

Project Report – Design Exercise

Leon Scammell

2017986



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

21/03/2023

—

L6 – Power Electronics & Drives

—

Module Code – ACDA6004

—

BEng Electrical & Electronic Engineering

Contents

1. Table of Figures	3
2. Table of Tables	3
3. Abstract	5
4. Introduction	6
5. Selection of Suitable Technology For Controlling Five Types of Induction Motors.....	7
5.1. Background.....	7
5.1.1. Motor Drives	7
5.2. Selection of Motor Drives.....	10
5.2.1. Comparison of Different Drive Technologies.....	10
5.2.2. Comparisons of Available Drives.....	11
5.2.3. Chosen Drives.....	21
5.3. Conclusion	22
6. Rectification of the Incoming Mains	23
6.1. Background.....	23
6.2. Use of Diodes, Thyristors, and IGBTs for Rectification.....	25
6.3. Conclusion	29
7. References	30

1. Table of Figures

Figure 1 - Block Diagram of a Motor Speed Control Drive [14]	7
Figure 2 - Simplified VFD Diagram [15]	8
Figure 3 - LS Electric Frequency converter-Variable frequency Drive H100 [23]	11
Figure 4 - ABB ACS880- 07-0880A-3 Cabinet-Built Single Drive [2]	11
Figure 5 - Variable speed drive, Altivar Process ATV900 [24]	11
Figure 6 - Danfoss VLT® AutomationDrive FC 302 [25]	11
Figure 7 - ABB ACH580-07 0206A-4 [3]	14
Figure 8 - Danfoss VACON® NXC 0261 5 A 2 H 0 SSF [27]	14
Figure 9 - Schneider Electric Variable Speed Drive ALTIVAR 630 Series [28]	14
Figure 10 - Siemens Converter G120C Series [30]	14
Figure 11 - RS PRO Inverter Drive [32]	16
Figure 12 - Danfoss Inverter Drive VLT FC51 Series [35]	16
Figure 13 - Variable Frequency Drive ABB Inverter [6]	16
Figure 14 - Schneider Electric Variable Speed Drive ATV930 Series [38]	16
Figure 15 - RS PRO Inverter Drive [42]	18
Figure 16 - Danfoss Inverter Drive VLT FC51 Series [45]	18
Figure 17 - Schneider Electric Variable Speed Drive ATV63 Series [48]	18
Figure 18 - ABB Inverter Drive ACS355 Series [8]	18
Figure 19 - RS PRO 1.5 kW DOL Starter [50]	20
Figure 20 - Schneider Electric 1.1 kW DOL Starter [52]	20
Figure 21 - ABB 5.5 kW DOL Starter [11]	20
Figure 22 - Automation Electric 1.5kW DOL start Single phase pump control panel [53]	20
Figure 23 - Simplified VFD Diagram [15]	23
Figure 24 - Closed-Loop VFD Control System [54]	23
Figure 25 - AC Voltage Rectified to a Rippling DC Voltage [56]	24
Figure 26 - Smoothed Rippling DC Voltage [57]	24
Figure 27 - Duty Cycle in Relation to the Generated Sine Wave [59]	25
Figure 28 - Illustration of a Diode [61]	25
Figure 29 - SCR Symbol and Appearance [63]	26
Figure 30 - Wiring Diagram of an IGBT [66]	26
Figure 31 - Illustration of the Design of an IGBT Chip [67]	26
Figure 32 - Rectifier with an Inductor Added [70]	27
Figure 33 - Typical Harmonic Current Spectrum for a Rectifier [71]	27
Figure 34 – 6-Pulse Rectifier Simulation	28
Figure 35 – 12-Pulse Rectifier Simulation	28
Figure 36 - Formula for Calculating Power Factor [77]	29

2. Table of Tables

Table 1 - Comparison of the Different Motor Drive Technologies	10
Table 2 - Rolling Mill Specifications	11
Table 3 - Comparison of Suitable Drives for the Rolling Mill	13

Table 4 - Gantry Crane Specifications	14
Table 5 - Comparison of Suitable Drives for the Gantry Crane	15
Table 6 - Conveyor Specifications	16
Table 7 - Comparison of Suitable Drives for the Conveyor	17
Table 8 - Cutting Machine Specifications	18
Table 9 - Comparison of Suitable Drives for the Cutting Machine	19
Table 10 - Pumps/Fans Specifications	20
Table 11 - Comparison of Suitable Drives for the Pumps/Fans	21

3. Abstract

This report is split into two sections, including the comparison and selection of a suitable technology for various motor drive systems in different applications, as well as a comparison of different rectifier components and an explanation of the effects of harmonic distortion on power factor in VFDs.

Motor Drive Research and Selection

This section covers research and comparison of the different drive technologies that are currently available, and the selection of the best suited drive for each application. The reasons for the selection of each drive is explained in this report.

The selected drives were as follows:

- A. Rolling Mill** - ABB ACS880- 07-0880A-3 Cabinet-Built Single Drive [1] [2]
- B. Gantry Crane** - ABB ACH580-07 0206A-4 [3] [4] [5]
- C. Conveyor** - ABB VFD ACH580-01 [6] [7]
- D. Cutting Machine** - ABB Inverter Drive ACS355 Series [8] [9] [10]
- E. Pumps/Fans** - ABB 5.5 kW DOL Starter [11] [12]

ABB was selected as the single supplier of the drives as this will aid with maintenance and spares, due to there only being one company to stay in contact with.

VFDs and Harmonic Noise Minimization

This section covers research on the use of diodes, thyristors, and IGBTs for use in rectifiers. IGBTs have a much faster switching frequency, which leads to less harmonic distortion in the VFD's output. It is explained how harmonic noise caused power factor to reduce. Harmonic noise is minimized with the following design considerations:

- Multi-pulse rectifiers
- High frequency IGBTs into the rectifiers,
- Addition of a diode to smooth the current
- Harmonic filters

4. Introduction

In this report, two different issues related to motor drive systems and variable frequency drives will be investigated. Firstly, suitable technology for a factory's motor drive system will be recommended based on various factors such as cost, flexibility, ability to obtain information on the processes, and protection from such as overloads and faults. Motor drive systems are used to control the speed and torque of electric motors. There are various types of motor drive systems available, including variable frequency drives (VFDs), soft starters, direct on-line starters,

Next, the report will compare and contrast the use of diodes, thyristors such as silicon-controlled rectifiers (SCRs) and insulated-gate bipolar transistors (IGBTs) for rectification in variable frequency drives. The impact of different rectifier components on harmonic noise and power factor in variable frequency drives will be looked into. The report will also examine the potential of reducing harmonic noise by implementing a well-thought-out rectifier design. Additionally, the effects of harmonics on power and power factor will be discussed.

5. Selection of Suitable Technology For Controlling Five Types of Induction Motors

5.1. Background

5.1.1. Motor Drives

Motor drives work by varying the frequency, voltage, or current of the electrical power supplied to the motor, which in turn controls its speed and torque. There are various technologies available for motor drive systems. These include variable frequency drives (VFDs), soft starters, and direct-on-line starters (DOL). These technologies offer different advantages and disadvantages in terms of cost, performance, and control flexibility.

All motor drives monitor the speed that the motor is rotating at by receiving some form of feedback. This is illustrated in figure 3 with the feedback being sent from the motor tachometer, and into the control circuit in the drive. The magnetic field and rotor in a motor rotates at a synchronous rate depending on the frequency and number of three phase poles in the stator. [13] The control circuit signals to the power circuit what output is required from the drive in order to increase or decrease the speed of the motor, depending on the feedback. The power circuits provide a varying voltage or frequency to the motor to match a required mechanical output. [14]

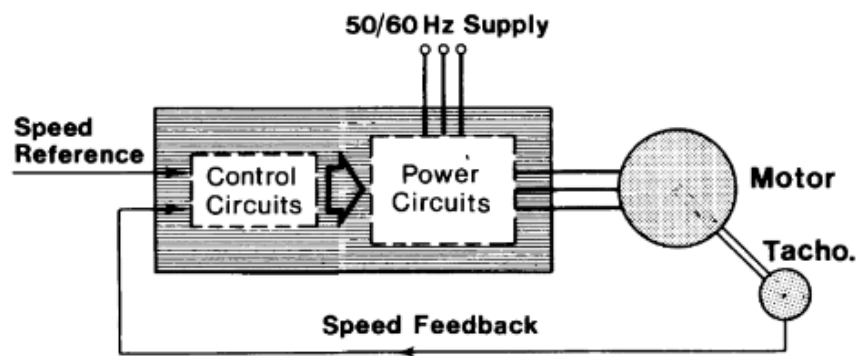


Figure 1 - Block Diagram of a Motor Speed Control Drive [14]

To select a suitable technology for each of the factory's motor drive systems, various factors such as the motor's power rating, the number of phases, the required reversibility, and the need for variable speed control need to be considered. Additionally, we need to consider factors such as cost, protection, and the flexibility of the control system.

The different motor drive technologies currently available include the following:

- **Variable Frequency Drives (VFDs)** – These control the speed and torque of AC induction motors by outputting a variable AC voltage to the motor. The frequency is increased to speed up or reduced to slow the motor down. These feature three main parts, including the rectifier, DC bus, and inverter. The rectifier features diodes or thyristors that are connected in parallel to each phase, which converts the three phase AC supply into a rippling DC voltage by blocking the AC current from flowing in. Next the DC bus/link section features one or more capacitors to smooth the rippling DC to a constant voltage, and an

inductor to filter the current. Finally the inverter converts the DC voltage back into an 'artificial AC' voltage [15] by using pulse width modulation. The length of the pulses is called the duty cycle, and varying this results in the voltage amplitude changing. Figure 4 illustrates all 3 parts of VFDs.

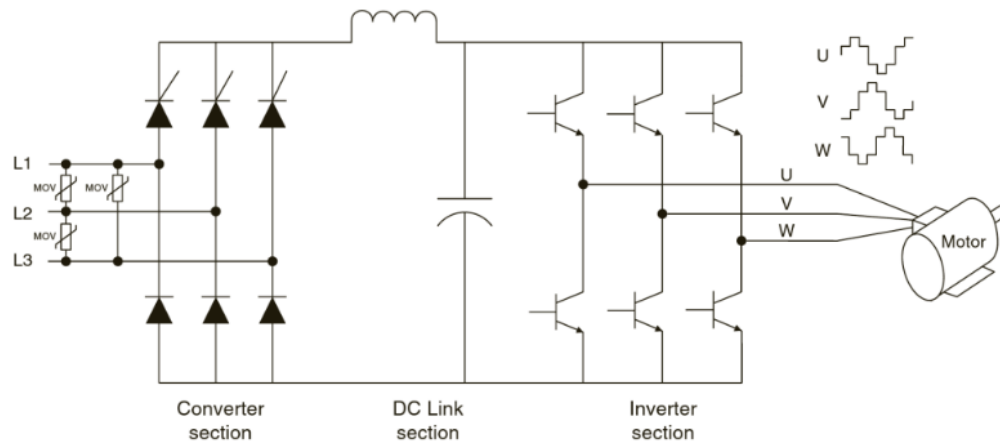
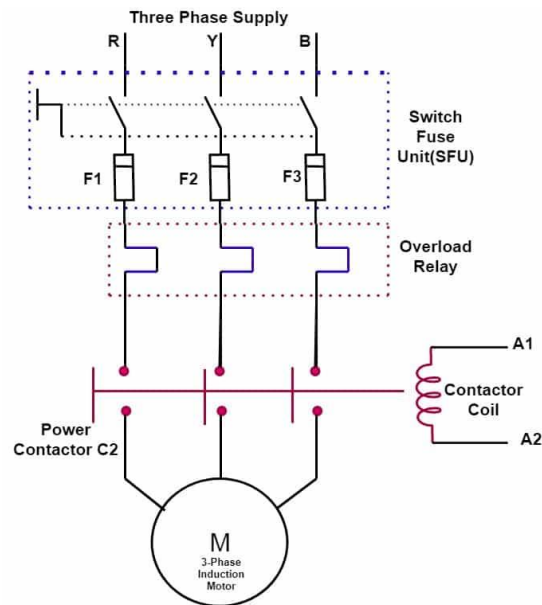


Figure 2 - Simplified VFD Diagram [15]

- **Direct-On-Line (DOL) Starters** – DOL starters switch the full supply voltage to the motor on startup. The motor will start at full speed immediately. Figure 5 shows the contactor that switches the motor supply either fully on or fully off. [16]



DOL Starter Power Circuit Diagram

Figure 5 - Direct Online Starter (DOL) Diagram [17]

- **Soft Starters** – Soft starters are comprised of solid-state electronic components such as SCRs or IGBTs to provide a smooth start, limit inrush current, and prevent damage to the motor and supply during startup. This reduces the stress on the motor hardware and prevents the supply breakers from tripping. Motors draw more current on startup due to there being no back EMF and low resistance in the motor windings when the rotor is stationary [18]. Figure 6 illustrates an example of an electronic soft starter, in which pulse width modulation signals to each thyristor to gradually reduce the gate-pulse phase angle of the thyristors to gradually increase the voltage output [19]. The thyristor pairs are in opposite directions to control the current in both directions. By reducing the gate-pulse phase angle, more of the voltage

waveform can be applied to the load as shown in figure 6, which gradually increases the voltage. [20] [21] Figure 7 illustrates how the current is maintained at a lower level than if a DOL starter was used.

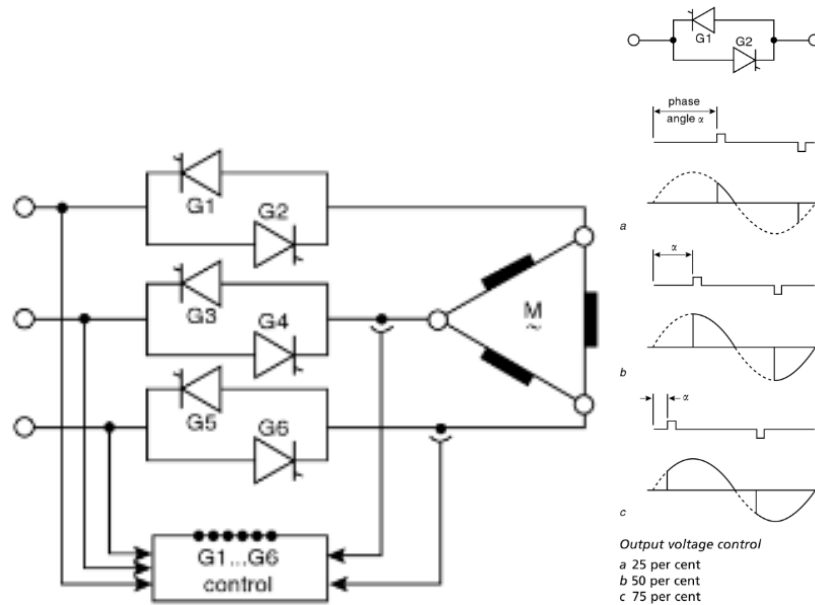


Figure 6 - Diagram of an Electronic Soft Starter [19]

Across-the-line current VS. Soft-starter current

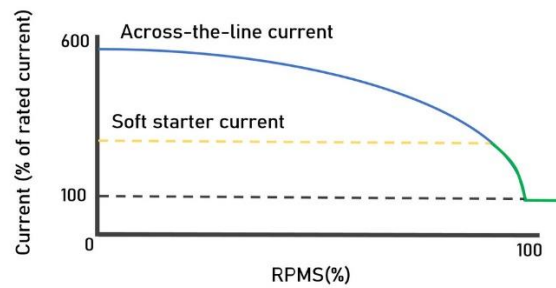


Figure 7 - Comparison of DOL Starters vs Soft Starter Current [22]

5.2. Selection of Motor Drives

5.2.1. Comparison of Different Drive Technologies

Parameters	(VFD) Variable Frequency Drives	Soft Starter	(DOL) Direct On Line
Variable Speed Control	Yes	No	No
Reversible	Yes	Yes	Yes
Limits start-up current	Yes	Yes	No
Cost	Expensive	Medium	Very low
Flexibility of the control system	High flexibility	Good	Low
Common DC bus	Yes	No	No
Information gathering ability	Excellent	Good	Very low
Protection - overvoltage, undervoltage, overcurrent, phase loss, or short circuit	Yes	Yes	No
Fault detection	Yes	Yes	No

Table 1 - Comparison of the Different Motor Drive Technologies

5.2.2. Comparisons of Available Drives

Motor A – Rolling Mill

Specifications – Rolling Mill	
Power	500kW
Voltage	3 phase 400V
Reversibility Required?	Yes
Variable Speed Required?	Yes
Quantity	5

Table 2 - Rolling Mill Specifications

A VFD is most suitable as it meets all of the requirements of this large and high powered motor, with start-up current limitation, protection, and information gathering capability. A soft starter may have been suitable, but doesn't provide variable speed control. A DOL does not provide any of the requirements.

Parameters	VFD 1	VFD 2	VFD 3	VFD 4
	LS Electric Frequency converter-Variable frequency Drive H100 [23]	ABB ACS880- 07- 0880A-3 Cabinet- Built Single Drive [1] [2]	Variable speed drive, Altivar Process ATV900, APM, single 400 V, 500 kW [24]	Danfoss VLT® AutomationDrive FC 302 P560 [25] [26]
Images	 Figure 3 - LS Electric Frequency converter-Variable frequency Drive H100 [23]	 Figure 4 - ABB ACS880- 07-0880A-3 Cabinet-Built Single Drive [2]	 Figure 5 - Variable speed drive, Altivar Process ATV900 [24]	 Figure 6 - Danfoss VLT® AutomationDrive FC 302 [25]
Part Number	LSLV5000H100-4COFD	ACS880- 07-0880A-3	ATV9A0C50Q4	134U0146
Voltage Range	380-480V 3 phase	380-415V 3 phase	400V 3 phase	380-500V 3 phase
Supply Frequency	50-60Hz	50-60Hz	50-60Hz	50-60Hz
Output Frequency	0-400Hz	0-500Hz	0.1-599Hz	0-500Hz
Current Rating	962A	883.3A	900A	1040A
Power Rating	500kW	500kW	500kW	560kW
User Interface	Keypad and LCD screen.	Keypad with no LCD screen. Has a web-based control	Keypad with LCD display. Has built-in web servers for	Local control panel with

		interface and PC connectivity for control.	ethernet connectivity, allowing remote control and monitoring.	keypad and LCD display.
Variable Speed	Yes	Yes	Yes	Yes
Reversible	Yes	Yes	Yes	Yes
Control Method	Vector Control (V/F Control) (adjusts the motor supplies frequency and voltage to	Vector and V/F control	- Flux vector control (FVC) - Direct torque control (DTC) - Sensor less vector control (SVC)	- Flux vector control (FVC) - Direct torque control (DTC) - Sensor less vector control (SVC)
IP Protection Class	IP20	IP54	IP54	IP54
Protection	- Overcurrent protection - Overvoltage protection - undervoltage protection - Overload protection - Overheat protection	Overvoltage category 3, protective class 1.	- Overcurrent protection - Thermal protection - Short circuit protection - Phase loss protection - Overspeed protection - Overvoltage protection - Earth fault protection	- Overcurrent protection - Overvoltage protection - Overload protection - Phase loss protection - Earth fault protection - Thermal protection - Short circuit protection
Filter Type	EMC Category C3 Filter 110-500kW Built-in DC Reactor 37-500kW for improved power factor and reduced harmonic distortion. [23]	Sine filter type NSIN0900-6 (passive sine filter)	EMC filter	- RFI filter - DV/dt or sine wave filter
Communication Protocol	- Programmed via USB or RJ45. - BACnet MS/TP, Modbus-RTU	- Modbus - Profibus - ethernet.	- EtherNet/IP - Modbus serial	- Modbus - Profibus DP - DeviceNet - CANopen - Ethernet
Operating Temperature	-10 °C to +50 °C	0-+40°C	-10-40°C	-10-50°C
Weight	265kg	580kg	60-100 kg	230kg

Dimensions	776 x 1054 x 500 mm	2145 x 830 x 698mm	1000 x 1000 x 600mm	2000 x 510 x 640mm
Price	£23709.45	Contact ABB for a quote	Contact Schneider Electric for a quote	£72923.60 [26]
Chosen Drive		✓		

Table 3 - Comparison of Suitable Drives for the Rolling Mill

Motor B – Gantry Crane

Specifications – Gantry Crane	
Power	80kW
Voltage	3 phase 400V
Reversibility Required?	Yes
Variable Speed Required?	Yes
Quantity	10

Table 4 - Gantry Crane Specifications

A VFD would also be best suited for motor B as this would meet the requirements for speed control, protection, starting current limitation and information gathering ability. A soft starter does not provide speed control.

Parameters	VFD 1 ABB ACH580-07 0206A-4 [3] [4] [5]	VFD 2 Danfoss VACON® NXC NXC02615A2H0SSF [27]	VFD 3 Schneider Electric Variable Speed Drive, 90 kW, 3 Phase, 400 V, ALTIVAR 630 Series [28] [29]	VFD 4 Siemens Converter G120C Series [30] [31]
Images	 <i>Figure 7 - ABB ACH580-07 0206A-4 [3]</i>	 <i>Figure 8 - Danfoss VACON® NXC 0261 5 A 2 H 0 SSF [27]</i>	 <i>Figure 9 - Schneider Electric Variable Speed Drive ALTIVAR 630 Series [28]</i>	 <i>Figure 10 - Siemens Converter G120C Series [30]</i>
Part Number	ACH580-07 0206A-4	NXC 0261 5 A 2 H 0 SSF	ATV630D90N4	6SL3210-1KE31-7UF1
Voltage Range	380-480V 3 phase	380-500V 3 phase	400V 3 phase	380-480V 3 phase
Supply Frequency	50-60Hz	45-66Hz	50-60Hz	47-63Hz
Output Frequency	0-599Hz	0-320Hz	0.1-500Hz	No data
Current Rating	206A	261A	145A	164A
Power Rating	110kW	132kW	90kW	90kW
User Interface	Keypad with an LCD display	Keypad with an LCD display	Keypad with LCD display	Requires external operator panel

				for user interfacing.
Variable Speed	Yes	Yes	Yes	Yes
Reversible	Yes	Yes	Yes	Yes
Control Method	Vector and V/F control	Open and closed loop vector control	- V/F control - Sensor less vector control - Flux vector encoder control	- V/F control - Sensor less vector control
IP Protection Class	IP54	IP21	IP21	IP20
Protection	- Overvoltage category 3 & 2. - Short circuit protection - Earth fault protection - Thermal protection - Overload protection	- Overvoltage protection - Short circuit protection - Earth fault protection - Thermal protection - Overload protection - Motor phase supervision - Mains supervision	- Overcurrent protection - Overvoltage protection - Overload protection - Thermal protection - Earth fault protection - Phase loss detection - Motor phase supervision	- Overvoltage protection - Overcurrent protection - Short circuit protection - Motor overload protection - Earth fault protection
Filter Type	RFI/EMI filter	No data	EMC filter	Unfiltered
Communication Protocol	- Ethernet - Modbus RTU and TCP - Profibus - BACnet - Others can be added.	- RS485 - Profibus - Modbus/TCP - BACNet - Profinet - Ethernet - Devicenet - SELMA 2 protocol	- Ethernet - Modbus TCP & serial	- Profinet - Ethernet
Operating Temperature	0-+50°C	-40-+70°C	-15-+50°C	-20-+40°C
Weight	220kg	680kg	58.5kg (no enclosure)	57.50kg (no enclosure)
Dimensions	R7 frame – 2144.5 x 600 x 430mm	FR9 frame 1150 x 480 x 362mm	922 x 290 x 323mm	708 x 305 x 357mm
Price	£8662.77	Contact Danfoss for quote	£9,661.44	£8,880.16
Chosen Drive	✓			

Table 5 - Comparison of Suitable Drives for the Gantry Crane

Motor C – Conveyor

Specifications – Conveyor	
Power	10kW
Voltage	3 phase 400V
Reversibility Required?	No
Variable Speed Required?	Yes
Quantity	23

Table 6 - Conveyor Specifications

A VFD would be required here as soft starters and DOLs do not provide variable speed control.

Parameters	VFD 1	VFD 2	VFD 3	VFD 4
	RS PRO Inverter Drive [32] [33] [34]	Danfoss Inverter Drive [35] [36] [37]	ABB VFD ACH580-01 [6] [7]	Schneider Electric Variable Speed Drive ATV930 Series [38] [39]
Images	 Figure 11 - RS PRO Inverter Drive [32]	 Figure 12 - Danfoss Inverter Drive VLT FC51 Series [35]	 Figure 13 - Variable Frequency Drive ABB Inverter [6]	 Figure 14 - Schneider Electric Variable Speed Drive ATV930 Series [38]
Part Number	RS Stock No.: 174-8222 Manufacturer: RS PRO	RS Stock No.: 891-8845 Mfr. Part No.: 132F0058	SKU: ACH580-01-026A-4+B056	RS Stock No.: 162-4946 Mfr. Part No.: ATV930D15N4
Voltage Range	380-480V 3 phase	380-480V 3 phase	380-480V 3 phase	380-480V 3 phase
Supply Frequency	50-60Hz	50-60Hz	48-63Hz	50-60Hz
Output Frequency	0-599Hz	0-400Hz	0-500Hz	0.1-599Hz
Current Rating	24A	23A	25A	20.6A
Power Rating	11kW	11kW	11kW	11kW
User Interface	Keypad	Keypad	Keypad	Keypad
Variable Speed	Yes	Yes	Yes	Yes
Reversible	Yes	Yes (1-2 times/min) [36]	Yes	Yes
Control Method	Vector control	Vector control	Vector control	Vector control
IP Protection Class	IP20	IP20	IP55	IP21
Protection	Overcurrent protection	Overcurrent protection	Over and under voltage protection	Thermal protection

	• Over and under voltage protection • Short-circuit protection • Earth fault protection • Stall prevention • Momentary power loss restart	• Over and under voltage protection • Overtemperature protection • Earth fault protection • Short-circuit protection	• Earth leakage monitoring • Short-circuit protection • Overtemperature protection • Motor overload protection • Phase loss detection • Under load and stall detection	• Over voltage and current protection • Short-circuit protection • Phase loss protection • Overspeed protection
Filter Type	EMC class A RFI filter	RFI filter	RFI filter	RFI filter
Communication Protocol	• BACnet • Modbus • RS485	• Modbus • RS485	• BACnet • Modbus • Ethernet	• Modbus
Operating Temperature	-10-+40°C	<50°C	-15-+50°C	-40-+70°C
Power factor	No data	>0.98	0.98	0.98
Weight	6.3kg	No data	7.8kg	13.6kg
Dimensions	273x187x190mm	125x241x291mm	394x125x239mm	211x545.9x235mm
Price	£666.24	£1,639.22	£1,379.99	£3,200.24
Chosen Drive			✓	

Table 7 - Comparison of Suitable Drives for the Conveyor

Motor D – Cutting Machine

Specifications – Cutting Machine	
Power	5kW
Voltage	3 phase 400V
Reversibility Required?	Yes
Variable Speed Required?	No
Quantity	17

Table 8 - Cutting Machine Specifications

A VFD will be required for this application, due to reversibility being required. Soft starters only offer soft acceleration and deceleration, with no reversibility being offered. [40] [41]

Parameters	VFD 1 RS PRO Inverter Drive [42] [43] [44]	VFD 2 Danfoss Inverter Drive VLT FC51 Series [45] [46] [47]	VFD 3 Schneider Electric Variable Speed Drive ATV63 Series [48] [49]	VFD 4 ABB Inverter Drive ACS355 Series [8] [9] [10]
Images	 Figure 15 - RS PRO Inverter Drive [42]	 Figure 16 - Danfoss Inverter Drive VLT FC51 Series [45]	 Figure 17 - Schneider Electric Variable Speed Drive ATV63 Series [48]	 Figure 18 - ABB Inverter Drive ACS355 Series [8]
Part Number	RS Stock No.: 174-8220	RS Stock No.: 891-8833 Mfr. Part No.: 132F0028	RS Stock No.: 125-3276 Mfr. Part No.: ATV630U55N4	RS Stock No.: 887-4733 Mfr. Part No.: ACS355-03E-12A5-4
Voltage Range	380-480V 3 phase	380-480V 3 phase	380-480V 3 phase	380-480V 3 phase
Supply Frequency	50-60Hz	50-60Hz	50-60Hz	48-63Hz
Output Frequency	0-599Hz	0-400Hz	0.0001-500Hz	0-599Hz
Current Rating	14.3A	12A	10.4A	12.5A
Power Rating	5.5kW	5.5kW	5.5kW	5.5kW
User Interface	Keypad with LCD display	Keypad with LCD display	Keypad with LCD display	No keypad or LCD display, changes made in the program via a PC.
Variable Speed	Yes	Yes	Yes	Yes
Reversible	Yes	Yes	Yes	Yes

Control Method	Vector control & SLV control	No data	No data	Vector or scalar control
IP Protection Class	IP20	IP20	IP21	IP20
Protection	• Overcurrent protection • Over and under voltage protection • Short-circuit protection • Earth fault protection • Stall prevention • Momentary power loss restart	• Thermal motor protection • Short-circuit protection • Earth fault monitoring • Overload protection	• Thermal protection • Phase loss detection • Over and undervoltage protection • Overload protection • Short-circuit protection	• Overload protection • Over and under voltage protection • Short-circuit protection • Earth fault protection • Thermal protection
Filter Type	Built in class A filter. (categoryC2) [44]	RFI filter	Integrated EMC filter	Integrated EMC filter
Communication Protocol	• RS485 • BACnet • Profibus • DeviceNet • CANopen • TCP/IP	• Modbus	• Modbus serial and TCP • Ethernet	• Fieldbus • Modbus • CANopen • Profibus DP
Operating Temperature	-10-+40°C	No data	-40-+70°C	-10-+40°C
Power factor	No data	>0.98	No data	No data
Weight	2.7kg	No data	4.7kg	No data
Dimensions	197x129x148mm	194x239x90mm	350x144x203mm	169x195x236mm
Price	£532.02	£1,001.36	£1,180.67	£1,028.40
Chosen Drive				✓

Table 9 - Comparison of Suitable Drives for the Cutting Machine

Motor E – Pumps / Fans

Specifications – Pumps / Fans	
Power	1kW
Voltage	230V single phase
Reversibility Required?	No
Variable Speed Required?	No
Quantity	127

Table 10 - Pumps/Fans Specifications

A DOL starter will be suitable for these motors as no variable speed control is required, and the power is low enough to not require the soft start function. The motors will not have a significant start up current, so soft start is not required. DOL starters are simpler in design, meaning lower installation and maintenance costs for the large quantity of 127 units, than VFDs or soft starting devices.

Parameters	DOL 1	DOL 2	DOL 3	DOL 4
	RS PRO 1.5 kW DOL Starter [50]	Schneider Electric 1.1 kW DOL Starter [51] [52]	ABB 5.5 kW DOL Starter [11] [12]	Automation-Electric 1.5kW DOL start Single phase pump control panel [53]
Images	 Figure 19 - RS PRO 1.5 kW DOL Starter [50]	 Figure 20 - Schneider Electric 1.1 kW DOL Starter [52]	 Figure 21 - ABB 5.5 kW DOL Starter [11]	 Figure 22 - Automation Electric 1.5kW DOL start Single phase pump control panel [53]
Part Number	RS Stock No.: 909-4098	RS Stock No.: 744-7872 Mfr. Part No.: LE1M35U708	RS Stock No.: 811-0767 Mfr. Part No.: 1TVC230050S5699	No part number shown
Voltage Range	240V AC	240V AC	230V AC	230V AC
Current Rating	10A	2.6A	9A	No data
Power Rating	1.5kW	1.1kW	5.5kW	1.5kW
User Interface	On and off buttons	On and off buttons	On and off buttons	Manual and automatic control switch. Not supplied with buttons for operation.
Variable Speed	No	No	No	No

Reversible	No	No	No	No
IP Protection Class	IP55	IP65	IP55	No data
Protection	- Thermal overload - Overload protection	Overload protection	- Overload protection - Short-circuit protection	- Overload protection - Earth fault protection
Operating Temperature	-5-+40°C	-5-+40°C	No data	No data
Weight	No data	0.6kg	No data	No data
Dimensions	134x104x174mm	160x78x108mm	184x184x165mm	No data
Price	£96.18	£157.30	£132.42	£200
Chosen Drive			✓	

Table 11 - Comparison of Suitable Drives for the Pumps/Fans

5.2.3. Chosen Drives

The ABB drives have been chosen as purchasing from the same manufacturer makes maintenance and servicing more straightforward for the business. This is because the factory will only require a service contract with a single supplier, which will reduce costs when compared with sourcing drives from different manufacturers. The suppliers that offer drives suitable for all applications here are ABB and Schneider Electric, meeting the following requirements:

- power ratings,
- current ratings
- data recording and transmission via the communications protocols
- Protection
- Ease of use with a simple user interface and user manuals available

ABB devices were cheaper than Schneider, with all specifications matching, meaning similar performance. This is why the following ABB drives were chosen:

1. Motor A - ABB ACS880- 07-0880A-3 Cabinet-Built Single Drive
2. Motor B - ABB ACH580-07 0206A-4 HVAC Drive
3. Motor C - ABB VFD ACH580-01
4. Motor D - ABB Inverter Drive ACS355 Series
5. Motor E - ABB 5.5 kW DOL Starter

5.3. Conclusion

After comparing different drives and starters from different manufacturers online, the ABB devices were found to be most suitable for use in this factory. These all met the requirements of each motor, including the power, current, and voltage ratings, as well as data communication capability. ABB had drives available to suit all 5 motors, being cheaper than their competitor Schneider.

6. Rectification of the Incoming Mains

6.1. Background

Variable frequency drives are installed at the supply of a motor to control the speed and torque of the motor's rotation. These receive an AC mains supply, which is rectified and converted to DC, then converted back to a variable AC voltage at the drive's output. Frequency and voltage are then varied to control the motor speed. This allows precise control of the motors' speed, with the drive receiving feedback of the motors speed so that changes can constantly be made to the output supply. This 'closed loop' control is illustrated in figure 24 below, with the error signal being calculated from the difference between the feedback signal, and the reference supply voltage, then fed to the control circuitry or microcontroller. [54] [55]

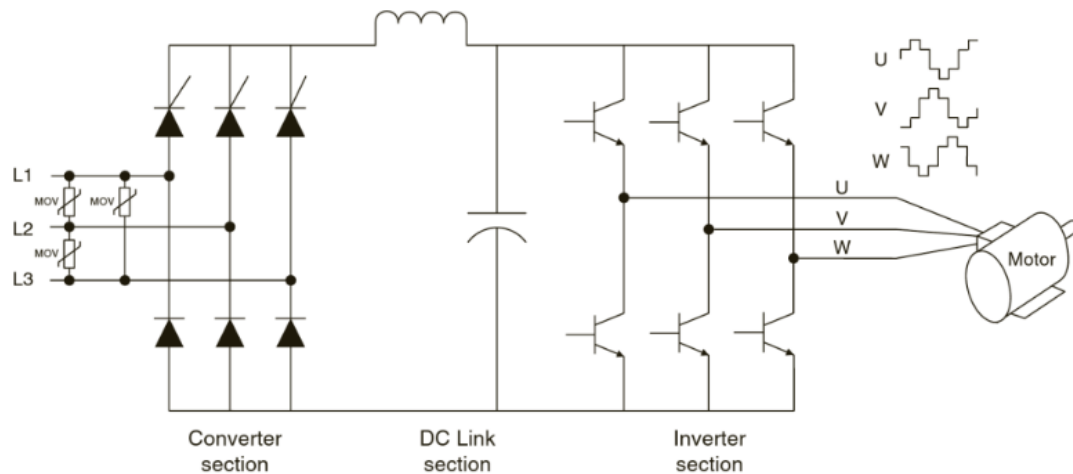


Figure 23 - Simplified VFD Diagram [15]

Figure 23 shows three sections of a VFD, the converter or rectifier section at the left, DC bus at the center, and inverter on the right.

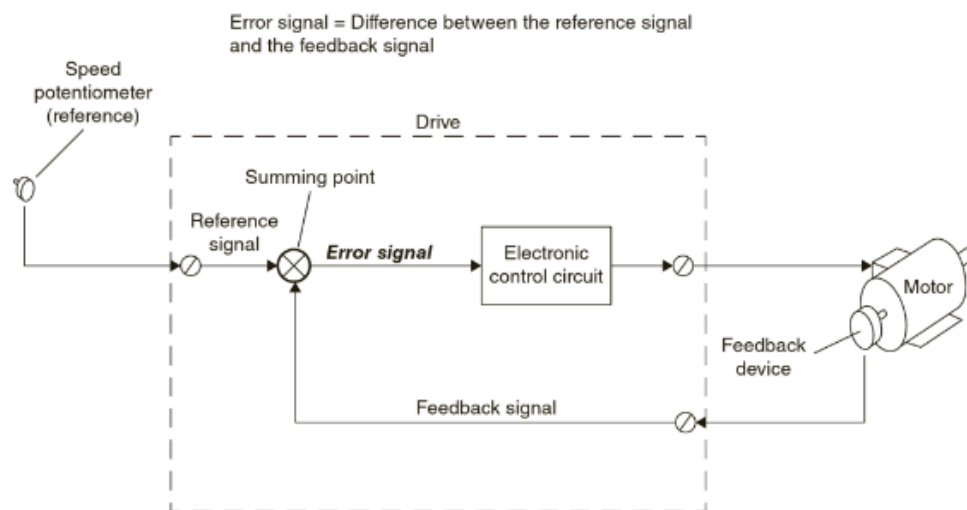


Figure 24 - Closed-Loop VFD Control System [54]

Rectifier

This converts the AC voltage to DC by using 6 diodes which are connected in a three phase bridge configuration, blocking two out of three phases, leaving a rippling DC voltage. Current runs through the top diodes and the rest of the VFD, then returns to the supply via the bottom diodes. Current cannot flow in the opposite direction due to the diodes only allowing current flow in one direction, leaving a rippling DC voltage as illustrated in figure 25.

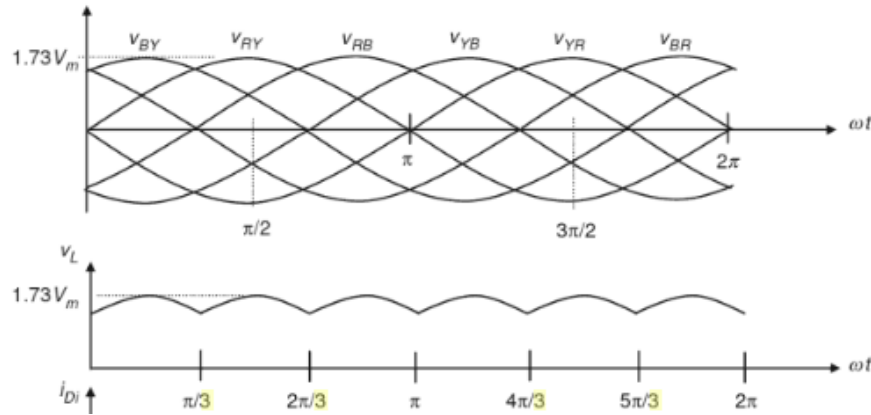


Figure 25 - AC Voltage Rectified to a Rippling DC Voltage [56]

DC Link

In this section, a capacitor charges and discharges with the voltage ripples, outputting voltage during the voltage dips, which smooths the output into a DC voltage. Inductors smooth the current ripples caused by the rectifier. [15] This smoothing effect is shown in figure 26, with the rippling DC voltage as the dotted line, and the capacitor smoothed DC voltage in red.

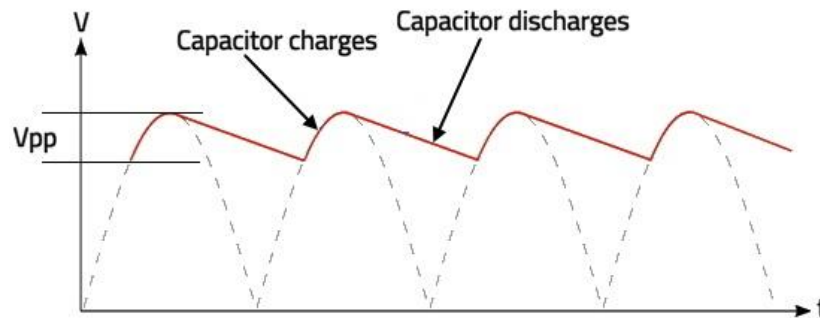


Figure 26 - Smoothed Rippling DC Voltage [57]

Inverter

This consists of 6 IGBTs or SCRs that act as switches to generate a 3 phase AC voltage output to the motor. These IGBTs are controlled by the VFD's control circuitry and switch a top and bottom IGBT on in sequence. When they are on the top IGBT will provide a positive voltage for one phase, and the bottom will provide a negative voltage for another phase, producing a 3 phase quasi-sinusoidal voltage. [58]

To produce a sinusoidal wave form, pulse width modulation is utilized by alternating the duty cycle of the IGBTs depending on the amplitude of the voltage. This now produces a near smooth sine wave for supplying and controlling the speed of the motor. The duty cycle is either increased to increase the voltage or decreased

to reduce it. Frequency is controlled by alternating the timing of the IGBT switching. Figure 28 illustrates how increasing duty cycle increases the voltage amplitude.

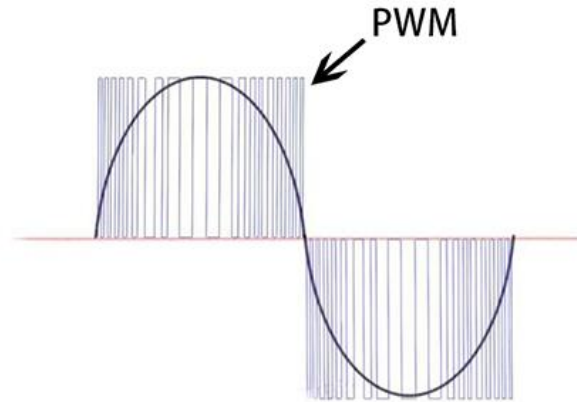


Figure 27 - Duty Cycle in Relation to the Generated Sine Wave [59]

6.2. Use of Diodes, Thyristors, and IGBTs for Rectification

The rectifier can feature diodes, thyristors (SCRs) or insulated-gate bipolar transistors (IGBTs).

Diodes

Diodes are the most simple and inexpensive, but result in high harmonic distortion, causing a poor power factor and unwanted power losses in the VFD. This harmonic distortion is caused by the rippling DC voltage output from the diodes implemented in a bridge rectifier configuration. Figure 28 illustrates the symbol and shape of a diode, with current flowing from the anode to the cathode. [60]

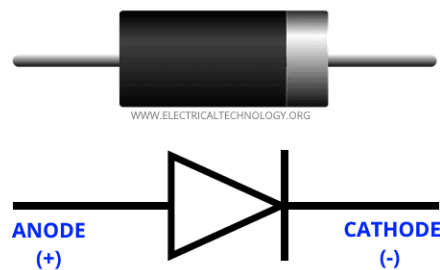


Figure 28 - Illustration of a Diode [61]

Thyristors (SCRs)

Thyristors or silicon-controlled rectifiers, provide more precise control over the rectification process, due to their gates being controlled by the VFD's control circuitry. This prevents deviations from the required DC signal, reducing harmonic distortion. These are more expensive and require more complex control circuitry to implement into VFDs but are more efficient. [62] Figure 29 shows the electronic symbol and appearance, with the anode and cathode providing a path for current flow, and the gate acting as a signal input for the switch.

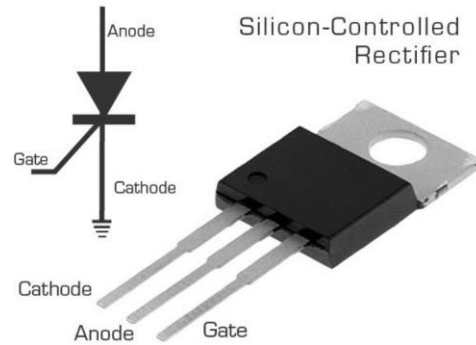


Figure 29 - SCR Symbol and Appearance [63]

IGBTs

Insulated gate bipolar transistors are devices that switch at extremely high speeds, with frequencies up to 100kHz. [64] This high switching frequency is desirable for a smooth output current waveform. [65] These consist of three terminals, including the emitter and collectors which function as the switch contacts, and the gate which is what operates the switch to allow current flow. These terminals are illustrated in figure 30, and the overall design of an IGBT shown in figure 31. With higher switching frequencies, less ripple is produced in the DC signal, meaning less harmonic distortion.

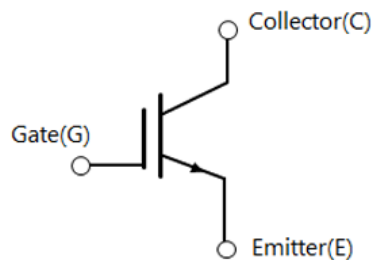


Figure 30 - Wiring Diagram of an IGBT [66]

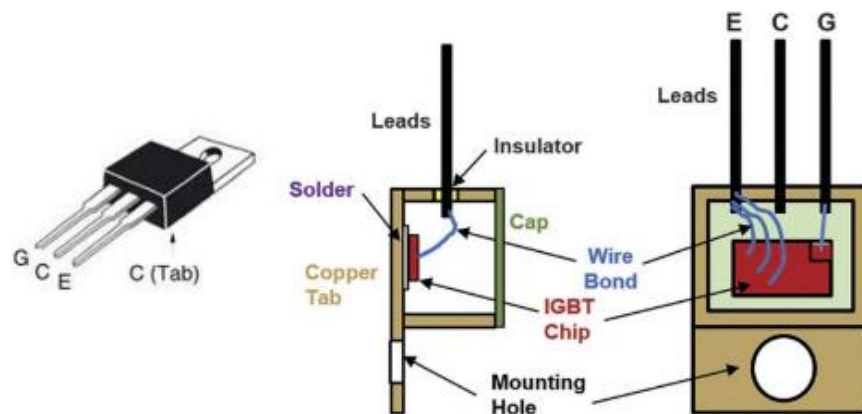


Figure 31 - Illustration of the Design of an IGBT Chip [67]

Minimizing Harmonic Noise in Rectifier Design

Harmonic noise are unwanted frequencies in multiples of the input frequency that are present in the voltage. [68] Harmonic Noise is reduced in the design of rectifiers in VFDs by selecting IGBTs with the highest switching frequency to reduce rippling in the DC voltage and current, and by using multi-pulse rectifiers. These utilize multiple rectifier circuits to produce a smoother output voltage, resulting in less noise. For example, a 12-pulse rectifier can be used rather than a 6-pulse rectifier, with the two circuits being phase shifted by 30 degrees. Multi-pulse rectifiers will produce outputs that are smoother than single rectifiers, with less harmonic noise. [69] Good grounding and shielding in the VFD will reduce harmonics also. Adding an inductor to the rectifier smooths the current and helps it match the sinusoidal shape of the supply wave form, reducing current harmonics. Figure 32 shows a rectifier with an inductor added.

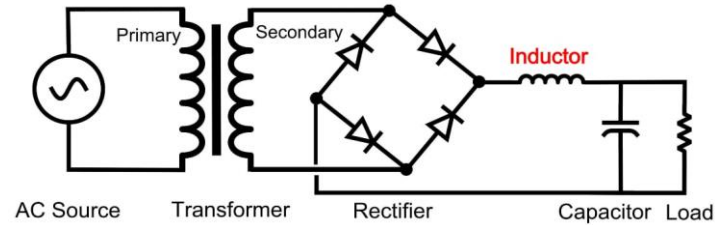


Figure 32 - Rectifier with an Inductor Added [70]

Figure 34 shows a Proteus simulation of a 6-pulse rectifier, and figure 35 shows a 12-pulse rectifier, with each being 30° out of phase with each other. The 12-pulse rectifier involves two rectifiers with combined outputs. The Fourier analysis graphs (harmonic current spectrum) [71] show the amplitude of the harmonic frequencies/components (noise) present at different frequencies in the signal at multiples of the fundamental frequency [72] [73], and the 12 pulse's output has less harmonics than the 6 pulse. Figure 33 shows a typical harmonic current spectrum for a rectifier, which matches the Proteus simulations. The higher the total harmonic distortion (THD) value in the Fourier graphs, the more the output voltage has become distorted from the nominal required voltage value. The analogue analysis graphs show the three phase input AC voltages in red, blue, and green, and the DC output in yellow. The DC signal for the 12-pulse rectifier is smoother than the 6 pulse, due to there being more sine wave pulses to charge the capacitor(s). This results in less harmonics being produced by 12-pulse rectifiers. [74] [75]

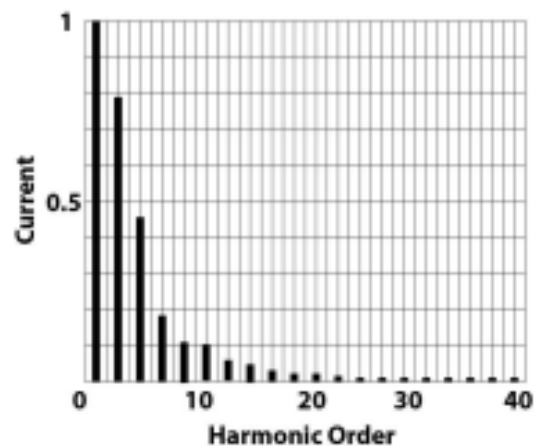


Figure 33 - Typical Harmonic Current Spectrum for a Rectifier [71]

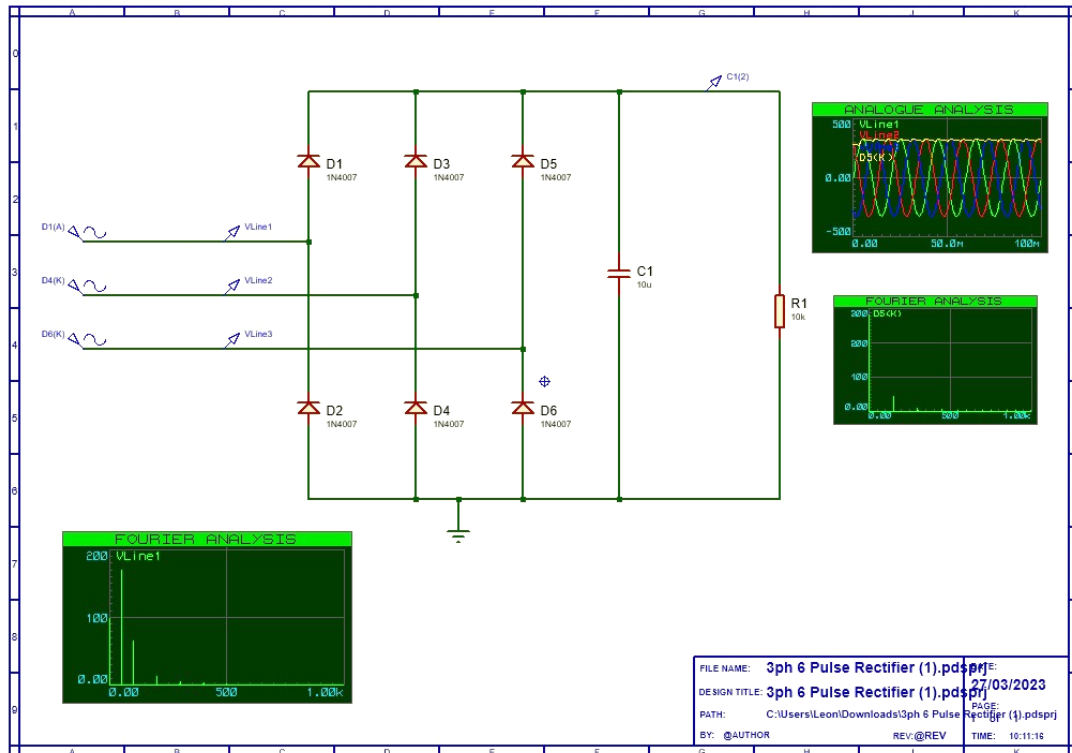


Figure 34 – 6-Pulse Rectifier Simulation

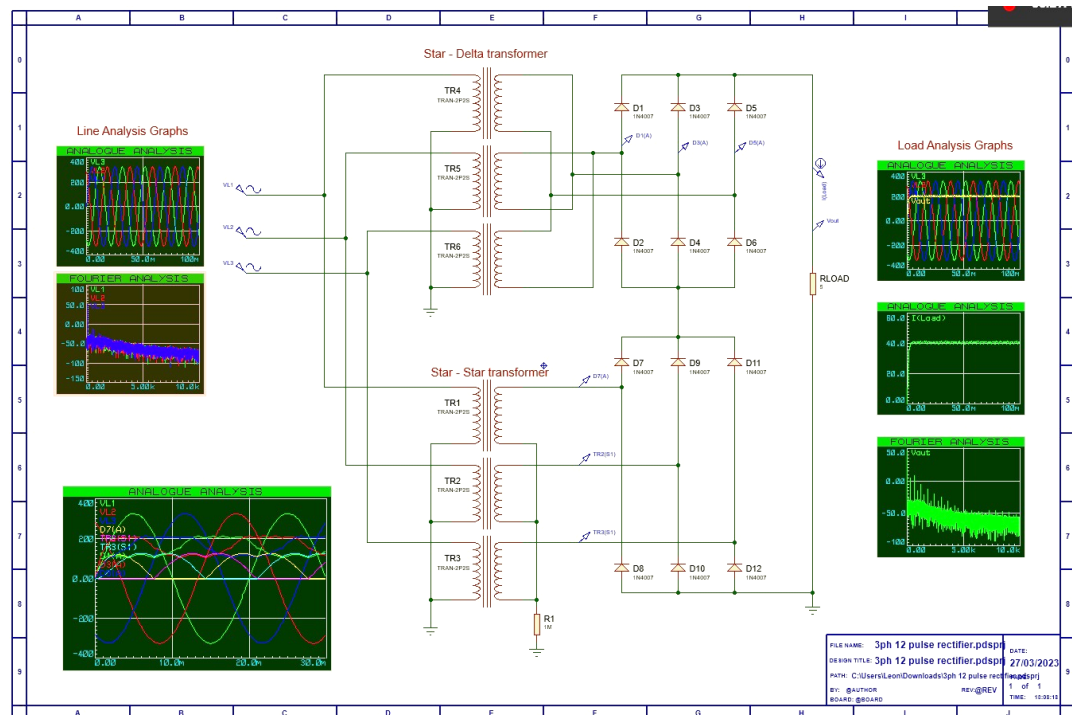


Figure 35 – 12-Pulse Rectifier Simulation

Power factor is the ratio of real power to apparent power. Harmonic distortions (THDs) reduce the power factor as they result in a non-sinusoidal waveform with current being out of phase with the voltage. Total RMS current increases as a result of the waveform being distorted from harmonics, and thus the power factor decreases. In the formula: $I = I_1 \sqrt{1 + \text{THD}^2}$ [76], current will increase with the THD. The power factor formula in figure 36 explains the relationship between real power, apparent power, and power factor. It's affected by the total RMS current, which increases due to harmonic distortion. [77]

$$\begin{aligned} \text{PF} &= \frac{\text{real power}}{\text{apparent power}} = \frac{\frac{1}{T} \int_0^T v i \, dt}{V_{\text{RMS}} I_{\text{RMS}}} \\ &= \frac{\sum_{n=1}^N V_n I_n \cos(\phi_n)}{V_{\text{RMS}} I_{\text{RMS}}} \end{aligned}$$

Figure 36 - Formula for Calculating Power Factor [77]

6.3. Conclusion

To conclude, if basic diodes or thyristors are implemented into the design of a VFD's rectifier, a large amount of harmonic distortion will be present in the DC output. Harmonic distortion is minimized in VFDs via multi-pulse rectifiers such as 12 or 18-pulse rectifiers, high frequency IGBT rectifiers, implementing diodes to smooth the current, as well as using harmonic filters. Using these methods to reduce harmonic distortion will improve the efficiency of the VFD, and will improve its power factor, minimizing power losses.

7. References

- [1] ABB, "ACS880-07, cabinet-built single drives," N.D. [Online]. Available: <https://new.abb.com/drives/low-voltage-ac/industrial-drives/acs880-single-drives/acs880-07>. [Accessed 01 04 2023].
- [2] ABB, "ACS880-07 drives (45 to 710 kW, 50 to 700 hp) Hardware manual," 08 11 2021. [Online]. Available: https://library.e.abb.com/public/7d6812c7f190407d96eef5e47385250b/EN_ACS880-07_HW_H.pdf?x-sign=i7kRAHnhdAYg1ghZWp2YCmYLRJSZl+ED7KqwJRxeP89SZIeUFzCPMewMGNX4lPO. [Accessed 01 04 2023].
- [3] ABB, "ACH580 drives for HVAC," N.D. [Online]. Available: <https://new.abb.com/drives/low-voltage-ac/industry-specific-drives/ach580>. [Accessed 04 04 2023].
- [4] ABB, "ACH580-07 Hardware Manual," 14 04 2022. [Online]. Available: https://library.e.abb.com/public/97a3753299d740ad9019395bee98e972/EN_ACH580-07_HW_F_A4.pdf?x-sign=pkgX3kss6BXLdJCQur6sf/utEG4G34sFwS2O432+Z8ADuWLGb1zeODHAQeUavbFw. [Accessed 04 04 2023].
- [5] E. E. T. CC, "ACH580-07 - Cabinet-built drive for HVAC ABB ACH580-07-0206A-4," N.D. [Online]. Available: <https://www.online.elio.co.za/product/abb-ach580-07-0206a-4/>. [Accessed 04 04 2023].
- [6] IACS, "ACH580-01-026A-4+B056 - IP55 Variable Frequency Drive 11 Kw | ABB Inverter," N.D. [Online]. Available: <https://www.i-acis.co.uk/store/ach580-01-026a-4-b056-ip55-variable-frequency-drive-11-kw-inverter-abb.html>. [Accessed 10 04 2023].
- [7] ABB, "ACH580-01 technical data sheet," 2016. [Online]. Available: <https://www.i-acis.co.uk/store/documentation/datasheets/abb/ACH580-01-02A6-4-TDS.pdf>. [Accessed 10 04 2023].
- [8] RS-Online, "ABB Inverter Drive, 5.5 kW, 3 Phase, 400 V ac, 12.5 A, ACS355 Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/8874733>. [Accessed 11 04 2023].
- [9] ABB, "ABB machinery drives ACS355, 0.37 to 22 kW / 0.5 to 30 hp," 2013. [Online]. Available: <https://docs.rs-online.com/0694/0900766b81536937.pdf>. [Accessed 11 04 2023].
- [10] ABB, "Datasheet ACS355 drives with IP66/67 / UL Type 4X enclosure (0.37...7.5 kW, 0.5...10 HP)," 01 01 2010. [Online]. Available: <https://docs.rs-online.com/1c58/0900766b816295f6.pdf>. [Accessed 11 04 2023].
- [11] RS-Online, "ABB 5.5 kW DOL Starter, 230 V ac, 3 Phase, IP55," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/8110767>. [Accessed 11 04 2023].
- [12] ABB, "Enclosed control products Starters, heating/lighting, pushbuttons Catalogue," 2015. [Online]. Available: <https://www.230plus.co.uk/pdf/1TVC230050S5699.pdf>. [Accessed 11 04 2023].
- [13] A. Iqbal, S. Moinoddin and B. P. Reddy, "10.3 Working Principle," in *Electrical Machine Fundamentals with Numerical Simulation using Matlab/Simulink*, Chennai, Wiley, 2021, p. 691.

- [14] A. Hughes, "General arrangement of drive," in *Electric Motors and Drives, Fundamentals, Types and Applications*, University of Leeds, Newnes, 1993, p. 42.
- [15] M. E. Brumbach and J. A. Clade, "Inverter," in *Electronic Variable Speed Drives, Fourth Edition*, Boston, Cengage Learning, 2018, p. 20.
- [16] M. I. Ahmed, S. Singhal and S. Chourasiya, *COMPARISON & POWER QUALITY IN DOL & SD STARTER OF IM*, p. 401, 2017.
- [17] Rahul, "Direct Online Starter (DOL Motor Starter): Circuit Diagram and Working Principle," 12 06 2020. [Online]. Available: <https://www.electricalvolt.com/2019/03/direct-online-starter-dol-motor-starter-circuit-diagram-and-working-principle/>. [Accessed 26 03 2023].
- [18] A. Hughes, in *Electric Motors and Drives: Fundamentals, Types and Applications*, Oxford, Newnes, 2006, p. 240.
- [19] T. I. o. E. Engineers, "Electronic Soft Start, Chapter 6.4," in *The Control Techniques Drives and Controls Handbook*, London, The Institution of Electrical Engineers, 2001, p. 171.
- [20] R. Miller, M. R. Miller and H. L. Stewart, "Chapter 12: Motor Controls," in *Electrical and Electronic Principles and Technology, 6th ed.*, Routledge, 2019, pp. 384-392.
- [21] A. Hughes and B. Drury, "Types, and Applications," in *Electric Motors and Drives: Fundamentals*, Oxford, Newnes, 2013, pp. 170-173.
- [22] C. Cavallo, "All About Motor Soft Starters - What They Are and How They Work," N.D. [Online]. Available: <https://www.thomasnet.com/articles/machinery-tools-supplies/motor-soft-starters/>. [Accessed 26 03 2023].
- [23] Goto-Automation.com, "Frequency converter-Variable frequency Drive LS Electric H100 3 Phase 500kW 400V, LSLV5000H100-4COFD," N.D. [Online]. Available: <https://www.goto-automation.com/en/products/frequency-inverters/frequency-inverters-3-phase-400-vac/frequency-converter-variable-frequency-drive-ls-industrial-136>. [Accessed 01 04 2023].
- [24] S. Electric, "Variable speed drive, Altivar," 02 04 2023. [Online]. Available: <https://www.se.com/ww/en/product/ATV9A0C50Q4/variable-speed-drive-altivar-process-atv900-apm-single-400-v-500-kw/>. [Accessed 02 04 2023].
- [25] Danfoss, "VLT® AutomationDrive FC 301 / FC 302," N.D. [Online]. Available: <https://www.danfoss.com/en-gb/products/dds/low-voltage-drives/vlt-drives/vlt-automationdrive-fc-301-fc-302/#tab-overview>. [Accessed 02 04 2023].
- [26] Danfoss, "134U0146 DANFOSS DRIVES VLT Automation Drive FC-302 560 KW / 750 HP, 525-690 VAC *, IP21 / Type 1, 12 Pulse," N.D. [Online]. Available: <https://www.electricalautomationnetwork.com/en/danfoss-drives/134u0146-danfoss-drives-vlt-automation-drive-fc-302-560-kw-750-hp-525-690-vac-ip21-type-1-12-pulse>. [Accessed 02 04 2023].
- [27] Danfoss, "VACON® NXC," N.D. [Online]. Available: <https://www.danfoss.com/en-gb/products/dds/enclosed-drives/vacon-enclosed-drives/vacon-nxc/#tab-overview>. [Accessed 04 04 2023].

- [28] RS-Online, "Schneider Electric Variable Speed Drive, 90 kW, 3 Phase, 400 V, ALTIVAR 630 Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/8724088>. [Accessed 04 04 2023].
- [29] S. Electric, "Variable speed drives Altivar Process Business optimization, real-time intelligence," N.D. [Online]. Available: <https://docs.rs-online.com/c96b/0900766b813ceff1.pdf>. [Accessed 04 04 2023].
- [30] RS-Online, "Siemens Converter, 90 kW, 3 Phase, 400 V, 156 A, G120C Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/2255453>. [Accessed 04 04 2023].
- [31] Siemens, "Data sheet for SINAMICS G120C," 05 05 2021. [Online]. Available: <https://docs.rs-online.com/5fd8/A700000008066624.pdf>. [Accessed 04 04 2023].
- [32] RS-Online, "RS PRO Inverter Drive, 11 kW, 3 Phase, 380 → 480 V ac, 26.4 A," N.D. [Online]. Available: <https://my.rs-online.com/web/p/inverter-drives/1748222>. [Accessed 10 04 2023].
- [33] R. PRO, "Microprocessor Controlled IGBT Drive Inverter Motor Speed Regulator Operating Manual," N.D. [Online]. Available: <https://docs.rs-online.com/e8c3/A700000006570784.pdf>. [Accessed 10 04 2023].
- [34] "Inverter 11kW, 15HP, WITH FILTER Datasheet," N.D. [Online]. Available: <https://docs.rs-online.com/f001/0900766b816e81f1.pdf>. [Accessed 10 04 2023].
- [35] "Danfoss Inverter Drive, 11 kW, 3 Phase, 400 V ac, 23 A, VLT FC51 Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/8918845>. [Accessed 10 04 2023].
- [36] Danfoss, "VLT® Micro Drive Datasheet," 09 2014. [Online]. Available: <https://docs.rs-online.com/cb5b/0900766b8142601f.pdf>. [Accessed 10 04 2023].
- [37] Danfoss, "VLT® Micro Drive Datasheet," 09 2007. [Online]. Available: <https://docs.rs-online.com/d2d7/0900766b81426022.pdf>. [Accessed 10 04 2023].
- [38] RS-Online, "Schneider Electric Variable Speed Drive, 11 kW, 15 kW, 3 Phase, 400 V ac, 20.6 A, 27 A, ATV930 Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/1624946>. [Accessed 10 04 2023].
- [39] S. Electric, "ATV930D15N4 variable speed drive - ATV930 - 15kW - 400/480V - with braking unit - IP21," 17 01 2018. [Online]. Available: <https://docs.rs-online.com/07f5/0900766b81618023.pdf>. [Accessed 10 04 2023].
- [40] RS-Online, "RS PRO 22 kW Soft Starter, 400 V ac, 2 Phase, IP20," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/1359720>. [Accessed 11 04 2023].
- [41] S. Electric, "How can Schneider Electric Soft Starts be used to run three phase motors in both direction(Forwards and Reverse)," 30 09 2021. [Online]. Available: <https://www.se.com/uk/en/faqs/FA22870/#:~:text=Soft%20Starters%20can%20not%20reverse,before%20changing%20contactors%20and%20restarting..> [Accessed 11 04 2023].
- [42] RS-Online, "RS PRO Inverter Drive, 5.5 kW, 3 Phase, 380 → 480 V ac, 14.3 A," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/1748220>. [Accessed 11 04 2023].
- [43] R. PRO, "Inverter 5.5 kW, 8HP, WITH FILTER Datasheet," N.D. [Online]. Available: <https://docs.rs-online.com/6c91/0900766b816e81ef.pdf>. [Accessed 11 04 2023].

- [44] RSPRO, "Microprocessor Controlled IGBT Drive Inverter Motor Speed Regulator Operating Manual," N.D. [Online]. Available: <https://docs.rs-online.com/4c73/A700000006570788.pdf>. [Accessed 11 04 2023].
- [45] RS-Online, "Danfoss Inverter Drive, 5.5 kW, 3 Phase, 400 V ac, 12 A, VLT FC51 Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/8918833>. [Accessed 11 04 2023].
- [46] Danfoss, "VLT® Micro Drive," 09 2014. [Online]. Available: <https://docs.rs-online.com/cb5b/0900766b8142601f.pdf>. [Accessed 11 04 2023].
- [47] Danfoss, "VLT® Micro Drive Small drive – maximum strength and reliability," 09 2007. [Online]. Available: <https://docs.rs-online.com/d2d7/0900766b81426022.pdf>. [Accessed 11 04 2023].
- [48] RS_Online, "Schneider Electric Variable Speed Drive, 5.5 kW, 3 Phase, 400 V ac, 10.4 A @ 380 V ac, ATV63 Series," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/inverter-drives/1253276>. [Accessed 11 04 2023].
- [49] "Product datasheet ATV630U55N4 variable speed drive ATV630 - 5.5kW/7.5HP - 380...480V - IP21/UL type 1," 23 11 2016. [Online]. Available: <https://docs.rs-online.com/57eb/0900766b8154a32c.pdf>. [Accessed 11 04 2023].
- [50] RS-Online, "RS PRO 1.5 kW DOL Starter, 240 V ac, 1 Phase, IP55," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/9094098>. [Accessed 11 04 2023].
- [51] RS-Online, "Schneider Electric 1.1 kW DOL Starter, 240 V ac, 3 Phase, IP65," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/7447872>. [Accessed 11 04 2023].
- [52] S. Electric, "Product data sheet LE1M35U708 enclosed DOL non reversing starter TeSys - LE1-M - 1.8...2.6 A - coil 240 V AC," 03 09 2013. [Online]. Available: <https://docs.rs-online.com/2537/0900766b814cecb7.pdf>. [Accessed 11 04 2023].
- [53] Automation-Electric, "1.5 kW DOL start Single phase pump control panel," 13 06 2016. [Online]. Available: <https://automation-electric.co.uk/?product=1-5-kw-dol-start-single-phase-pump-control-panel&>. [Accessed 11 04 2023].
- [54] M. E. Braumbach and J. A. Clade, "Review of Physical, Electrical, and Motor Terminology," in *Electronic Variable Speed Drives, Fourth Edition*, Boston, Cengage Learning, 2018, p. 19.
- [55] B. Wu, "Multipulse Diode Rectifiers," in *High-Power Converters and AC Drives*, New Jersey, John Wiley & Sons, Inc, 2006, p. 37.
- [56] M. H. Rashid, "Three-phase Bridge Rectifiers," in *Power Electronics Handbook, Second Edition*, Pensacola, Florida, Academic Press, 2007, p. 154.
- [57] Ametek, "How To Minimize Ripple In DC Power Supplies," 14 07 2017. [Online]. Available: <https://blog.programmablepower.com/how-to-minimize-ripple-in-dc-power-supplies>. [Accessed 12 04 2023].
- [58] A. D. Falehi, "Suggested odd-nary multilevel inverter," *Novel harmonic elimination strategy based on Multi-Objective Grey Wolf Optimizer to ameliorate voltage quality of odd-nary multi-level structure*, vol. 6, no. 3, 2020.

- [59] Inverter.com, "Difference between Sine Wave and Square Wave of Inverter," 08 02 2021. [Online]. Available: <https://www.inverter.com/difference-between-sine-wave-and-square-wave-of-inverter>. [Accessed 12 04 2023].
- [60] H. F. Hofman and H. W. Meyer, "Active Rectifiers Improve Efficiency and Power Factor," *IEEE Industry Applications Magazine*, vol. 7, no. 6, pp. 21-29, 2001.
- [61] E. Technology, "What is Diode? Construction & Working of PN Junction Diode," N.D. [Online]. Available: <https://www.electricaltechnology.org/2020/06/diode.html>. [Accessed 13 04 2023].
- [62] M. K. Kazimierczuk and R. Kruszka, "The comparison of AC-DC converters for low power applications," *Electrical Review*, vol. 89, no. 5, pp. 237-240, 2013.
- [63] A. P., "Fungsi SCR (Silicon Controlled Rectifier) Adalah," N.D. [Online]. Available: <https://serviceacjogja.pro/fungsi-scr-adalah/>. [Accessed 13 04 2023].
- [64] A. Dmowski, R. Bugyi and P. Szewczyk, "High efficiency resonant converter based on IGBTs with 100 kHz operation frequency," 28 10 1994. [Online]. Available: <https://ieeexplore.ieee.org/document/341626/metrics#metrics>. [Accessed 22 04 2023].
- [65] M. Barnes, "Insulated Gate Bipolar Transistor (IGBT)," in *Practical Variable Speed Drives and Power Electronics*, Oxford, Newnes, 2003, pp. 109-111.
- [66] Components101, "A Brief Overview of IGBT - Insulated Gate Bipolar Transistor," 06 04 2020. [Online]. Available: <https://components101.com/articles/what-is-igbt-working-operation-symbol-and-types>. [Accessed 13 04 2023].
- [67] B. J. Baliga, "Package and Module Design," in *The IGBT Device*, Amsterdam, Elsevier, 2023, p. 184.
- [68] J. Agnew, Ph.D., "Total Harmonic Distortion," *The Causes and Effects of Distortion and Internal Noise in Hearing Aids*, vol. 3, pp. 82-118, 1998.
- [69] G. P. K. and K. A. M., "A review on harmonic elimination techniques used in rectifier-inverter fed induction motor drives," *International Journal of Electrical Power & Energy Systems*, pp. 48-59, 2016.
- [70] D. Williams, "Power Factor, THD, and Why Linear Power Supplies Fail to Meet Power Standards," 08 12 2016. [Online]. Available: <https://www.allaboutcircuits.com/technical-articles/power-factor-thd-why-linear-power-supplies-fail-meet-electricity-standards/>. [Accessed 22 04 2023].
- [71] K. O'Connell, "Typical Supply Voltage Harmonic Distortion," *Heating & Cooling Effects Through Harmonic Distortion on Electric Cables in the Built Environment*, pp. 28-31, 23 07 2013.
- [72] I. V. Blagouchine and E. Moreau, *Analytic Method for the Computation of the Total Harmonic Distortion by the Cauchy Method of Residues*, vol. 9, pp. 2478-2491, 2011.
- [73] A. P. Technologies, "Total Harmonic Distortion and Effects in Electrical Power Systems," N.D. [Online]. Available: <https://www.aptsources.com/wp-content/uploads/pdfs/Total-Harmonic-Distortion-and-Effects-in-Electrical-Power-Systems.pdf>. [Accessed 22 04 2023].
- [74] S. K. Pyakuryal, M. A. Matin, D. Gao and G. Edwards, "State of the art," *Control of Harmonics in 6-Pulse Rectifiers*, p. 3, 2013.

- [75] L. W. Y. and S. E., "A review of three-phase voltage source inverters for motor drives," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1050-1072, 2016.
- [76] T. T. O. Koehorst, "Efficiently Powering UV Sources," 06 09 2020. [Online]. Available: <https://uvsolutionsmag.com/articles/2020/efficiently-powering-uv-sources/>. [Accessed 22 04 2023].
- [77] N. W. R. B. J. W. W.J.B. Heffernan, "Power factor and displacement power factor," *Harmonic performance of heat-pumps*, p. 3, 2013.
- [78] F. Group, "MOTORS BASIC. PART TWO: BASIC PRINCIPLES - AC INDUCTION MOTORS," 29 07 2020. [Online]. Available: <https://www.flaktgroup.com/en/news/news-archive/2020/july/basic-principles-of-ac-induction-motors/>. [Accessed 21 03 2023].
- [79] K. Sahay and S. Pathak, "Cage Rotor," in *Basic Concepts of Electrical Engineering*, Lucknow, New Age International Publishers, 2006, p. 232.
- [80] D. Sang, "Fleming's Left Hand Rule," in *Cambridge IGCSE Physics Coursebook*, University of Cambridge, Cambridge, 2010, p. 222.
- [81] RS-Online, "RS PRO 11.0kW @ 400Vac Soft Starter, 187 → 575 V ac, 3 Phase, IP42, 22 Amps," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/2275225>. [Accessed 04 04 2023].
- [82] R. PRO, "RS PRO Soft Starter range 0.75kW – 75kW, 400Vac, 3-phase control + RS485," [Online]. Available: <https://docs.rs-online.com/7e09/A700000008071718.pdf>. [Accessed 04 04 2023].
- [83] RS-Online, "ABB 11 kW Soft Starter, 208 → 600 V ac, 3 Phase, IP20," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/8517632>. [Accessed 04 04 2023].
- [84] ABB, "Softstarters PSR, PSE and PSTX," 01 2020. [Online]. Available: <https://docs.rs-online.com/63fb/0900766b8138b45b.pdf>. [Accessed 04 04 2023].
- [85] RS-Online, "Siemens 11 kW Soft Starter, 400 V ac, 3 Phase, IP20," N.D. [Online]. Available: <https://uk.rs-online.com/web/p/motor-starters/7464940>. [Accessed 04 04 2023].
- [86] A. Electric, "1.1 kW DOL start Single phase pump control panel," N.D. [Online]. Available: <https://automation-electric.co.uk/?product=1-1-kw-dol-start-single-phase-pump-control-panel>. [Accessed 11 04 2023].
- [87] ElProCus, "Silicon Controlled Rectifiers – Basics, Operation & Applications," N.D. [Online]. Available: <https://www.elprocus.com/silicon-controlled-rectifiers-basics-operation-applications/>. [Accessed 13 04 2023].