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by David Thomas

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This is a well structured and presented report

Generally well written but has some spelling errors

Executive summary is very good but too long

Research utilises a wide range of sources mostly credible except for one which is ambiguously cited

Good understanding shown

Analysis of results is very good and very good conclusions drawn up

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1. Executive Summary

The use of DC motors in industry has declined over the years due to inefficiencies resulting from older control method technology, being superseded by the rapid proliferation of AC power-conversion drives. However, advances in DC drive technology have created drives with effective, simple speed control methods, capable of efficient regeneration and 4-quadrant operation, retaining their use in many applications.

The project aimed to demonstrate established theory of DC-drive operation and control methods. Research was initially undertaken into modern four-quadrant DC-drive design and control hardware and firmware features and their relationship to operation, comparing these to similar drive control types and relating them to application choice. The knowledge gained was then used to inform the practical element of the project and, predict and understand the reasons for results obtained.

The practical element consisted of both simulation and classroom-based activities. Initially a separately-excited DC motor with a 6-thyristor bridge providing full-wave fully-controlled rectification was simulated. Thyristor firing angles were adjusted (15, 30 and 45°) to confirm the effect on armature voltage and compared to theoretical calculations, followed by circuit modification to create a second 6-thyristor bridge enabling a reversal of polarity and demonstration of the move through each of the four quadrants. Comparing the values obtained from the oscilloscope waveforms to that expected from the literature and calculations made.

Analysis of waveforms and HMI data using a DC and AC drive and motor was undertaken. Initial stages successfully demonstrated known relationships between positive and negative voltage and currents in each of the four quadrants. Operation in quadrant one was used to analyse changes made to torque and speed setpoints in continuous and discontinuous current respectively. Changes in speed setpoint at constant torque with discontinuous current affected armature voltage, thyristor firing angles and back EMF, with speed setpoint increase requiring increased power. Conversely with continuous current, torque setpoint decreases resulted in decrease in armature current and power required to drive the motor at a constant speed.

In summary, successful demonstration of DC drive control and operation was achieved, with results obtained supporting the established DC drive theory.

2. Research

ABB DSC880-S02 series drive is a three-phase four-quadrant regenerative DC-thyristor drive that, according to ABB (ABB industrial drives, 2019), offers a scalable, reliable and safe option for industries. They offer a compact design adaptable to customer specifications, able to operate multiple motors, reducing environmental footprints. DSC880-S02 is marketed as an 'All-Compatible' drive, its many design and control features enabling compatibility and flexibility with a number of applications over a significant voltage and power range (ABB industrial drives, 2019).

DCS880-S02 incorporates hardware and firmware enabling operation, fault-finding and system maintenance (ABB industrial drives, 2019). Power conversion of incoming AC to DC is performed by silicon-controlled rectifiers (SCR) (thyristors), available as 6 or 12-SCR pulse configurations, 12-pulse incorporating a converter transformer (3-winding transformer connecting modules), offering reduced 'notching' and better harmonics, reduced noise, and a larger converter output current/voltage (ABB Automation, 2021).

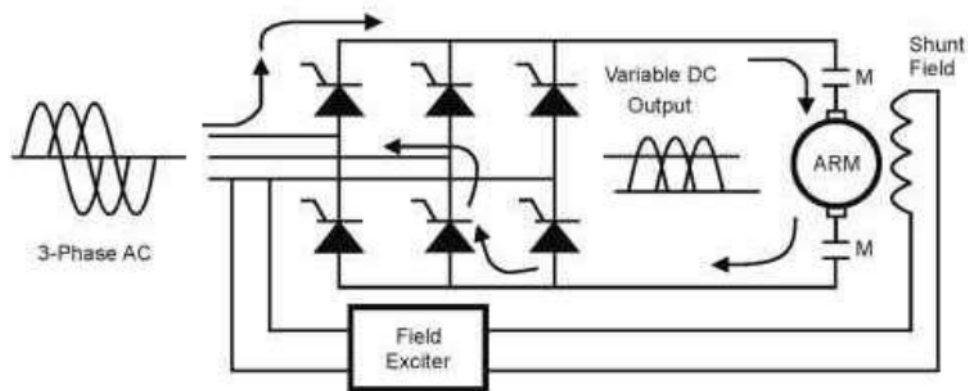


Figure 1 - SCR Full-Wave Bridge Rectification

(What When How, Unknown)

Control is achieved by an electronic unit consisting of an armature converter, (plus optional field-exciter), and thyristor control in the form of a heatsink mounted 6/12-thyristor bridge providing adjustable DC voltage (with little impedance) to the armature (ABB industrial drives, 2019). Drive control programme (firmware) offers improvements in response time and flexibility over older drive types (What When How, Unknown), providing precise control of speed/torque, drive-logic, I/O, fieldbus interface, protection and feedback, which can be individually configured and/or programmed using defined parameters, and further extended by application programs (ABB industrial drives, 2019).

To ensure precision speed control, DCS880-S02 operates a closed (two) loop system (Hughes, 2006), incorporating high-quality tachometer (speed-proportional voltage) feedback, mounted to remove external influences such as ambient temperature. A digital-encoder (ABB Automation Products, 2017) further minimises drift, adding flexibility for self-tuning and interfaces (Hughes, 2006). Reference feedback enables extremely small microprocessor corrections, output voltage for required speed determined by microprocessor response to the reference (What When How, Unknown). The outer-loop acts as a speed-controller (Hughes, 2006):

- reference signal fed to controller
- differences between actual and required speed detected by tachometer,
- speed-error signal produced (What When How, Unknown).

This acts an input to the inner (current) control loop, as simultaneously, the microprocessor signals (using PI amplified error) to SCRs to conduct ('gate-on/fire'), altering thyristor-firing angles, allowing required line voltage to enter the drive and subsequently the armature. Actual speed lower than reference/desired, requires increased acceleration/torque, therefore increase in motor armature current reference. To prevent excessive converter current flow, 'current limiting' is included, important where load seizure results in a sudden motor stalling. Control, paramatizing and diagnosis via serial interfaces adds to control precision. Control of ripple (common problem encountered with DC supply following AC-DC conversion) is also provided, armature inductance minimising/smoothing the effect (acting as a low-pass filter), providing armature time-constant is prolonged in comparison to pulse duration e.g. $1/6^{\text{th}}$ cycle in a 6-pulse drive. Voltage returns to the SCR bridge and power line, and as the cycle reaches completion, a second phase conducts through the next SCR, repeated a set number of times per second determined by line input frequency, providing continuous current, where mean voltage determined by the converter is a result of thyristor angles only, not load current (Hughes, 2006).

To create four-quadrant operation (operation in forward and reverse direction), and allow for rapid reversal and regenerative braking, the power-conversion unit is designed as two antiparallel (double-armature) bridges (ABB Automation Products, 2017).

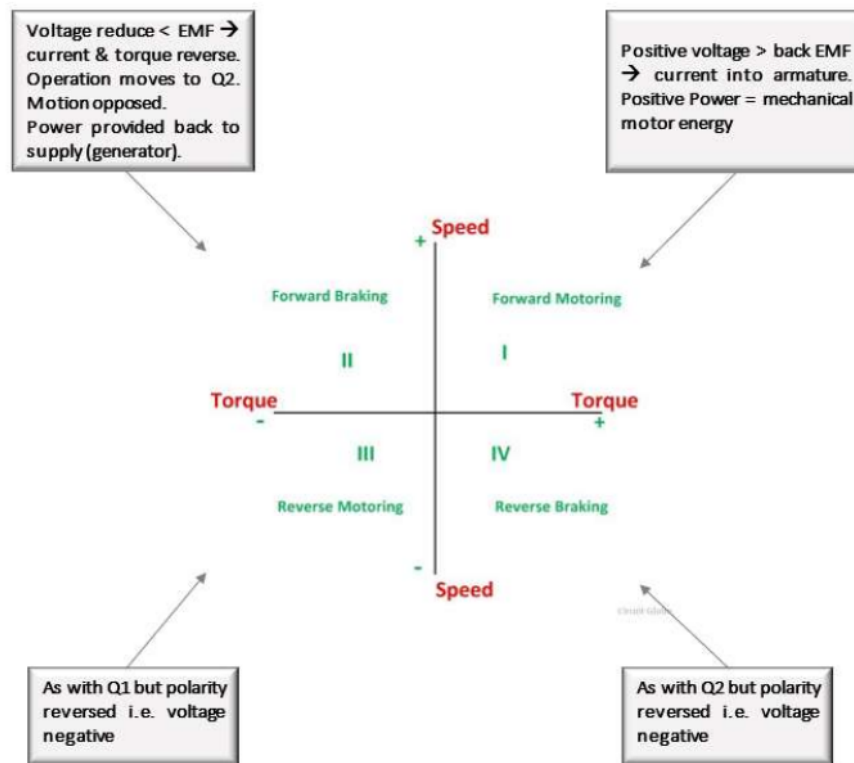


Figure 2 - Four-Quadrant Drive Operation

(Circuit Globe, 2022) (Hughes, 2006)

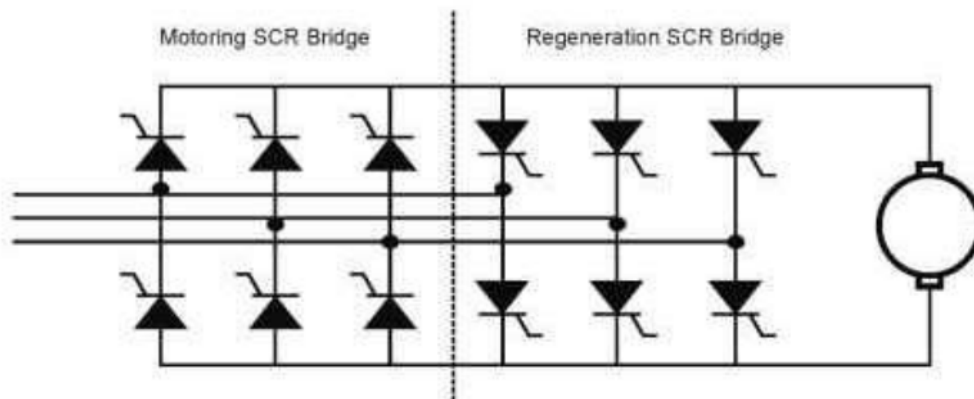


Figure 3 - Regenerative DC drive with two antiparallel bridges

(What When How, Unknown)

These operate with almost equivalent DC voltage to minimise circulating current. Positive and negative voltage is supplied by either, however positive and negative current can only be supplied to the DC motor by each of the two separate converters (bridges), which are phase-controlled to ensure required voltages for the reference are applied to the motor (Drury, 2003). For a change in torque direction, in a millisecond timeframe to maintain dynamic torque-control, one bridge ceases to conduct before the other activates, ensuring no short-circuiting across the armature supply (Austin Hughes, 2019). To minimise 'notching' (momentary line-to-line shorting during current commutation across thyristors (Hughes, 2006), and clean power lines for other equipment as SCRs gate 'on'/'off' (What When How, Unknown), DCS880-S02 includes a line reactor ($\leq 1\%$ impedance) (ABB Automation Products, 2017), important where large drives are connected to weak supplies. Also included is a motor blower providing constant through-ventilation, to ensure continuous motor operation at full torque without overheating (Hughes, 2006).

The dual SCR bridge four-quadrant drive enables regenerative braking, delivering motor energy back into the AC supply as current conducts in the opposite direction. Advanced processing design ensuring SCR signal timing is in-line with line phases, synchronizes voltage generation and feedback to enable efficient operation (What When How, Unknown).

Included as optional extras are field-excitors, providing field windings with constant voltage, generating constant shunt field flux. If the motor is to operate above base speed, the drive can reduce field voltage, and subsequently flux, allowing less EMF counter-effect on the armature, increasing speed (What When How, Unknown).

ABB defined wiring procedures ensure components subject to radiation (interference) from operations such microprocessor and semiconductor switching (ABB Automation Products, 2017), e.g. tachometer and process sensors, are subject to grounding/shielding (What When How, Unknown).

An essential control design element is provided by firmware and embedded programmable drives enabling efficient end-user application. DCS880-02 offers adaptive programming allowing control programs for different applications, and support of fieldbus protocols. Flexibility for command location means it can have fieldbus, master-follower, hardware signal control, or a combination (ABB industrial drives, 2019). For efficient operation, application changes result in swift drive functioning reprogramming through simple software design with fibre-optic capability. Remote monitoring with web interfaces allow drive parameters to be configured, performance monitored, and maintenance performed, with all data stored in a removable memory device and fed into a centralized database (ABB Automation Products, 2017). Further design benefits include multi-language programming (ABB industrial drives, 2019) allowing use across different countries with simple language changes of the programming set-up (What When How, Unknown).

DC-thyristor drives retain prominence in industry where speed-control is required. Three-phase four-quadrant drives similar to above enable DC machines to operate as bi-directional energy converters with regenerative braking and rapid reversal (Hughes, 2006). Applications involve; loads using an 'up/down' motion, where the risk of speed exceeding that commanded exists e.g. cranes, hoists, and conveyers, or with machine tools where these drives offer high speed and performance, and ability to rapidly change direction (What When How, Unknown). Three-phase converter drives are used in high-power applications, with continuous current enabling better motor performance. (Hughes, 2006)

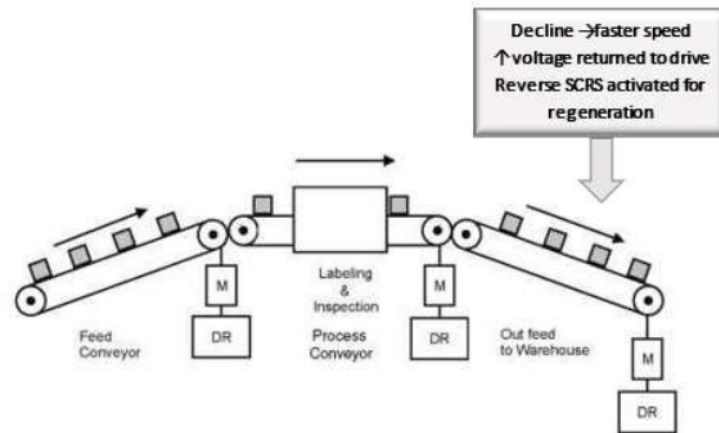


Figure 4 - Conveyor system using regenerative drive operation

(What When How, Unknown)

Similar to three-phase, single-phase converters are capable of 4-quadrant operation, but require a dual-converter (Sushmita, Unknown). As single-phase supply is only up to 230V, (compared to three-phase 415V) and has a lower power-factor regulation, these are used for small appliances ($\leq 15\text{kW}$) such as fans, heaters and coolers. Comparatively to three-phase, single-phase converters require special start windings, and are larger in size (Hughes, 2006).

With DC rather than AC supply, applications requiring speed control commonly employ the chopper drive, allowing a fixed input to generate a variable output. Comparatively to three-phase four-quadrant DC-thyristor drives with continuous current supply, motor current from chopper drives flows only for part of the cycle from each supply terminal. With single-switch choppers, only positive voltage/current is supplied, resulting one-quadrant operation. Similar to thyristor-drives, four-quadrant operation is possible, however significant costs are incurred with regeneration or fast reversal due to more complicated circuitry incorporating multiple power switches (Hughes, 2006). These drives are extensively used in battery-operated vehicles/transit systems requiring bi-directional operation (Arof S, 2019), replacing

conventional DC-thyristor drives due to flexibility, efficiency and fast response in a small, lightweight form. They have less armature ripple-current due to high-switching frequencies, reducing motor losses (Hughes, 2006).

Although DC drive advances have continued industrial application (Hughes, 2006), especially in low-speed high-torque applications such as cranes, modern power-electronic development has proliferated variable-speed control AC drives, allowing both DC and AC motors to have the same torque-speed response (Epri, 1998), four-quadrant AC-drive operation requiring a second set of reverse-connected power semi-converters (What.When.How, Unknown). Generally, AC drives are more energy-efficient, with lower operation costs, maintenance needs, and ability for rapid-speed reversal. They are increasingly used in industry over DC drives for applications with significant load variability, and extended periods of lighter loads where DC drive motor brushes/commutators wear rapidly (ElectricalTechnology, 2021).

However, drive selection is not as simple as the above suggests. With significant overlap between drive types, and many other factors to be considered, a comprehensive specification is essential (Hughes, 2006).

Factors to Consider	Comments
Cost to purchase	Initial drive expenditure
Operating costs	Maintenance, processing and logistics
Technological requirements	Voltage range, dynamic response, 4-quadrant operation, size, regeneration, emergency stop etc.
Reliability	Availability of drives/spares, environmental conditions, servicing, rapid response repairs
Distortion possibilities	Effects on surrounding networks
Heat emission	Form factor used to match drive & motor. High ripple = additional heating & ↓efficiency. Affected by rectifier type; SCR = ↓form factor & ↑cost
Space constraints	Size of the drive (and motor), accessibility for repairs

Table 1 - Example of factors to consider in drive selection

(ElectricalTechnology, 2021) (ABB Automation Products, 2001)

The first obvious selection criteria is type of motor requiring controlled i.e. driver-motor compatibility (ABB Automation Products, 2001), essential for economic comparisons to be made (Epri, 1998). Consideration of load requirements must factor; where loads with constant torque require speed control, although induction/inverter-fed motors, DC or any self-synchronous drives could be used, the only drive able to automatically operate continuously at low speeds at full torque is DC. AC drives incorporating such capabilities are expensive and operationally complex (Hughes, 2006). Comparatively, wide-range, fan-type loads can operate with cheaper inverter-fed induction motors. Torque-speed characteristics at

steady-state must be considered e.g. rolling mills requiring constant speeds despite load change benefit from regeneration DC or AC drives incorporating tachometer/encoder feedback. Full regeneration capability comes at considerable cost, it is not simply energy-saving to consider, but more often performance, such as rapid-reversal requiring kinetic energy removal. AC drives are smaller, lighter, less noisy, have a higher power-to-weight ratio, and are more readily available than DC drives, the latter requiring space to incorporate SCR bridges, and cooling elements (Hughes, 2006). Additionally, AC drives are almost exclusively used in hazardous environments being ‘spark-free’ (no brushes) (ElectricalTechnology, 2021), with specialised enclosures significantly cheaper than their DC counterparts (Hughes, 2006). Lack of commutators and brushes in AC motors mean AC drives are more reliable, and have readily-accessible part replacements, meaning lower ongoing costs (ElectricalTechnology, 2021). However, it is accepted DC drive complexity is notably less, with a single power-conversion, and therefore are often less expensive initial outlay for many horsepower ratings (Epri, 1998).

Design Requirement	AC or DC (Cost)
1-quadrant drives <40 – 80kW	AC drive cheaper
4-quadrant drives >40...60 kW	DC drive cheaper
Regenerative 4-quadrant drives > 15 kW	DC drive cheaper

Table 2 - Example of cost comparison of AC/DC drives

The table below can aid initial AC/DC drive choice, more ‘Yes’ increasing the preference for DC drives (ABB Automation Products, 2001).

Requirement	Yes/No
Four quadrant operation PLUS regeneration	
Continuous operation in particular at lower speeds	
Minimise heat generation	
Acceleration/deceleration frequent	
Extensive speed range at a constant power >1:1.5	
No hazardous areas and degree of protection for motors $\leq$ IP54	
Accessibility for maintenance	

Table 3 - Useful pro-forma for drive consideration

(ABB Automation Products, 2001)

In a wider aspect, impact on incoming supply must be considered, with converter-fed drives causing distortion and interference with sensitive equipment. Evaluation and control of non-linear load harmonic distortion from power-conversion devices like thyristors is essential. Although some smaller drives incorporate power electronic conditioning factors, this is not common with larger industrial drives and the need to incorporate necessary filters, at a cost, must be

discussed with manufacturers (ABB Automation Products, 2017) to ensure compliance with statutory limitations e.g. EN-6100-6/IEEESTd519-1992 (ABB Automation Products, 2017) (Hughes, 2006)

Advancement in digital power-conversion technology means technically most industrial regenerative applications are achievable with both AC and DC four-quadrant drives/motors. With this comes significant technical overlap, a number of considerations required for drive/motor suitability. Implications on economics (outlay vs lifecycle), reliability and operation mean certain drive-types are more appropriate for individual applications. Upgrading an outdated speed-controller to a four-quadrant drive to provide significant efficiency and process gains for a functioning DC motor would be more economically viable than replacement with entire AC drive/motor system, however the latter may be preferential where complete replacement is required due to lifecycle economy gains. Defined user specifications with understanding over processes and needs, along with manufacturer engagement are key in decisions over configuration requirements and drive choice.

3. Simulation & Design Adaption

For the simulated model (shown in appendix 9.1), a separately-excited DC motor is modelled as a load, by an inductor, resistor and back EMF. For full-wave, fully-controlled rectification, 6 thyristors are placed in the circuit. The 6 thyristors are representative of bridge 1 of a DC drive, used to fully rectify the waveform. A controller is used to send a signal, dependant on value of alpha. Voltage inputted to the controller determines the simulation's firing angle, with 60° added to the firing input. 60Hz supply is simulated for the simulation input. 1:1 ratio transformers are used to supply power from the controller to thyristors, which although not required to power the simulation, represent real-world scenarios. Transformers provide isolation for the rectification, one side being connected to earth, providing device safety. Oscilloscope probes are placed across the separately-excited DC motor model and resistor, measuring current and voltage waveforms.

With the fully-controlled three-phase rectifier firing in quadrant 1 (positive current and voltage), the firing angle was set to zero to produce circuit V_{MAX} value. With V_{MAX} obtained, three values of α are selected to represent circuit firing angles.

$$V_{mean} = \frac{3V_{max}}{\pi} (\cos \alpha)$$

Equation 1 - Average Armature Voltage Equation

With simulated V_{MAX} obtained, and simulation firing angles selected, average armature voltages were calculated for each of the selected firing angles using the equation above.

Shown below, for selected firing angles (α), there is little difference between simulated and calculated average armature voltages. Differences seen can be attributed to volt drops in the thyristors.

Alpha α	V_{MAX}	Simulated Armature Voltage	Calculated Armature Voltage	Difference
15°	575.858v	530.78	531.17	0.39
30°	575.858v	475.856	476.23	0.374
45°	575.858v	388.46	388.841	0.381

Table 4 - Armature Voltage Comparison

Alterations were made to the simulated circuit (see appendix 9.1). By revising polarity of the back EMF and increasing α to beyond 90°, current remains positive whilst voltage goes negative, resulting in the simulated circuit firing in quadrant 2, simulating forward regenerating of the motor.

Illustrated below, (see appendix 9.2 for larger image), further simulation alterations were made. Addition of 6 further thyristors represent bridge 2 of the DC drive. With these thyristors having a reverse polarity compared to bridge 1, waveforms produced display firing angles of the drive in quadrant 3 (negative voltage and current), displaying motoring in reverse. Altering polarity of the back EMF as well as bridge 2 firing angles changes operation from quadrant 3 to quadrant 4 (negative voltage and positive current), displaying reverse regenerating (see appendix 9.2 for illustration of drive operation).

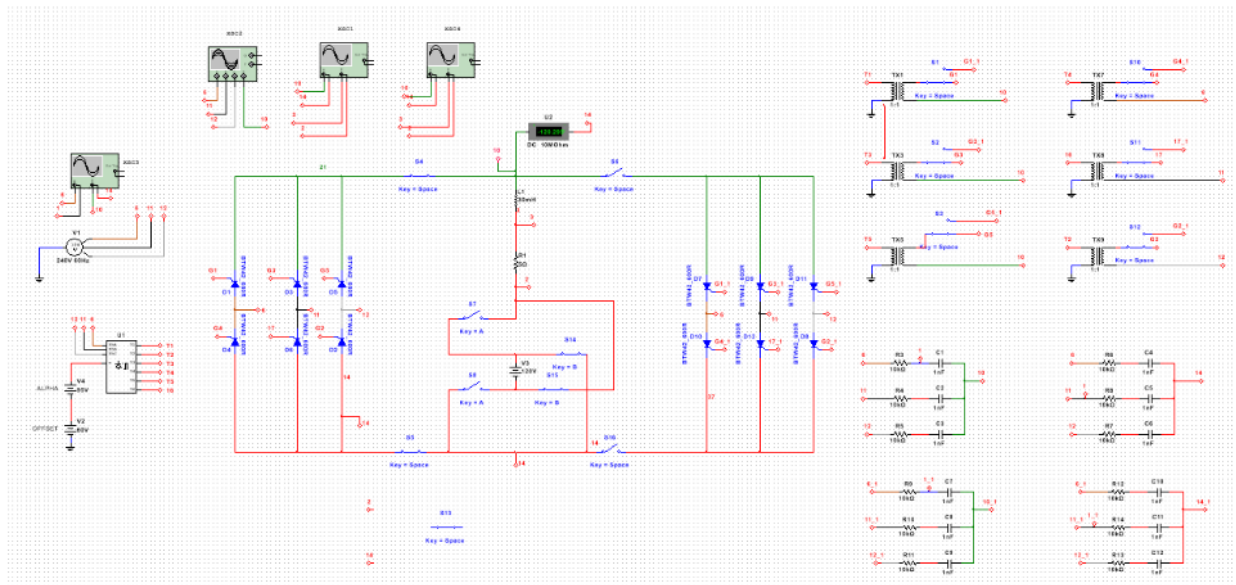


Figure 5 - Adapted Circuit for 2 Bridges

4. Practical Investigation

The experimental setup consisted of a sinamics DCM Converter Unit (drive 1), S120 AC drive (drive 2) and two motors, one DC (Motor 1) and one AC (Motor 2) (see appendix 9.3 for image of setup). Both drives are supplied by a filtered three-phase 400VAC supply, with each AC input and output phase having a choke to smooth current peaks caused by the inverter. The DCM converter unit regulates supply to the field and armature of motor 1 and is able to provide and maintain sufficient power for four-quadrant operation with integrated field power, as well as being capable of low-ripple torque at slower speeds and a wide range of speed control whilst providing constant power. The S120 AC drive operates and controls motor 2, used as part of the setup to simulate a load for motor 1. The HMI screen allows for complete setup control, allowing alteration of motor 2 resistance by defining the torque setpoint and input for motor 1 by defining the speed setpoint. A Profinet connection from the PLC and drives give the required data for the motor's feedback and drive outputs. Multiple monitoring devices, power analyser and Picoscope are used for monitoring and providing live values of voltage, current, back EMF, input supply current and field current of the DC motor.

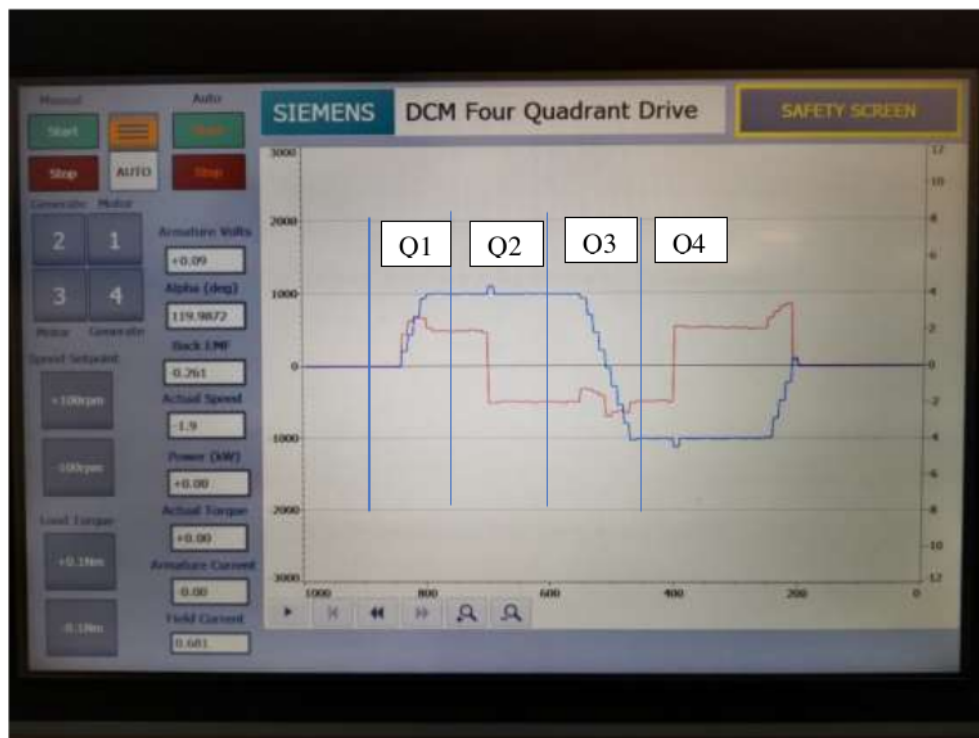


Figure 6 - HMI of all 4 Quadrants

Shown above is the HMI trace of DC current and voltage for the DCM four-quadrant drive controlling a DC motor; voltage blue trend line, current red trend line. The trace displays all four quadrants the drive is capable of producing. Initially the drive goes into quadrant 1, both current and voltage being positive, with the motor forward motoring. As the red trend line (current) drops to negative and blue trend line (voltage) remains positive, the drive is in quadrant 2; forward regenerating. When both current and voltage trend lines drop to negative, the drive is in quadrant 3 and reverse motoring. Finally, as current trend lines move positive and voltage remain negative, the drive is in quadrant 4, reverse regeneration of the motor.

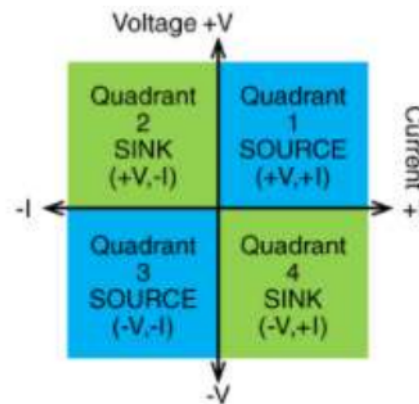


Figure 7 - Four Quadrant Operation Representation

(Matsusada, 2021)

Trend Line Colour	Trend Line Representation	Symbol
Green Line	Supply Voltage	V_s
Yellow Line	Supply Current	I_s
Blue Line	Armature Voltage	V_A
Red Line	Armature Current	I_A

Table 5 - Picoscope Trend Lines

Shown in appendix 9.3 are Picoscope images for operation all four quadrants. In each image, trend lines are representative of the recorded data shown in the table above. In each of the four quadrants the blue line represents armature voltage (V_A), displaying thyristor firing. Each time the thyristor fires, there is an oscillation, caused by settling of back EMF. Thyristor firing also causes a slight dip in supply voltage (V_s), likely 'notching' due to thyristor commutation. After firing of each thyristor, waveforms for each V_A , will match each waveform of the three-phase cycles of V_s ; between 90° and 180° for negative half cycles and 270° and 360° for positive half cycles. The negative cycle is rectified by the

thyristors, negative AC voltage changing to positive AC voltage. Armature current (I_A) (red line), will peak at a lower point compared to supply current (I_s) as a result of losses in the converter. When I_c trend lines peak, D_1 D_T are equal to zero. if no losses were present, waveforms of I_c and I_s would be identical.

The DC drive was run in quadrant one demonstrating discontinuous current. Three different speed values were selected using the same torque setpoint. Data for all three tests were recorded (illustrated below) (see appendix 9.3 for test waveforms and power analyser data).

Discontinuous Current Test Data				
	Symbol	Test 1	Test 2	Test 3
Speed	rpm	1001.2	1501	2046.4
Torque	N_M	1.83	1.8	1.86
Armature Voltage	V_A	185.95	273.13	362.26
Alpha	α	81.1285	71.142	52.64
Back EMF	E	178.754	270.961	361.522
Power	KW	0.27	0.41	0.6
Armature Current	I_A	1.46	1.48	1.71
Field Current	I_F	18.63	18.77	18.693
Cos	ϕ	0.256	0.501	0.665
Power factor	PF	0.256	0.379	0.491
Power	W	0.305k	0.461k	0.595k
Reactive Power	Nvar	1.154k	1.126k	1.056k
Apparent Power	VA	1.194k	1.216	1.213k

Table 6 - Discontinuous Current Test Data

Increase in speed from test one to three has little effect on torque, field current, reactive and apparent power readings. Although some discrepancies between the figures exist, the difference is negligible. However, significant changes appear for armature voltage, alpha, back EMF, power and power factor values. The significant changes are proportional to the desired speed setpoint; as motor speed setpoint is increased whilst maintainig a steady load (torque), more power is needed to provide the desired speed with negligible disruption to overall motor output performance.

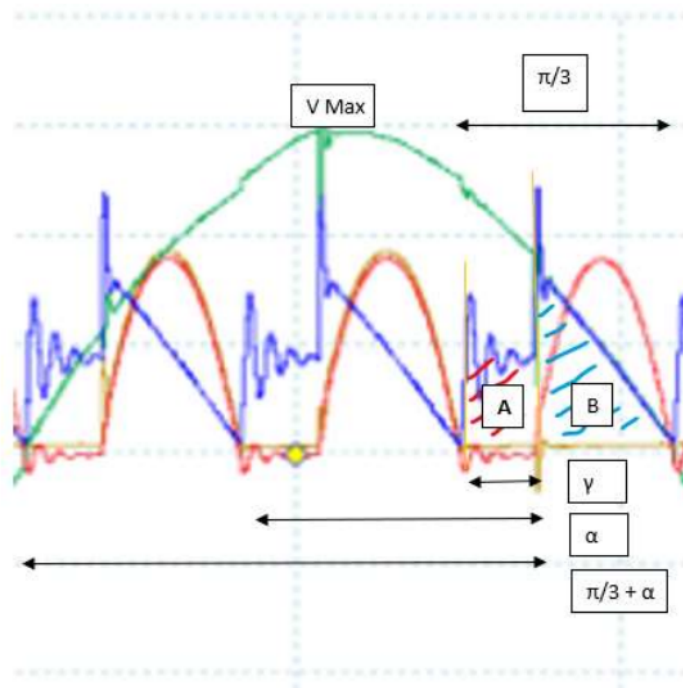


Figure 8 - Picoscope Waveform for Discontinuous Current

Data gathered from the picoscope waveform, (illustrated above) is required calculate average armature voltage for discontinuous current. The following equations are used to calculate section A and B areas of the waveform, in order to calculate average armature current (see appendix 9.3 for calculations).

$$\text{Area A} = E \times \gamma = E \left(\alpha - \frac{\pi}{3} \right)$$

Equation 2 - Calculation for V-mean Discontinuous Current Area A

$$\text{Area B} = V_{\max} \int_{\frac{\pi}{3} + \alpha}^{\pi} \sin(\theta) d\theta$$

Equation 3 - Calculation for V-mean Discontinuous Current Area B

Discontinuous Current Test Data				
	Simulated Armature Voltage	Calculated Armature Voltage	Difference	
Test 1	185.95v	187.66v	1.71v	0.991%

Table 7 - Discontinuous Current Test Comparison

Shown above are values for test one for the simulated and calculated armature voltage. The difference seen between values of 0.991% can be attributed to volt loss within the drive.

Another test was conducted, to demonstrate continuous current. The DC drive was run in quadrant 1 and three different torque values selected using the same speed setpoint. Data was recorded as illustrated below (see appendix 9.3 for test waveforms and power analyser data).

Continuous Current Test Data				
	Symbol	Test 1	Test 2	Test 3
Speed	rpm	2000.6	1999.0	1998.0
Torque	Nm	6.66	6.03	5.31
Armature Volts	V_A	372.53	371.67	373.81
Armature Current	I_A	5.22	4.61	4.21
Field Current	I_F	18.729	18.654	18.67
Alpha	α	45.791	46.1591	46.4337
Back EMF	E	355.412	355.05	355.277
Cos	ϕ	0.677	0.675	0.675
Power factor	PF	0.614	0.607	0.600
Power	W	1.980k	1.794k	1.611k
Reactive Power	Nvar	2.545k	2.348k	2.146k
Apparent Power	VA	3.224k	2.955k	2.684k

Table 8 - Continuous Current Test Data

Decrease in torque from test one to three has very little effect on drive output and motor performance with respect to speed, armature voltage, field current, alpha, back EMF, and power factor values. Although some discrepancy exists, it is negligible. As torque is decreased between tests, armature current and power values have more significant values of change. As loading of the motor is decreased, less power and current are required to maintain the setpoint speed of 2000rpm. The change in values illustrate the drive is capable of maintaining the same speed setpoint at different loads, with negligible disruption to overall motor output performance.

5. Conclusions & Recommendations

Four-quadrant DC drives remain a very realistic option for speed-control of industrial applications, providing simplicity in control, lower outlay cost and longevity.

The project, designed to demonstrate DC drive simulation, operation and control was successfully executed, with established drive control theory being reflected in motor operation and data produced, visual representation acting as an aid to the understanding of control theory. In all practical elements, similarity between calculated and data/responses generated from simulated and practical execution, demonstrated both calculation accuracy and the simulated design of the modelled DC drive. Four-quadrant capability and operation were evident during simulation and practical execution, with drive operation/control clearly demonstrated by the variation in waveforms and HMI data generated following changes in torque and speed setpoints across continuous and discontinuous current, which although demonstrated a degree of discrepancy from expected (calculated) values, overall reflected the theory. Discrepancies identified, as expected with most theoretical project execution, were likely to be a result of volt losses across the drive and motor.

Although considered a success, with established theory of DC drive operation reflected in the results obtained, comparison of theoretical calculation and simulated armature voltage values for discontinuous current tests at speed setpoints 1500 and 2000rpm were unable to be made, as data could not be obtained from the Picoscope waveforms. There would be value in repeating this to demonstrate theoretical calculated accuracy. In addition, incorporating a six-channel Picoscope into the practical element would allow for ACRMS waveforms to be observed, providing more data on thyristor firing e.g. ability to observe signs of commutation.

6. Team Working & Health & Safety Precautions

Team working was required for practical execution, and in accordance with current national guidelines for COVID-19, social distancing measures, including PPE, were implemented.

Discussions were held regarding data required from the investigation, including required setpoint values to obtain the best possible waveforms. My role was to record and document data and images, which were uploaded to a shared-google drive, for all group members to access.

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9.1. Simulation & Design Adaption



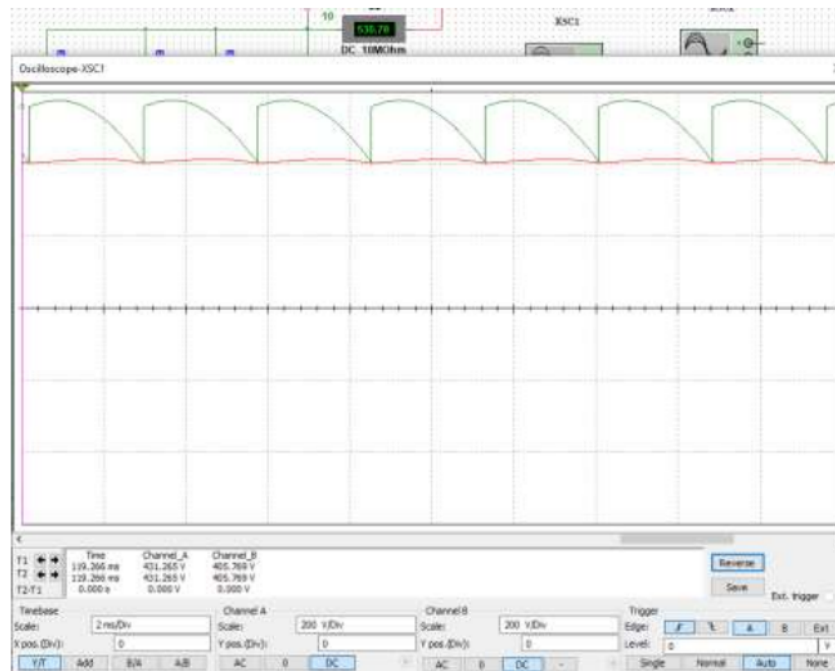


Figure 11 - Simulation - 15 Degree Firing Angle

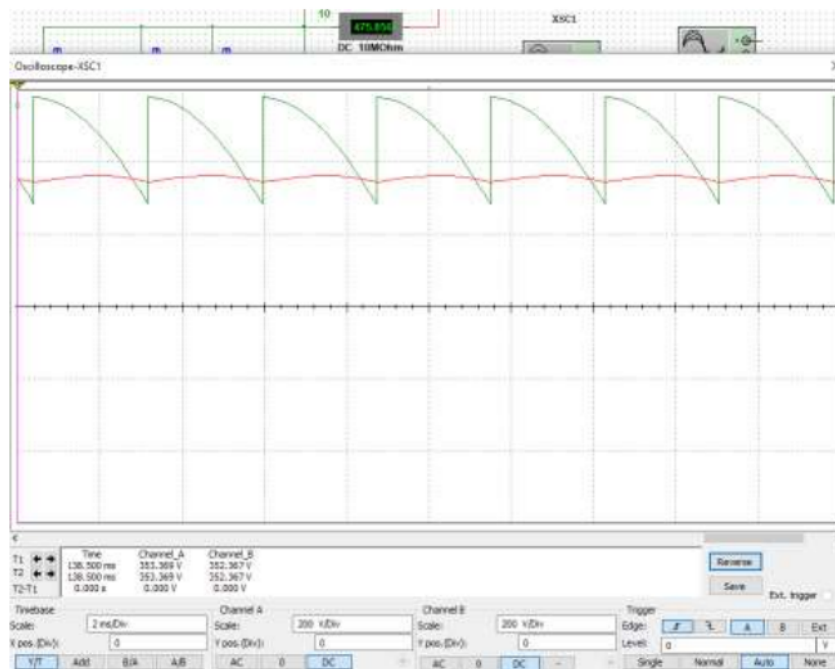


Figure 12 - Simulation - 30 Degree Firing Angle

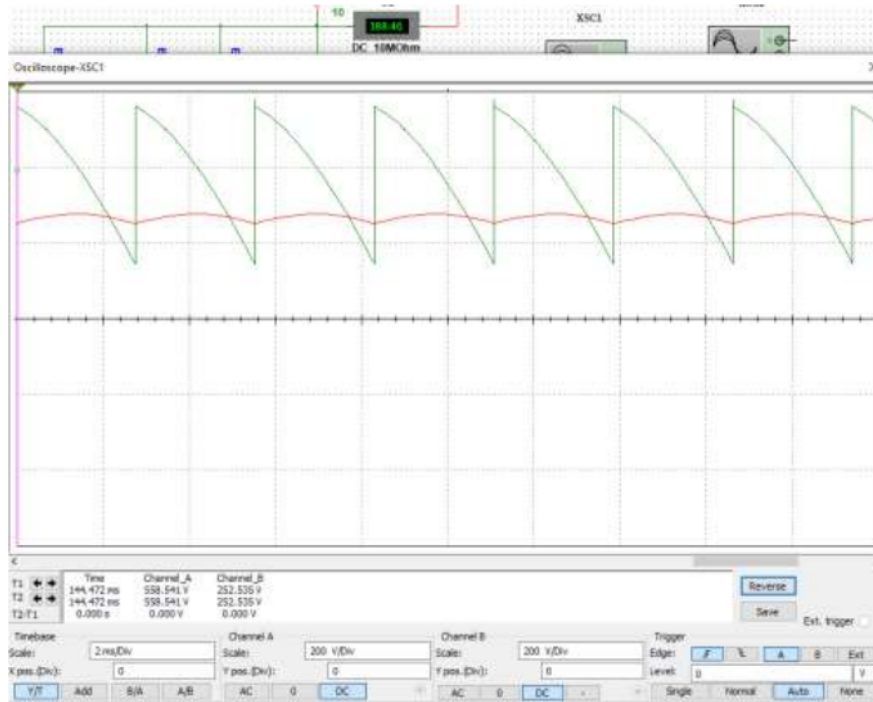


Figure 13 - Simulation - 45 Degree Firing Angle

$$V_{mean} = \frac{3V_{max}}{\pi} (\cos \alpha) = \frac{3 \times 575.858}{\pi} (\cos 15) = 531.17v$$

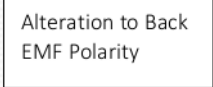
Equation 4 - Simulation - 15 Degree Average Armature Voltage Equation

$$V_{mean} = \frac{3V_{max}}{\pi} (\cos \alpha) = \frac{3 \times 575.858}{\pi} (\cos 30) = 476.23v$$

Equation 5 - Simulation - 30 Degree Average Armature Voltage Equation

$$V_{mean} = \frac{3V_{max}}{\pi} (\cos \alpha) = \frac{3 \times 575.858}{\pi} (\cos 45) = 388.841v$$

Equation 6 - Simulation - 45 Degree Average Armature Voltage Equation

[illegible]

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9.2 Simulation & Design Alteration

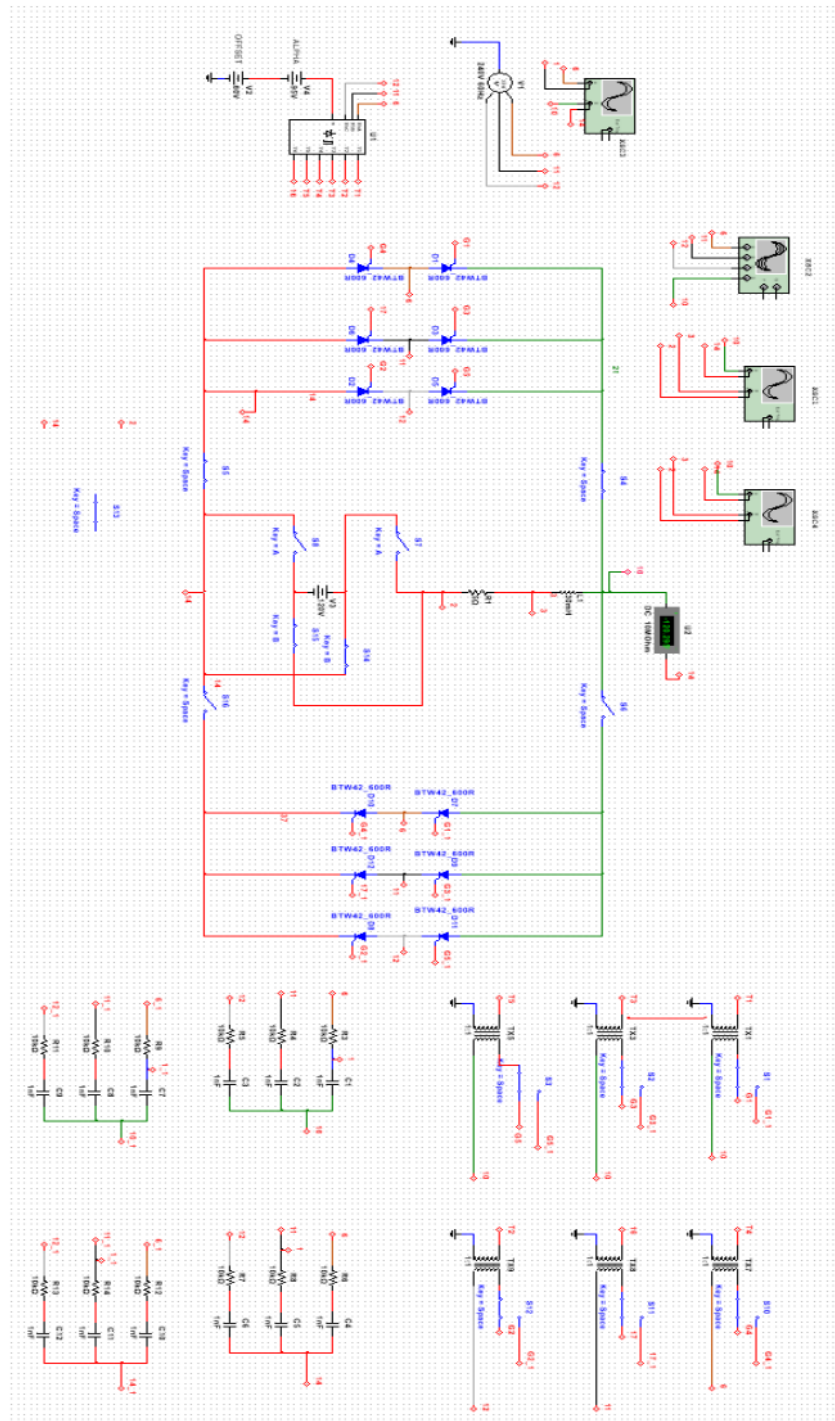


Figure 16 - Simulation - Adapted Circuit for 2 Bridges

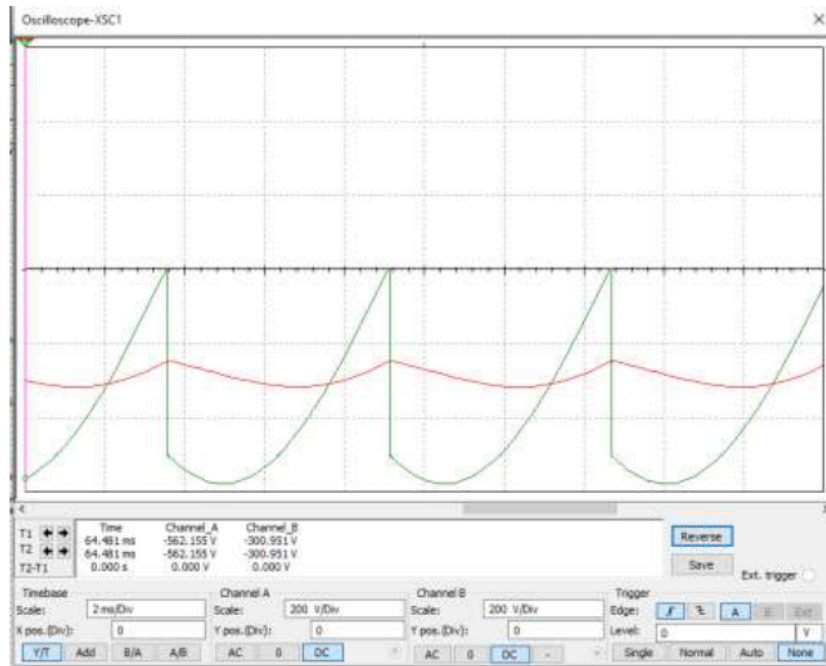


Figure 17 - Simulation - Quadrant 3 Firing Angle

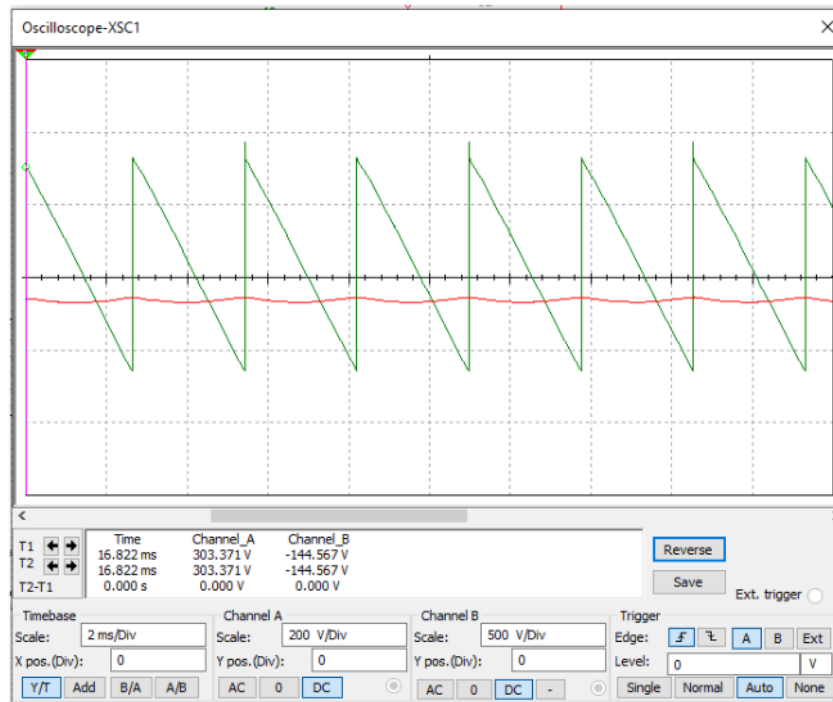


Figure 18 - Simulation - Quadrant 4 Firing Angle

9.3. Practical investigation



Figure 19 - Practical - Drive Setup



Figure 20 - Practical - Motor Setup

Quadrant 1

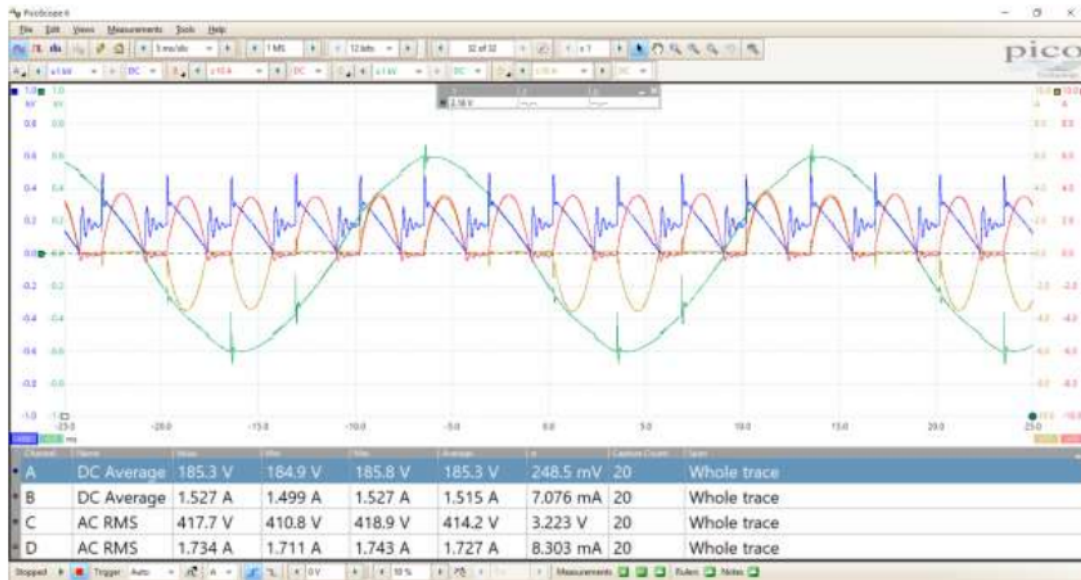


Figure 21 - Practical - Quadrant 1

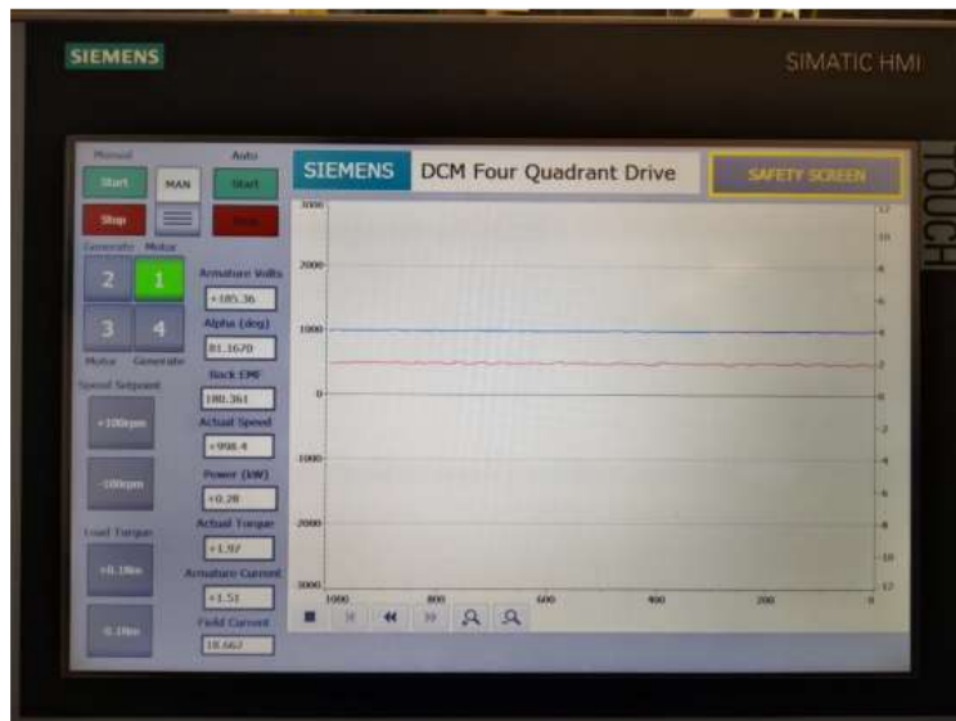


Figure 22 - Practical - Quadrant 1 HMI

Quadrant 2



Figure 23 - Practical - Quadrant 2

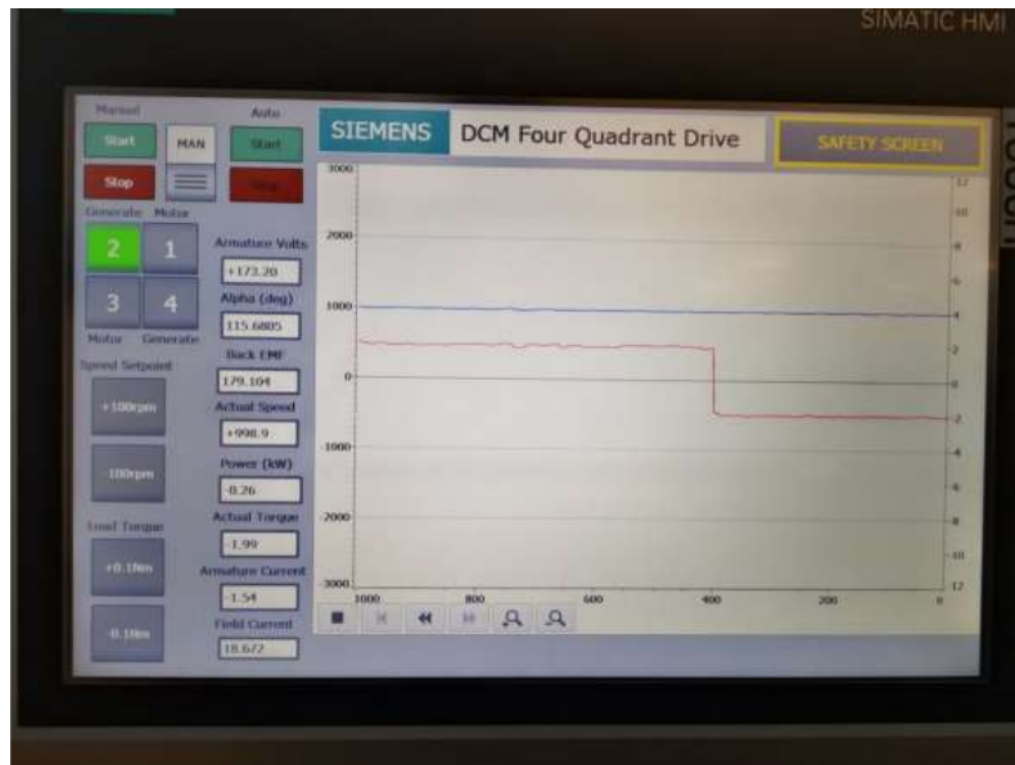


Figure 24 - Practical - Quadrant 2 HMI

Quadrant 3

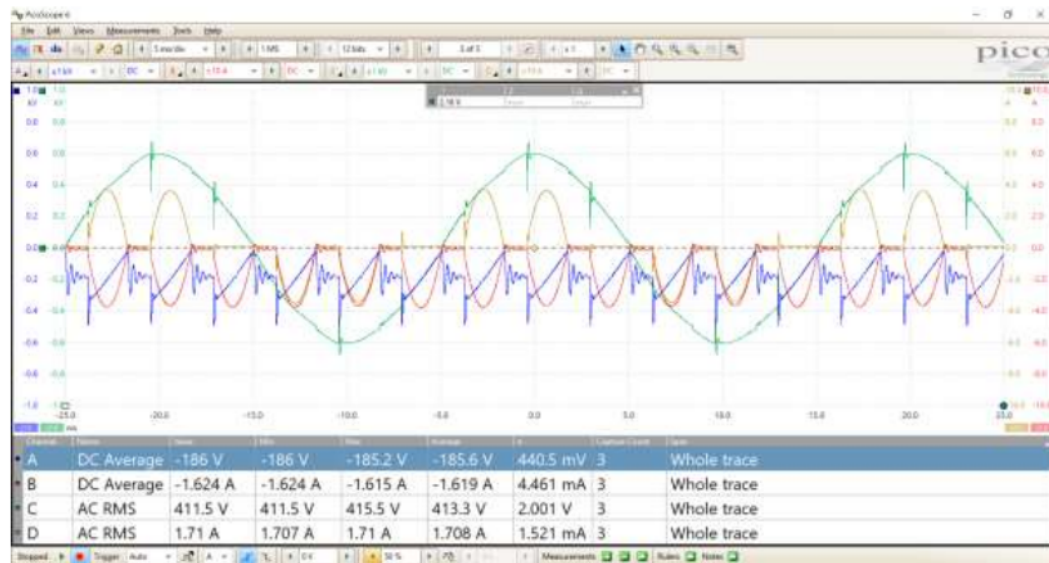


Figure 25 - Practical - Quadrant 3

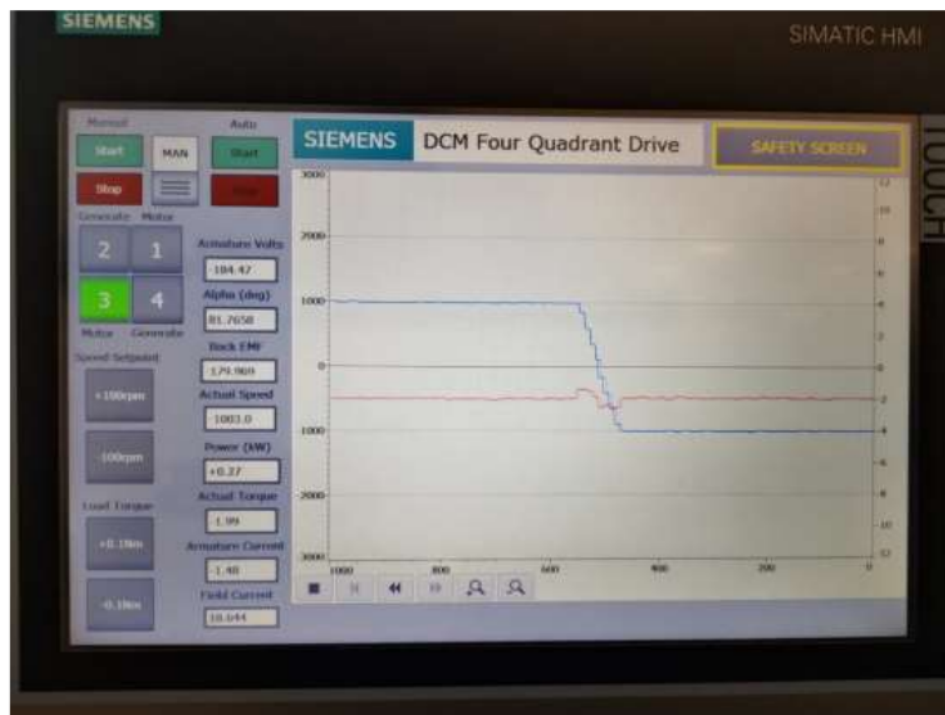


Figure 26 - Practical - Quadrant 3 HMI

Quadrant 4



Figure 27 - Practical - Quadrant 4

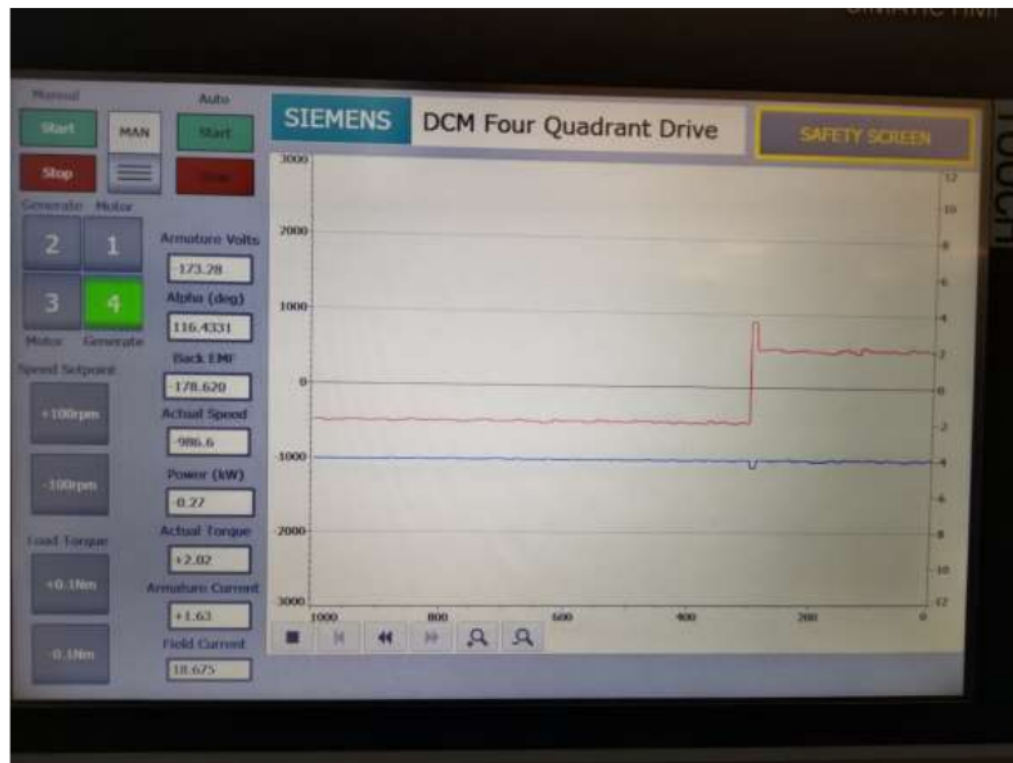


Figure 28 - Practical - Quadrant 4 HMI

Discontinuous Test 1



Figure 29 - Practical - Pico Scope Discontinuous Current 1000rpm

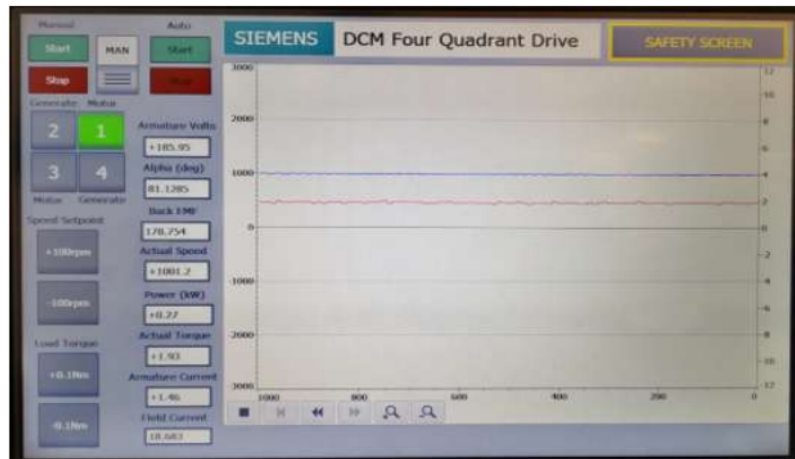


Figure 30 - Practical - HMI Discontinuous Current 1000rpm



Figure 31 - Practical - Power Analyser Discontinuous Current 1000rpm

Discontinuous Test 2



Figure 32 - Practical - Pico Scope Discontinuous Current 1500rpm

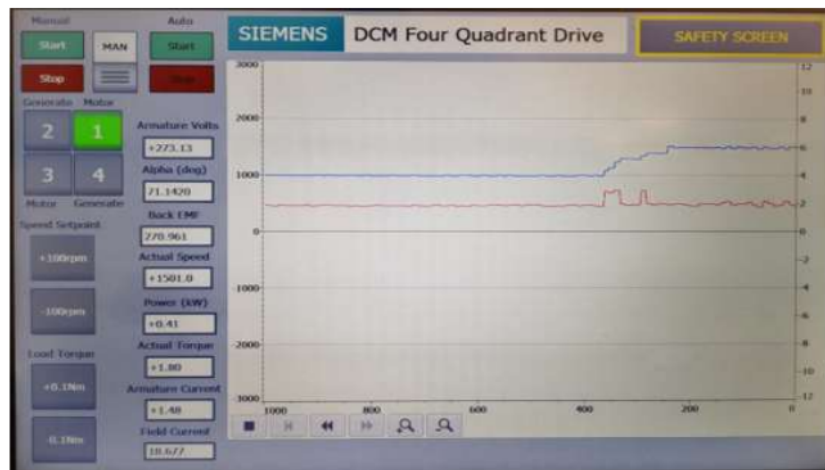


Figure 33 - Practical - Pico Scope Discontinuous Current 1500rpm

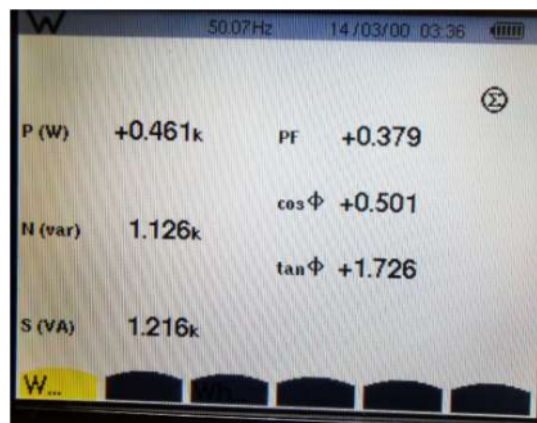
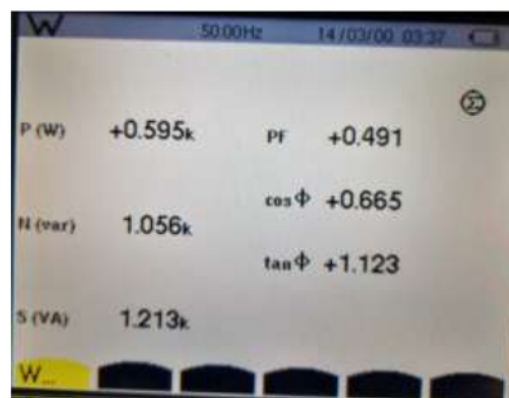
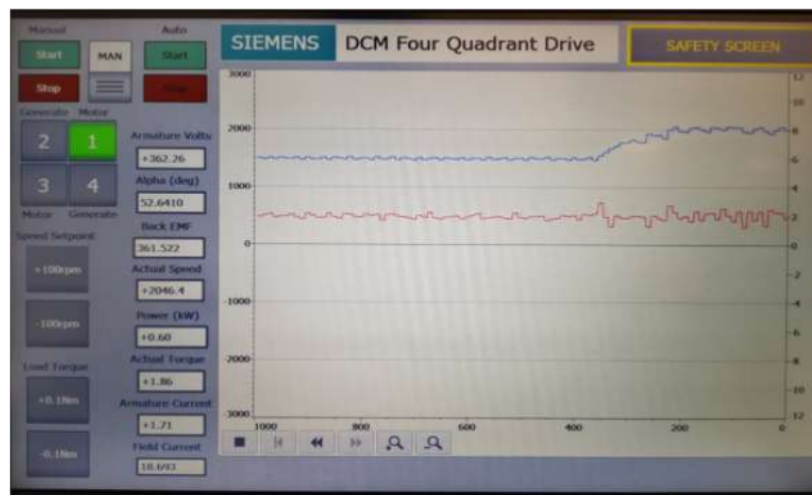


Figure 34 - Practical - Power Analyser Discontinuous Current 1500rpm

Discontinuous Test 3



Discontinuous Current Test 1 Calculations

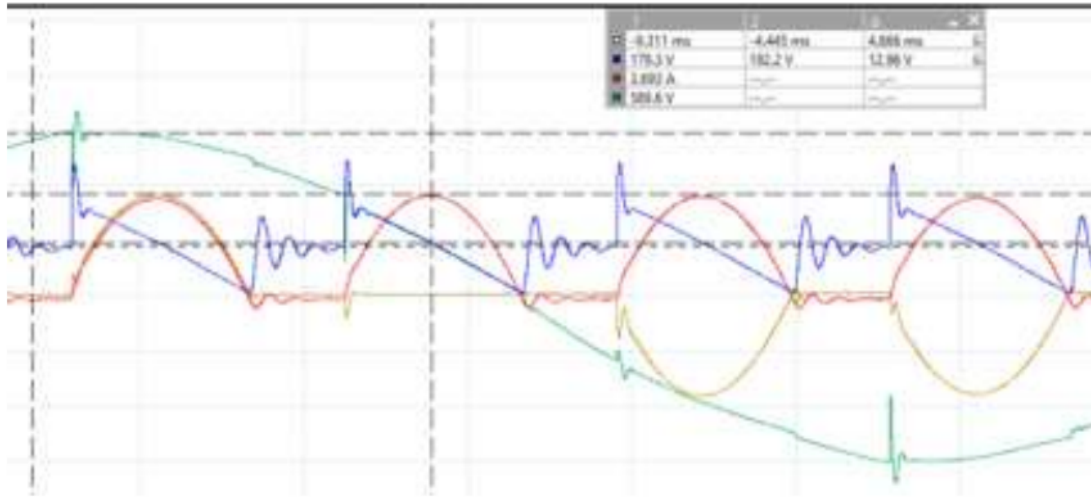


Figure 38 - Practical - Vmax Value

$$\text{Area A} = E \times \gamma = E \left(\alpha - \frac{\pi}{3} \right)$$

Equation 7 - Calculation for V-mean Discontinuous Current Area A

$$\text{Area B} = V_{\max} \int_{\frac{\pi}{3} + \alpha}^{\pi} \sin(\theta) d\theta$$

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

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

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

Equation 8 - Calculation for V-mean Discontinuous Current Area B

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

$$V_{\text{mean}} = \frac{3}{\pi} \left[178.754(1.416 - 1.0472) + 589.6 \left(1 + \frac{1}{2} \times 0.1542 - 0.866 \times 0.988 \right) \right]$$

$$= \frac{3}{\pi} [65.9244 + 130.5917] = 187.6591 \text{ v}$$

Equation 9 - Calculation for V-mean

Discontinuous Current Test 2 Calculations

$$Area A = E \times \gamma = E \left(\alpha - \frac{\pi}{3} \right)$$

Equation 10 - Calculation for V-mean Discontinuous Current Area A

$$Area B = Vmax \int_{\frac{\pi}{3} + \alpha}^{\pi} \sin(\theta) d\theta$$

$$Vmax [-\cos\theta]_{\frac{\pi}{3} + \alpha}^{\pi}$$

$$= Vmax \left[-\cos\pi - -\cos\left(\frac{\pi}{3} + \alpha\right) \right]$$

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

Equation 11 - Calculation for V-mean Discontinuous Current Area B

$$Vmean = \frac{Area A + Area B}{\frac{\pi}{3}}$$

$$Vmean = \frac{3}{\pi} \left[270.961(1.242 - 1.0472) + 589.6 \left(1 + \frac{1}{2} \times 0.3229 - 0.866 \times 0.9464 \right) \right]$$

$$= \frac{3}{\pi} [52.784 + 201.55] = 242.856$$

Equation 12 - Calculation for V-mean

Discontinuous Current Test 3 Calculations

$$\text{Area A} = E \times \gamma = E \left(\alpha - \frac{\pi}{3} \right)$$

Equation 13 - Calculation for V-mean Discontinuous Current Area A

$$\text{Area B} = V_{\max} \int_{\frac{\pi}{3} + \alpha}^{\pi} \sin(\theta) d\theta$$

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

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

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

Equation 14 - Calculation for V-mean Discontinuous Current Area B

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

$$\begin{aligned} V_{\text{mean}} &= \frac{3}{\pi} \left[361.522(0.9187 - 1.0472) + 589.6 \left(1 + \frac{1}{2} \times 0.6069 - 0.866 \times 0.7948 \right) \right] \\ &= \frac{3}{\pi} [46.4547 + 362.662] = 390.6777 \end{aligned}$$

Equation 15 - Calculation for V-mean

$$\alpha = \frac{\pi}{180} = \text{rad/s}$$

Equation 16 - Calculation for converting degrees to Radians

Continuous Current Test Data				
	Symbol	Test 1	Test 2	Test 3
VMAX	V	589.6	589.6	589.6
Back EMF	E	178.754	270.961	361.522
Alpha	α	81.1285	71.142	52.64
Radians	Rad/s	1.416	1.242	0.9187

Table 9 - Continuous Current Test Data

Continuous Current Test 1

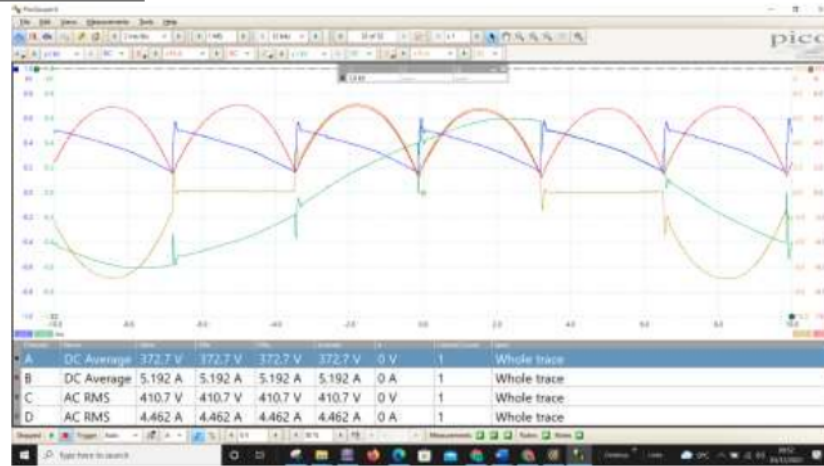


Figure 39 - Practical - Pico Scope Continuous Current 6.66Nm

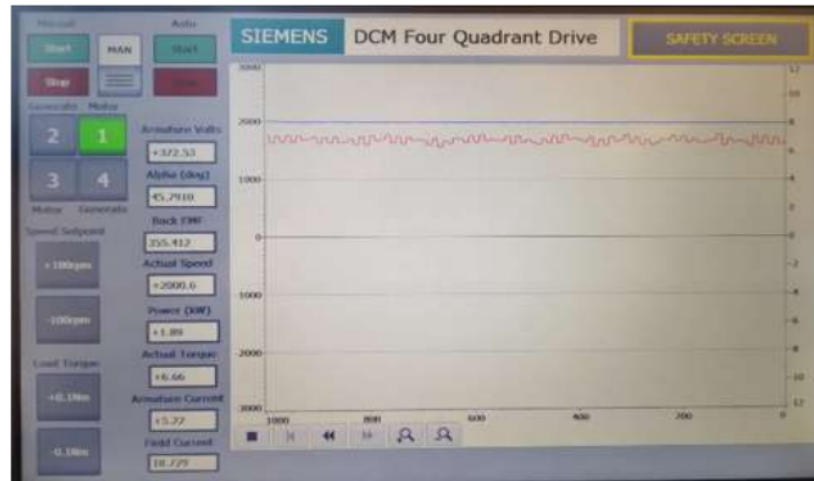


Figure 40 - Practical - HMI Continuous Current 6.66Nm

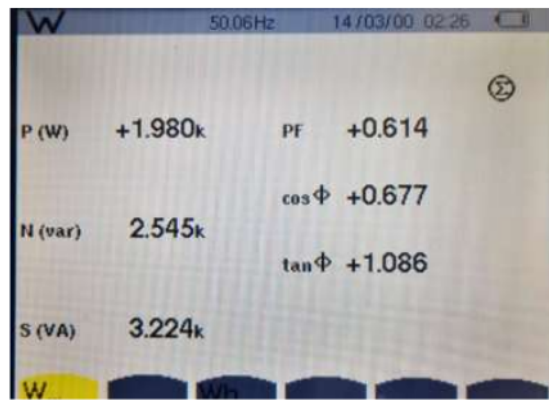


Figure 41 - Practical - Power Analyser Continuous Current 6.66Nm

Continuous Current Test 2

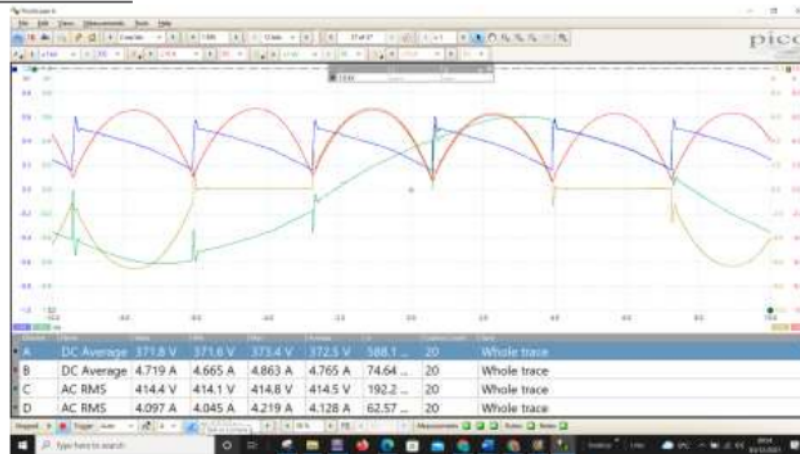


Figure 42 - Practical - Pico Scope Continuous Current 6.03Nm

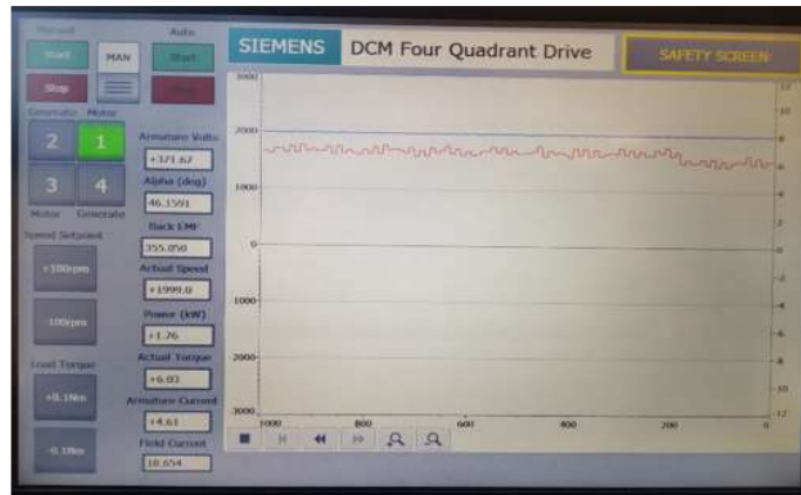


Figure 43 - Practical - HMI Continuous Current 6.03Nm

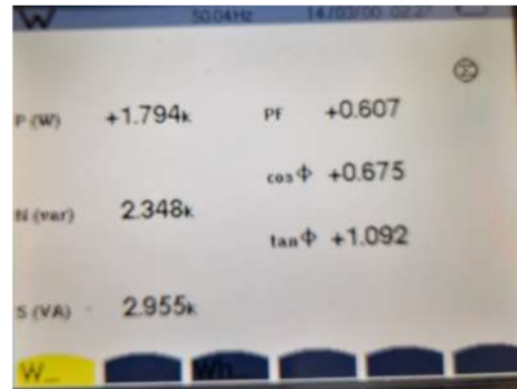


Figure 44 - Practical - Power Analyser Continuous Current 6.03Nm

Continuous Current Test 3

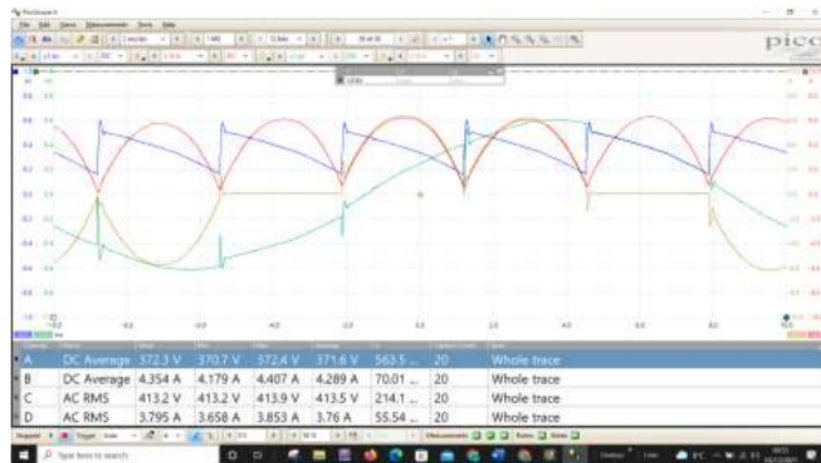


Figure 45 - Practical - Pico Scope Continuous Current 5.31Nm

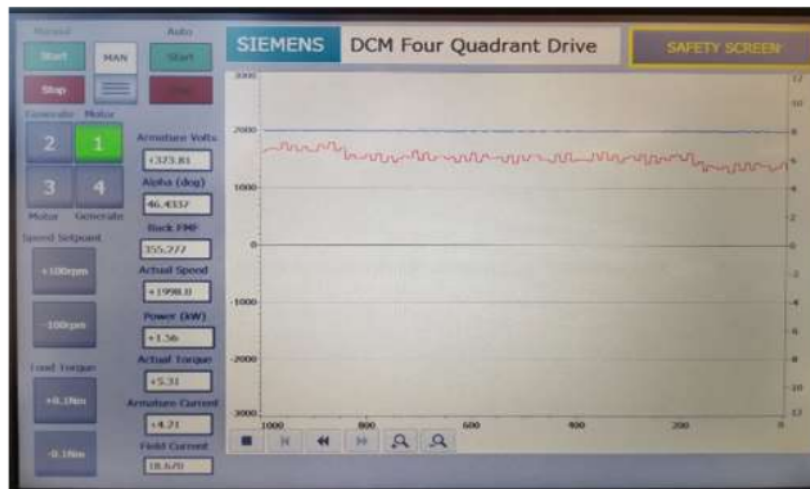


Figure 46 - Practical - HMI Continuous Current 5.31Nm

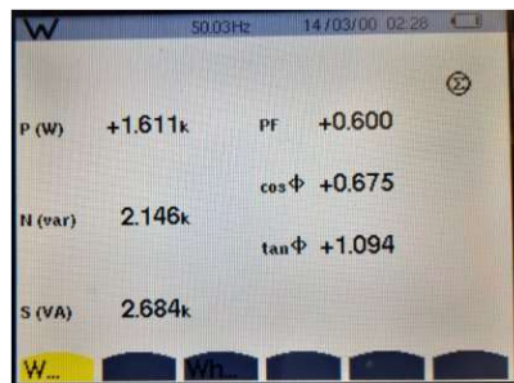


Figure 47 - Practical - Power Analyser Continuous Current 5.31Nm

Instructor

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PAGE 1

Text Comment. This is a well structured and presented report

Text Comment. Generally well written but has some spelling errors

Text Comment. Executive summary is very good but too long

Text Comment. Research utilises a wide range of sources mostly credible except for one which is ambiguously cited

Text Comment. Good understanding shown

Text Comment. Analysis of results is very good and very good conclusions drawn up

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GRADING FORM: NEW CSG-RUBRIC

DAVID THOMAS

71

1. ENGAGEMENT WITH LITERATURE



Engagement with an extensive range of relevant and credible literature, informed by the latest

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research. Consistently accurate application of referencing. (14/20)

2. KNOWLEDGE AND UNDERSTANDING

 Excellent coherent and detailed knowledge and systematic understanding of the principles and theories of current research and scholarship. Clear awareness of challenges to established views and the limitations of the knowledge base. (14/20)

14

3. COGNITIVE AND INTELLECTUAL

 Excellent critical thinking, analysis, synthesis and evaluation. Ability to investigate contradictory or incomplete information and make strong, persuasive, arguments and sophisticated judgements. Some evidence of independent thought and ability to 'see beyond the question', suggesting a grasp of the broader field and wider concepts. (15/20)

15

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. (15/20)

15

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 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. (13/20)

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