, managing conflict and meeting obligations. Demonstrates excellent graduate employment skills and an appetite for further development. Word count penalty applied (-5) (10/20)

10

