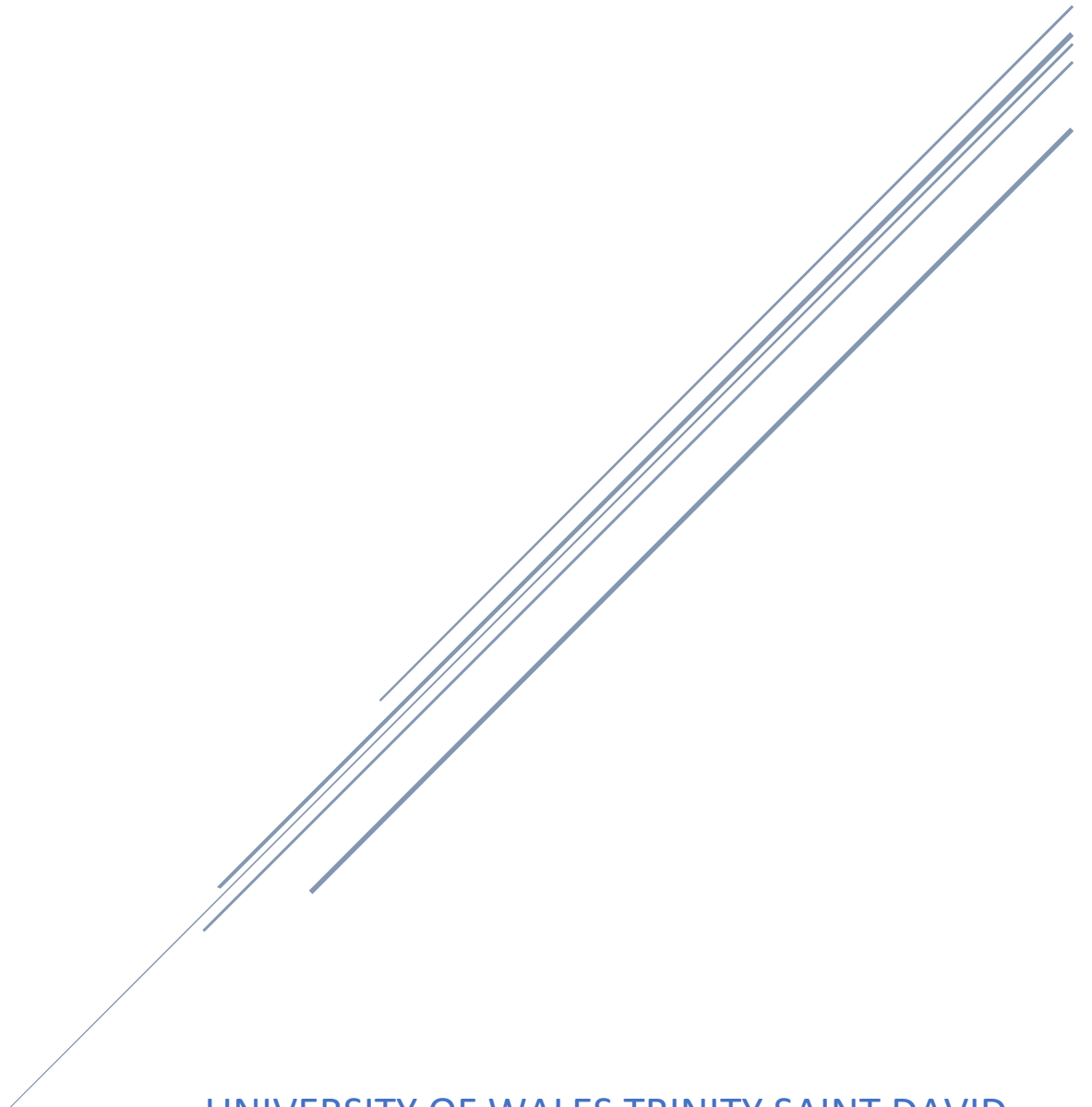


DESIGN EXERCISE

ASSIGNMENT 1

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POWER ELECTRONICS AND DRIVES – ACDA6004

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1 ABSTRACT

This document details existing induction motor technology and some drive circuit topologies. The first section explains some of the fundamental principles of how induction motors operate. A review of existing motor drive technology is also undertaken to find suitable solutions for specific induction motors within a factory. The final section further explores the VFD rectification stage, showing example circuits and their operating principles. Harmonics caused in the rectification stage is also discussed.

2 PART 1 MOTOR DRIVERS

2.1 BACKGROUND RESEARCH

2.1.1 WHAT IS A MOTOR?

A motor is a device that converts electrical energy into rotational force. The basic principle is that they exploit the mechanical force that is exerted on a current carrying conductor placed within a magnetic field [1].

2.1.2 INDUCTION MOTORS

One common type of motor construction architecture is the induction motor. This is comprised of 2 main parts: the stator and the rotor. The stator is the stationary part of the motor which houses the coils of wire that conduct a 3 phase AC.

The rotor is the part that will rotate, and it is most commonly constructed of numerous conductor bars that are connected by an end ring. This is often referred to as a squirrel cage. Within the squirrel cage is a stack of silicon steel laminations that have an oxide layer. These steel laminations act as an insulator, and they prevent any unwanted eddy-currents from flowing in the squirrel cage. The squirrel cages can be made out of copper but are more often made out of die-cast aluminium.

The 3 phase AC in the stator windings produce a rotating magnetic field which induces currents in the rotor and effectively drags the rotor around. The speed of the rotor is never greater than the speed of the rotating magnetic field. The lag of the rotor is called slip.

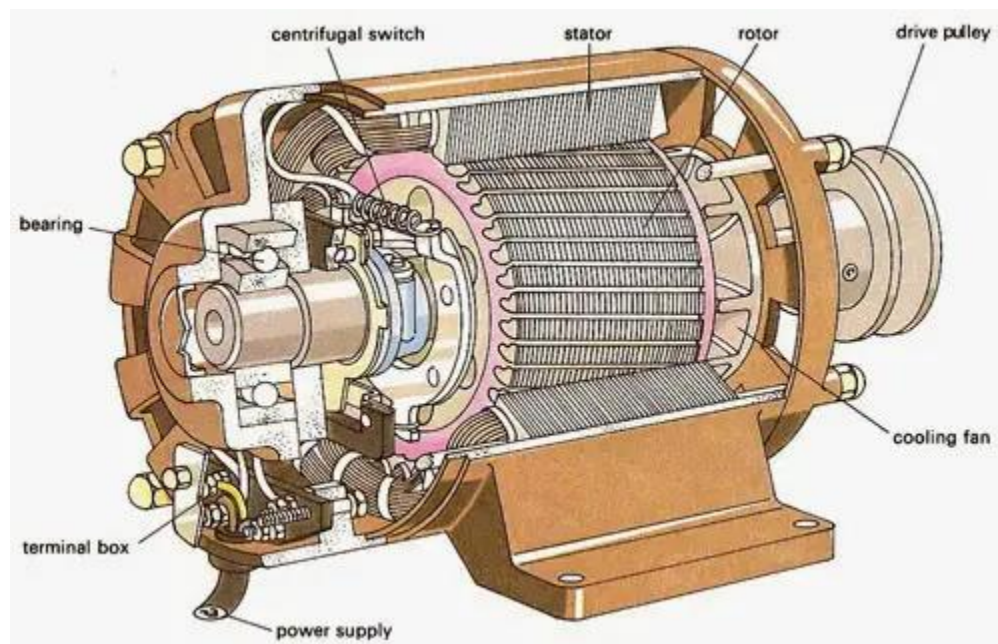


Figure 1 – Induction motor diagram [2]

The speed of the motor is dependent on the frequency of the AC as this will change the speed of the rotating magnetic field. Modulating the frequency of the AC in the stator windings can be used to control the rotational speed of the motor [3].

2.1.3 MOTOR DRIVE OVERVIEW

A motor driver is a circuit that takes the supply voltage from a source and supplies power to a motor at voltages and frequencies that will produce desired mechanical outputs.

In most motor drives, there are two main parts. Firstly, there is the power stage which allows energy to flow from the supply to the motor. Secondly, there is the control stage, which will take feedback from the motor and compare it with a desired reference and adjust the motor power accordingly [4]. Figure 2 shows an example of a drive system that could be used to control the speed of a motor.

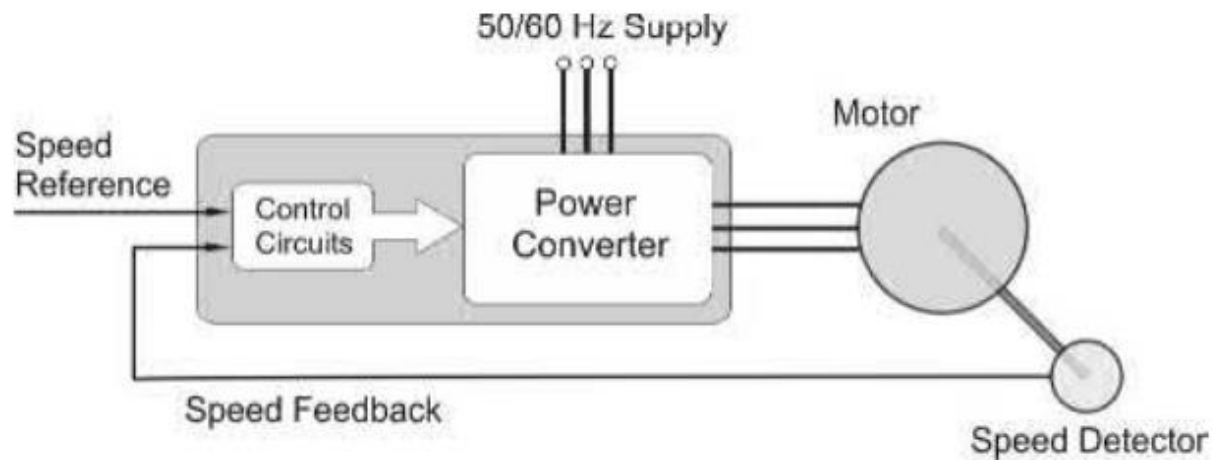


Figure 2 - Example speed control driver system [4]

The power converter stage architecture will be different depending on the type of supply and the type of motor used.

2.1.4 VARIABLE FREQUENCY DRIVES

As mentioned previously, the frequency of the AC supply used to power an induction motor is related to the speed of the magnetic field and therefore the speed of the motor. Equation 1 shows how the synchronous speed (N_s) (speed of the magnetic field) is related to the frequency of the supply. As the frequency increases, the synchronous speed increases [3].

$$N_s = \frac{120f}{p}$$

Equation 1 - Synchronous speed of induction motor [3]

A variable frequency drive is made up of 3 parts.

First is the rectifier section, in which an AC supply is converted to DC using some kind of rectification. This could be diodes, SCRs, IGBT or something else.

The next section of the VFD is the DC link. This section has a reservoir capacitor which is used to smooth out the DC voltage after the rectification stage [5].

Finally, is the inverter section. The method of converting a DC signal to AC is called inversion. An inversion circuit uses a switching component (BJT for example) to switch a DC signal across a load. A single-phase inverter can be seen in Figure 3. When switch 1 and 4 are active, the voltage at the load is positive. When switches 2 and 3 are active, the voltages at the load are reversed and so is negative. If no switch is active, then voltage is 0 at the load. This allows the load to be in 3 voltage states, +V, -V and 0V.

Flywheel diodes are also included to prevent damage from inductive loads switching on and off. Which can cause large voltage spikes when voltage across an inductor changes rapidly. The diode provides a path for the reverse current supplied from the inductive load when it has switched off.

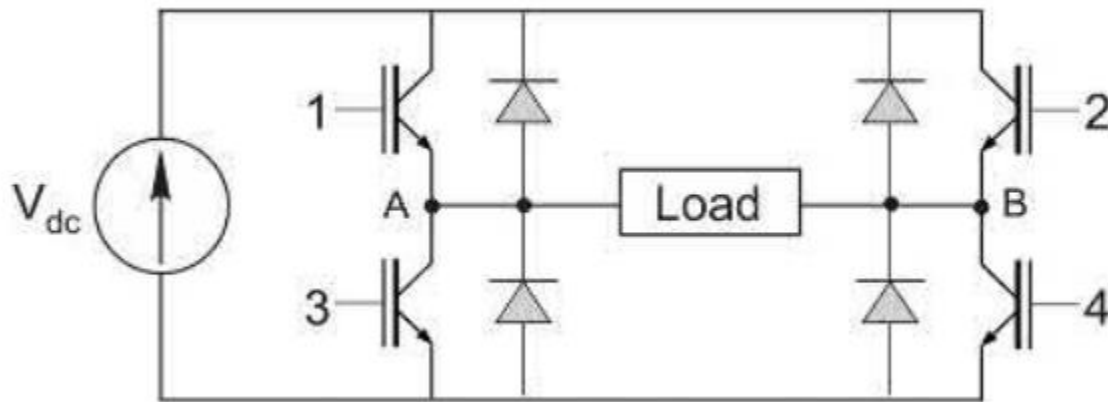


Figure 3 - Single Phase Inverter

Inversion can be used to control both the frequency and the voltage using pulse width modulation (PWM). PWM is the process of switching a connection on and off to control the duty cycle of a signal. By controlling the duty cycle you can reduce the average voltage and change the frequency of the waveform. As the frequency decreases, so does the average voltage. This can be seen in Figure 4. The waveform across the load is AC, however it is not smoothed and has sharp edges.

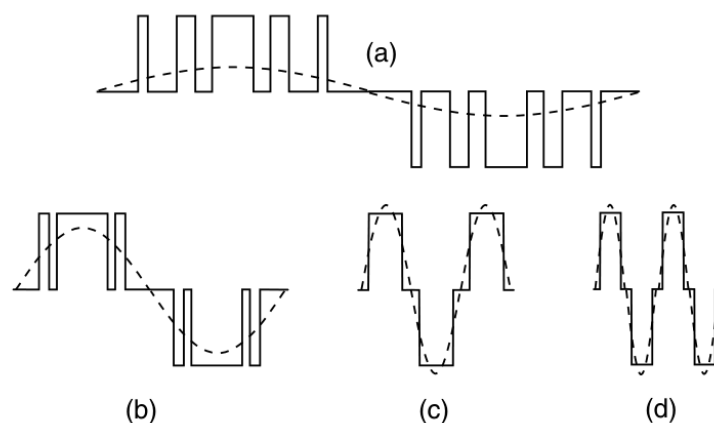


Figure 4 - Inverter output voltage and frequency controlled with PWM [6]

Figure 5 shows an example VFD with all stages. The example has a 3-phase input and uses diodes in the rectification stage. The inverter uses IGBTs as a switching device.

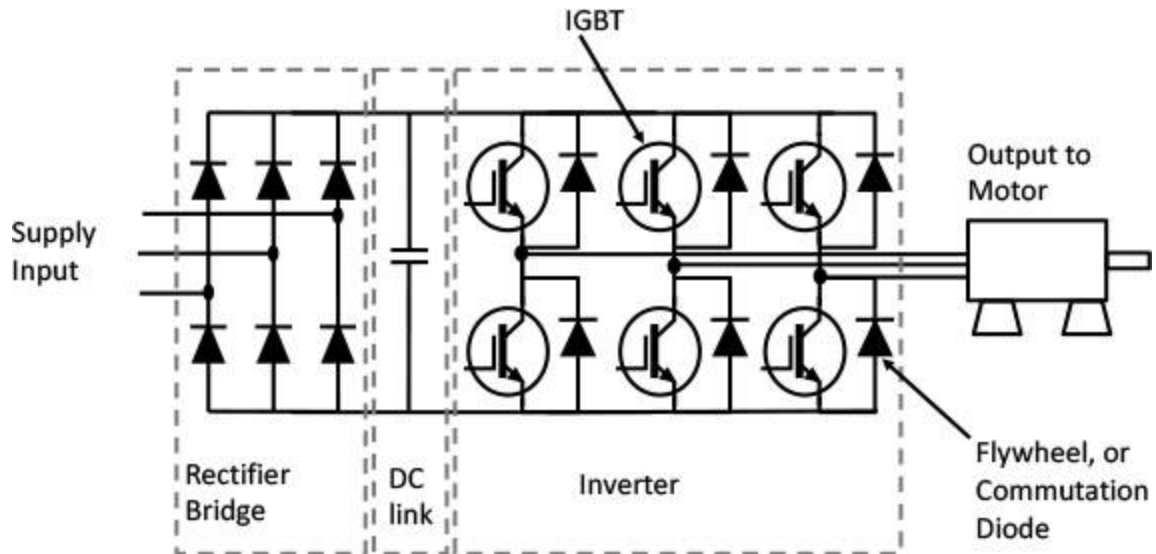


Figure 5 - Example VFD [5]

2.2 MOTOR DRIVES FOR FACTORY

Table 1 shows the different types of induction motors that are used around a factory. The following section will show some potential motor drivers that could be used to control these motors. Some comparable features of each motor drive will be specified in tables. The best drive option for each motor will be selected with reasons given as to why it was chosen.

	Motor A	Motor B	Motor C	Motor D	Motor E
Power	500 kW	80 kW	10 kW	5 kW	1 kW
Phases	3	3	3	3	1
Voltage	400	400	400	400	230
Required to be Reversible?	Yes	Yes	No	Yes	No
Variable speed required?	Yes	Yes	Yes	No	No
Quantity Installed	5	10	23	17	127
Example Application	Rolling Mill	Gantry Crane	Conveyor	Cutting machine	Pumps / Fans

Table 1 - Induction motors in factory

2.2.1 MOTOR A DRIVE SELECTION

MODEL NAME	ATV71EXC2C50N4H	ATV980C63Q4X1	LSLV5000H100-4COFD
MANUFACTURER	SCHNEIDER ELECTRIC	SCHNEIDER ELECTRIC	LS ELECTRIC
IP RATING	23	23	20
HEIGHT (mm)	2157	2150	1054
WIDTH (mm)	2400	2000	776
DEPTH (mm)	642	664	500
COMMUNICATION PROTOCOLS	MODBUS / CANopen	MODBUS TCP / MODBUS serial / Ethernet IP. Extra slots for CANopen module / EtherCAT / PROFINET / PROFIBUS / DEVICENET	LS INV 485 / MODBUS / BACnet/ Metasys-N2
NOTE	DISCONTINUED		
REF	[7]	[8]	[9]

Table 2 – Motor A Drive Options

From the drive options shown in Table 2, the first drive which can be eliminated is the ATV71EXC2C50N4H. While this product can still be purchased, it is probably not suitable due to it being discontinued. This unit will cost a significant amount of money and therefore it will probably be more suitable to select something that is not at the end of its life as manufacturers may not be able to supply spare parts if something goes wrong with it.

The ATV980C63Q4X1 has been selected as the most suitable product for the following reasons:

- It meets the drive requirements of motor A.
- More communication protocol options so can be connected to larger systems easily and it means there is flexibility in ways to communicate with it. Profinet will be used as a standard.
- Higher IP rating (23). The drive will most likely be installed in an environment that is not too extreme (very wet or very hot for example), it would be an additional benefit to have a better rating. 23 means that is protected against solid foreign objects of 2.5mm or greater and that it will protect against vertical falling water drops tilted up to 15 degrees [10].
- Schneider also offer a field service so that if there is an issue they can send a technician out. This service is not offered by LS Electric [11].
- Manufactured by Schneider Electric so can be standardized across the factory.

2.2.2 MOTOR B DRIVE SELECTION

MODEL NAME	CFW500G0211T4DB20C 3G2	VFD900C43A-00	ATV930D90N4Z U	VAR-UMA1090G4
MANUFACTURER	WEG	DELTA	SCHNEIDER ELECTRIC	UNIVERSAL MOTORS
HEIGHT (mm)	675	716	748	680
WIDTH (mm)	335	370	265	325
DEPTH (mm)	307	300	307	365
COMMUNICATION PROTOCOLS	Modbus RS485	Modbus RS485	MODBUS TCP / MODBUS serial / Ethernet IP. Extra slots for CANopen module / EtherCAT / PROFINET / PROFIBUS / DEVICENET	Modbus RS485
NOTE				
REF	[12]	[13]	[14]	[15]

Table 3 – Motor B Drive Options

The ATV930D90N4ZU has been selected as the most suitable product for the following reasons:

- It meets the drive requirements of motor B.
- Wide range of communication protocols. Profinet will be used as a standard.
- Manufactured by Schneider Electric so can be standardized across the factory.

2.2.3 MOTOR C DRIVE SELECTION

MODEL NAME	ATV950D11N4U	CFW500D24P0T4DB20C3G2	VAR- UMA1011G4	10G-44-0230-BF
MANUFACTURER	SCHNEIDER ELECTRIC	WEG	UNIVERSAL MOTORS	PARKER
HEIGHT (mm)	678	306.6	320	265
WIDTH (mm)	264	180	170	170
DEPTH (mm)	299	166.5	216	156
COMMUNICATION PROTOCOLS	MODBUS TCP / MODBUS serial / Ethernet IP. Extra slots for CANopen module / EtherCAT / PROFINET / PROFIBUS / DEVICENET	Modbus RS485	Modbus RS485	Modbus RS485
NOTE				
REF	[16]	[17]	[18]	[19]

Table 4 – Motor C Drive Options

The ATV950D11N4U has been selected as the most suitable product for the following reasons:

- It meets the drive requirements of motor C.
- Wide range of communication protocols. Profinet will be used as a standard.
- Manufactured by Schneider Electric so can be standardized across the factory.

2.2.4 MOTOR D DRIVE SELECTION

MODEL NAME	CFW300C12P0T4NB20	ATV950U55N4U	VAR-UMB15R5G4	10G-43-0120-BN
MANUFACTURER	WEG	SCHNEIDER ELECTRIC	UNIVERSAL MOTORS	PARKER
HEIGHT (mm)	214	678	256	235
WIDTH (mm)	89	264	146	138
DEPTH (mm)	164	272	167	152
COMMUNICATION PROTOCOLS	(RS-232, RS-485, USB, CANopen, DeviceNet, Profibus DP, Bluetooth or Ethernet)	MODBUS TCP / MODBUS serial / Ethernet IP. Extra slots for CANopen module / EtherCAT / PROFINET / PROFIBUS / DEVICENET	RS485 fieldbus. Modbus protocol.	Modbus RS485
NOTE				
REF	[20]	[21]	[22]	[23]

Table 5 – Motor D Drive Options

The ATV950U55N4U has been selected as the most suitable product for the following reasons:

- It meets the drive requirements of motor D.
- Wide range of communication protocols. Profinet will be used as a standard.
- Manufactured by Schneider Electric so can be standardized across the factory.

2.2.5 MOTOR E DRIVE SELECTION

MODEL NAME	ODE-3-220105-1F42-01	C200-02200056	ATV320U11M2W
MANUFACTURER	INVERTEK	CONTROL TECHNIQUES	SCHNEIDER ELECTRIC
HEIGHT (mm)	221	205	250
WIDTH (mm)	110	75	235
DEPTH (mm)	150	150	340
COMMUNICATION PROTOCOLS	Modbus RS485	AI-485 / SI-EtherCAT / SI-PROFIBUS / SI-Ethernet / SI-DeviceNet / SI-CANopen / SI-PROFINET	Modbus RS485 Extra slots for CANopen module / EtherCAT / PROFINET / PROFIBUS / DEVICENET
NOTE			
REF	[24]	[25]	[26]

Table 6 – Motor E Drive Options

The ATV320U11M2W has been selected as the most suitable product for the following reasons:

- It meets the drive requirements of motor E.
- Wide range of communication protocols. Profinet will be used as a standard.
- Manufactured by Schneider Electric so can be standardized across the factory.

2.3 DISCUSSION

The initial reason a drive was considered for selection was after it was confirmed to meet the drive requirements of a motor in Table 1. Some specs were not comparable due to the information not being readily available such as the cost. This would however need to be reviewed after quotes have been received as a company would have a budget for a project as large as this and overspending could be catastrophic for its financial stability.

One of the main strategies that was taken during the selection process was to try and standardize on the manufacturer of motor driver. There are several reasons for this choice:

- Potential to get price breaks for buying from the same manufacturer. This is possible due to the large amount of drives that would be required for the factory (182).
- There is also a potential to get customized drives from Schneider due the significant amount of money that would be required to acquire them.
- Maintenance teams will become familiar with the architecture of 1 manufacturer. This will decrease the time taken to train them.
- Reduction in the amount of different spare parts.
- Schneider offer field service plans which would apply to any of the motors that were used on site.
- Setup and communication to products from the same manufacturer could also be standardized. For example, all motors can be controlled using PROFINET. This would simplify the design of the system.
- Standardization may also lead to an improved workplace culture as the maintenance jobs are simplified and streamlined [27].

2.4 CONCLUSION

The choice to standardize the motor drives gives numerous benefits [28]. If drivers from lots of different manufacturers were selected, then the design and setup across the factory would become more complicated and could potentially have a wider range of issues.

3 PART 2 RECTIFICATION OF MAINS

3.1 BACKGROUND RESEARCH

3.2 WHAT IS A RECTIFIER?

A rectifier is a circuit that converts AC to DC. This is one of the key parts in a VFD.

3.3 DIODE RECTIFIER

Diode rectifiers use diodes to direct the flow of current when rectifying AC.

3.3.1 SINGLE PHASE DIODE RECTIFIERS

The simplest type of diode rectifier is a single diode in series with an AC supply and a load. This can be seen in Figure 6.

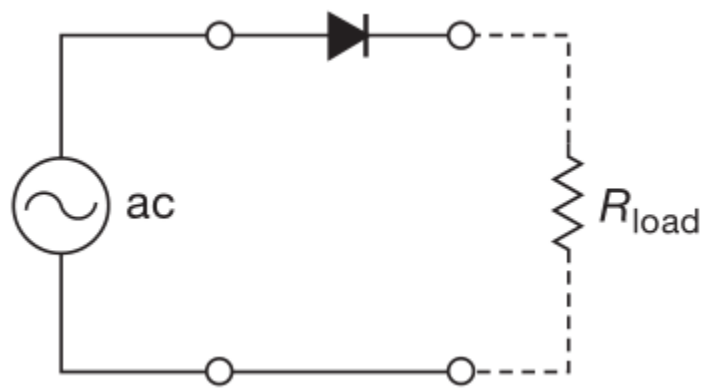


Figure 6 - Single Phase Half Wave Rectifier [29]

In this circuit, the positive half cycle of the AC will allow current to pass through the diode in its positive bias mode. However, the negative half cycle is blocked.



Figure 7 - Single Phase Half Wave Rectifier Voltage Waveform

The circuit in Figure 8 shows a full wave bridge rectifier. This circuit diverts both the positive and negative half cycles to the load using the diodes.

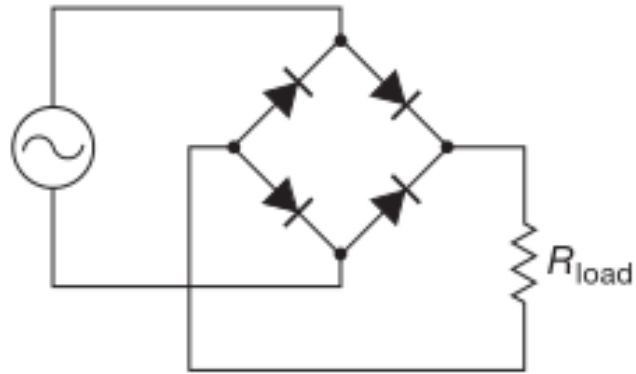


Figure 8 - Single Phase Full Wave Bridge Rectifier [29]

The output waveform of a full bridge rectifier can be seen in Figure 9. While this is technically DC, the waveform is not a constant voltage which is undesirable for most circuits.

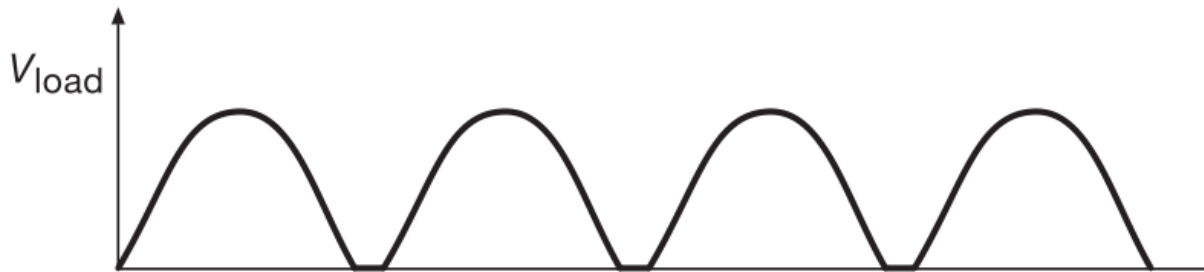


Figure 9 - Single Phase Full Wave Bridge Rectifier Voltage Waveform [29]

To reduce the variation in the output voltage, a smoothing capacitor is added in parallel with the load (Figure 10). In relation to VFDs, the smoothing capacitor is located within the DC link section.

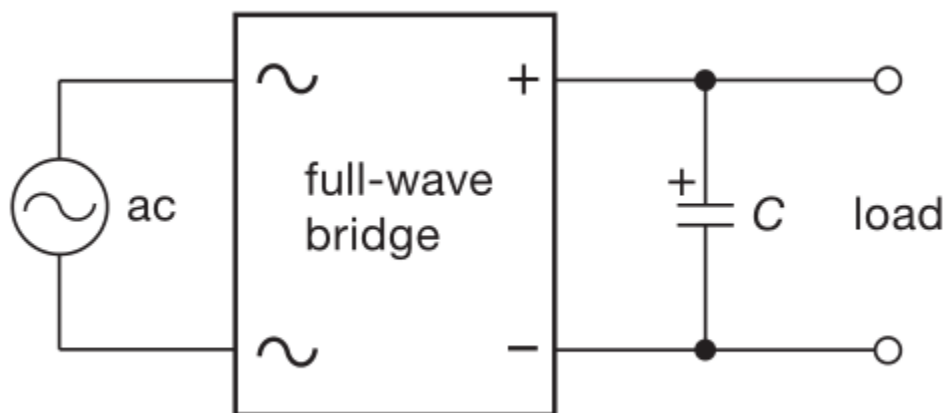


Figure 10 - Full Bridge Rectifier With Smoothing Capacitor [29]

The output voltage waveform of a full wave rectifier with a smoothing capacitor can be seen in Figure 11. The dotted line indicates the smoothed output.

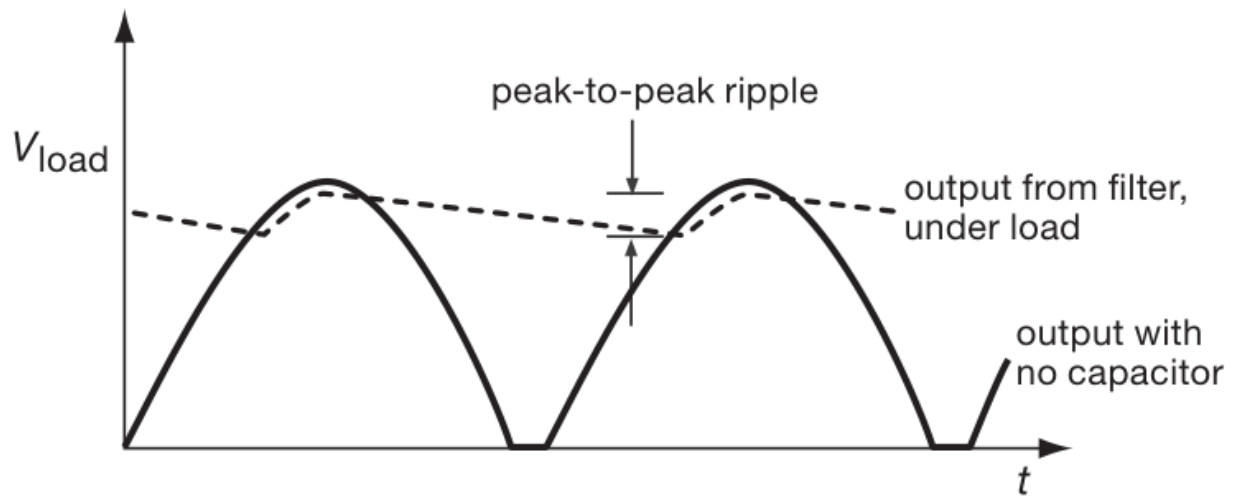


Figure 11 - Single Phase Full Wave Bridge Rectifier Voltage Waveform with Smoothing Capacitor [29]

3.3.2 3 PHASE DIODE RECTIFIER

The same principle of the single-phase rectifier applies to the three phase one. The diodes are still being used to divert the current flow from the AC supply. A 3-phase diode rectifier circuit can be seen in Figure 12. The diodes will conduct in a specific order that will depend on the phase of each AC line. The conduction sequence is as follows D1 D2, D2 D3, D3 D4, D4 D5, D5 D6, D6 D1 and then it repeats [30].

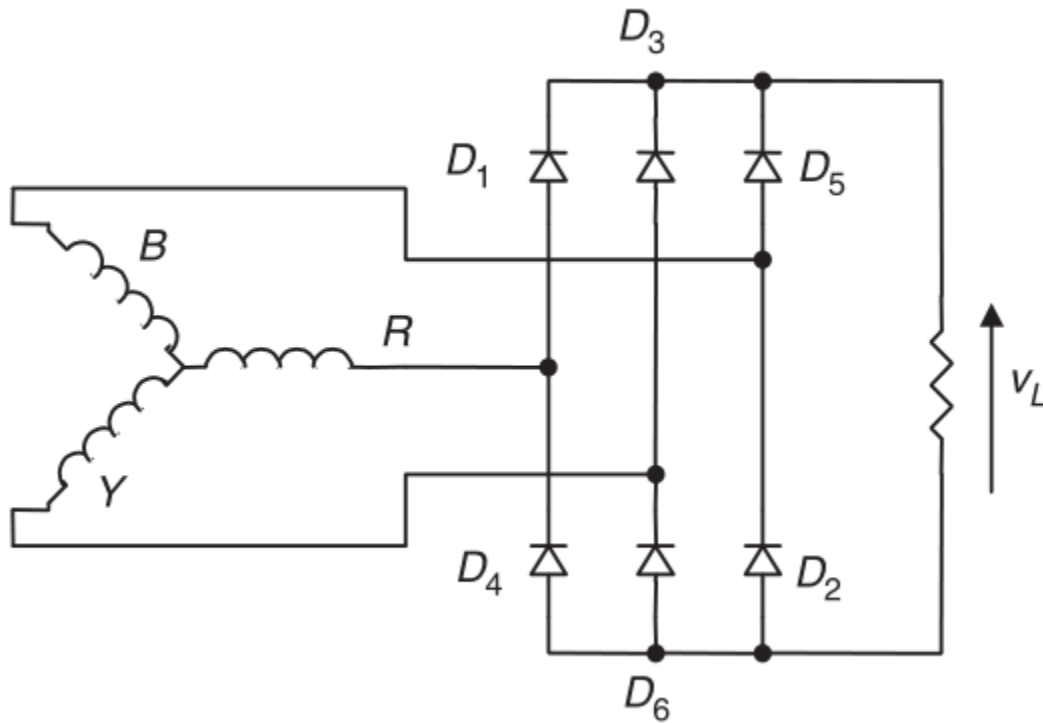


Figure 12 – Three Phase Bridge Rectifier [30]

The output waveform of the three-phase bridge rectifier can be seen in Figure 13. In the example shown in Figure 13, which has a star connected source the line voltage is 1.73 times larger than the phase voltage. This type of rectifier is very efficient and is used whenever there are high DC voltage and current requirements, which would make it a perfect rectifier for VFDs. Filters are often not included as the ripple voltage is relatively small at 4.2%. If they are included, they can be quite small due to the high ripple frequency of the DC output which is 6 times the supply frequency [30].

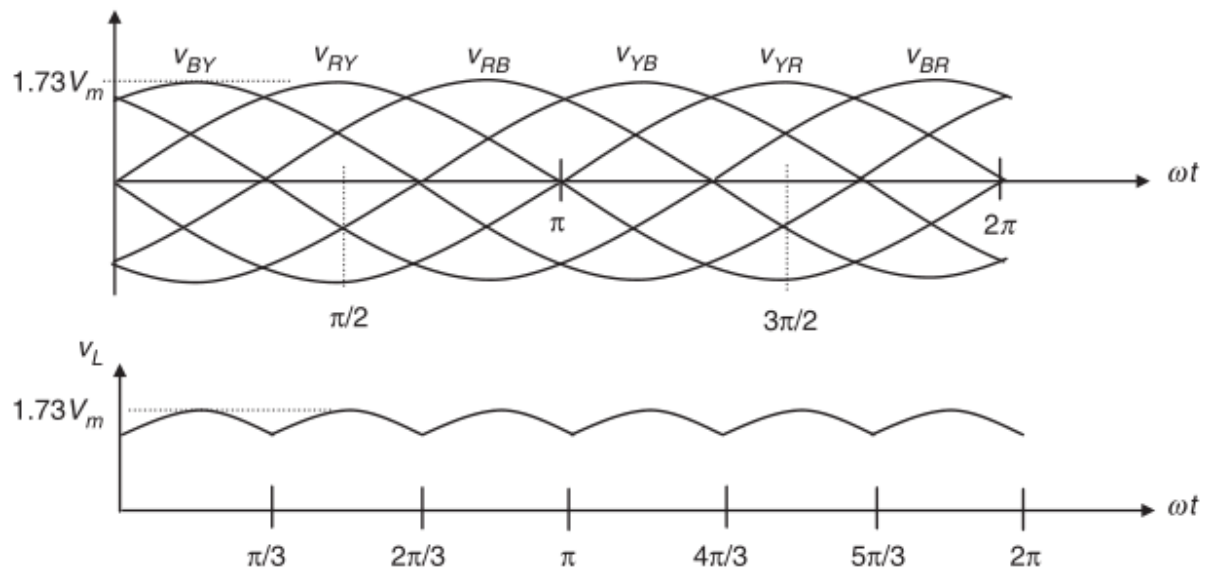


Figure 13 - Output Voltage waveforms on Three Phase Bridge Rectifier [30]

3.4 SCR RECTIFIER

3.4.1 SCR

A silicon-controlled rectifier (SCR) is a type of thyristor which is used as a power electronics switch. These devices have three terminal, anode, cathode, and gate. They behave in a similar manner to a diode in that they only conduct in one direction. The difference is that they will only conduct once the gate has been triggered by a voltage at a specific threshold. Once the SCR has been turned on, it will latch and continue to conduct until the current through it reaches 0A [31].

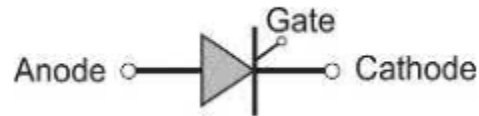


Figure 14 – Schematic Symbol of a Thyristor [31].

3.4.2 SINGLE PHASE SCR RECTIFIER

An example of a single phase SCR rectifier circuit can be seen Figure 15, along with its output waveform. The α symbol indicates the delay angle until the firing of the gate signal. By varying the delay angle, you can adjust how much of the phase of the AC signal is allowed to pass through the SCR. Therefore the average voltage at the output can be controlled [31].

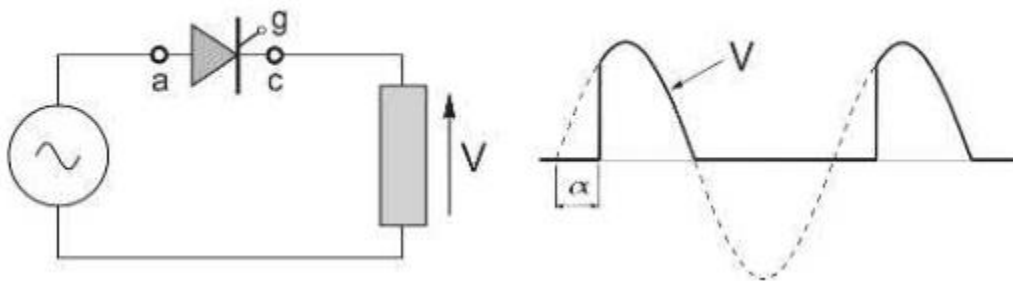


Figure 15 – Single Phase SCR Rectifier [31].

3.4.3 3 PHASE SCR RECTIFIER

The 3 phase SCR rectifier circuit is very similar to the 3-phase diode rectifier; however, all diodes have been replaced with SCRs. Each SCR will need to be controlled by a logic device, to ensure the gates are switched at the right time to get the desired output voltage.

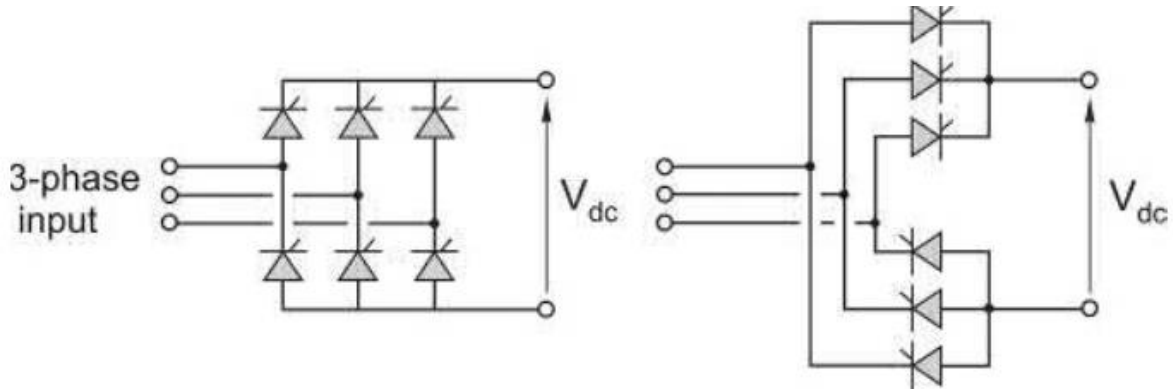


Figure 16 – 3 Phase SCR Rectifier [31]

Figure 17 shows the output voltage of a 3 phase SCR rectifier. It is very similar to the diode rectifier output when α is 0. However, there is much more control over the output voltage (average) which will change in relation to the phase at which the gate is fired.

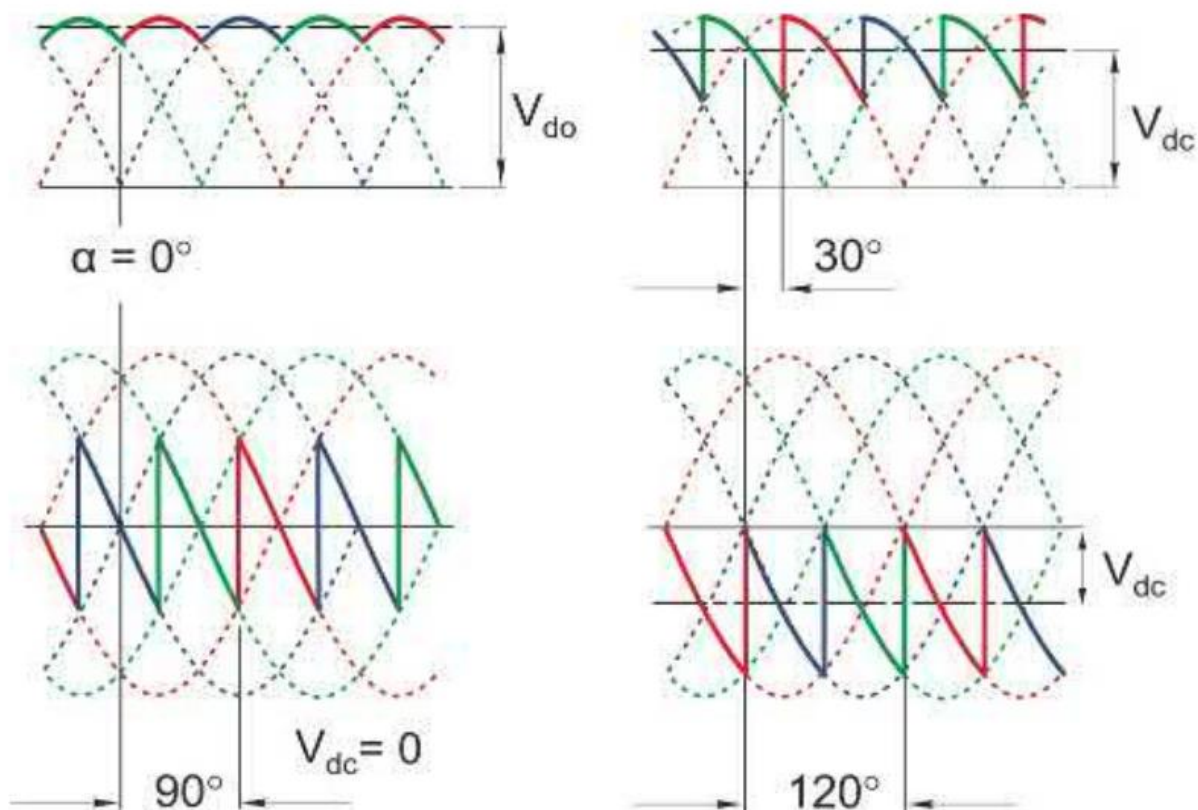


Figure 17 - 3 Phase SCR Rectifier Voltage Output [31]

3.5 IGBT RECTIFIER

3.5.1 IGBT

An insulated gate bipolar transistor (IGBT) is a three terminal device used for switching power. Their terminals are the gate for controlling the switching, collector and emitter which is the main switched conduction path. They comprise of a combination of a metal oxide field effect transistor (MOSFET) and a bipolar junction transistor (BJT) and are constructed in a way to get the best features of both devices; mainly the insulated gate input of the MOSFET and the low on-state resistance of the BJT. Other benefits include a comparable conduction characteristics to a BJT, however they can be used at higher frequencies, making them excellent choices for applications where PWM is required. They also require less silicon to make than similarly rated MOSFETS and therefore can be cheaper [32]. The circuit symbol can be seen in Figure 18.

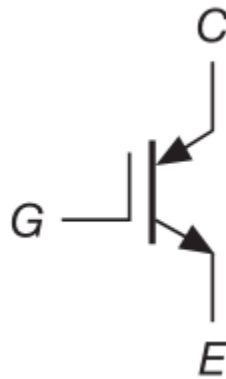


Figure 18 – Schematic symbol of an IGBT

3.5.2 3 PHASE IGBT RECTIFIER

The 3 phase IGBT rectifier is very similar in construction to the SCR rectifier. It can be connected in a bridge configuration and also requires logic to control the switching of the IGBTs.

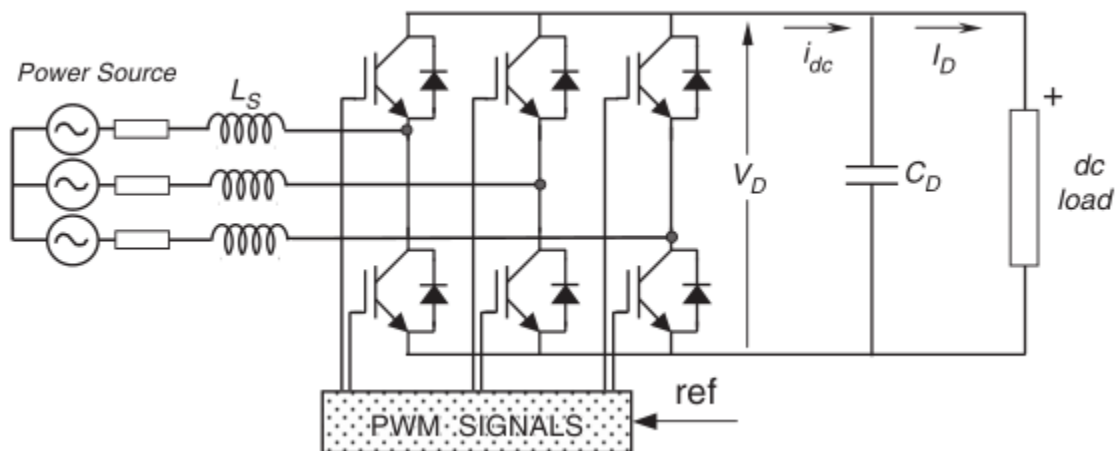


Figure 19 – 3 Phase IGBT rectifier [33]

3.6 DISCUSSION

3.6.1 COMPARISON OF RECTIFIERS

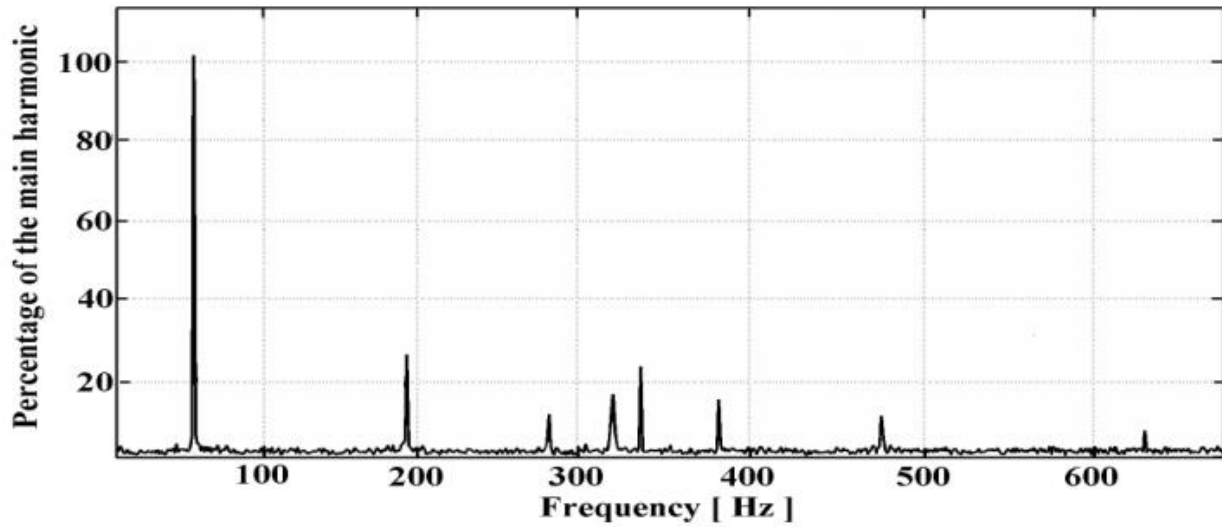
One of the key benefits of a IGBT rectifier is the ability to switch off the gate at will. This allows for full control over the rectifier which is not possible with the other variants that have been shown. The SCR is limited to switch once per period, however the IGBT can switch hundreds of times in one period. There are numerous benefits that come from this feature:

- The input current and voltage can be modulated using PWM
- Less harmonic contamination is generated
- Power factor can be controlled
- Allows them to be built as voltage or current sources
- Allows for both voltage and current reversal [33]

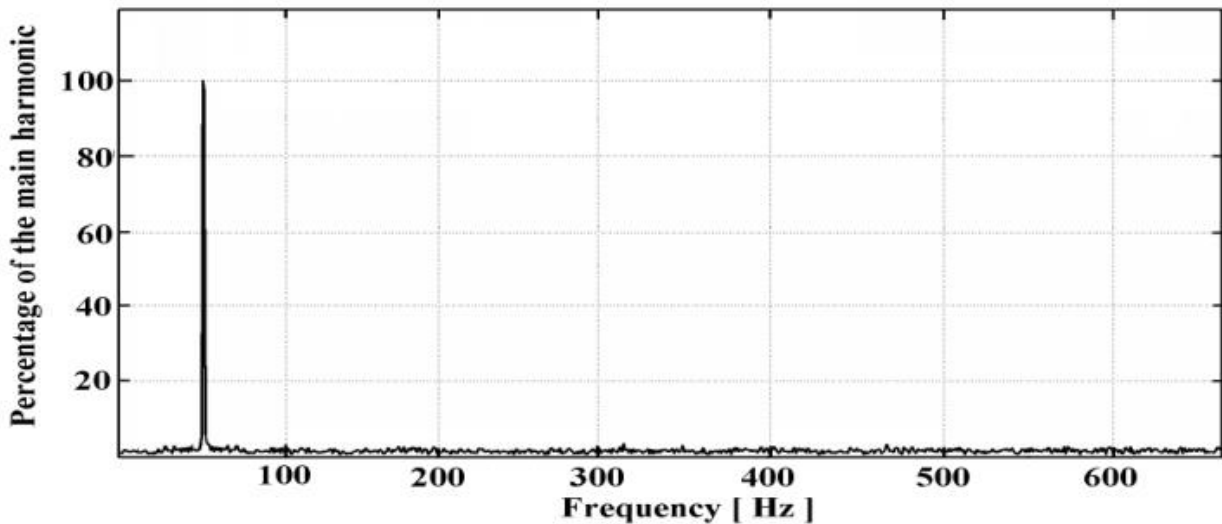
Diodes do have some advantages when compared to the other rectifier options. This would include:

- Low cost of the part
- Simplicity in its design which could make it simpler to maintain.

There are some existing case studies, comparing the use of IGBTs and thyristor-based rectifiers. The results show that the IGBTs had a lower reliability in harsher environments, however they did produce a higher quality DC output with less harmonics and therefore better power factor. The frequency components of the current output of the rectifiers can be seen in Figure 20. There is a clear reduction in harmonics in the IGBT rectifier [34].



(a)



(b)

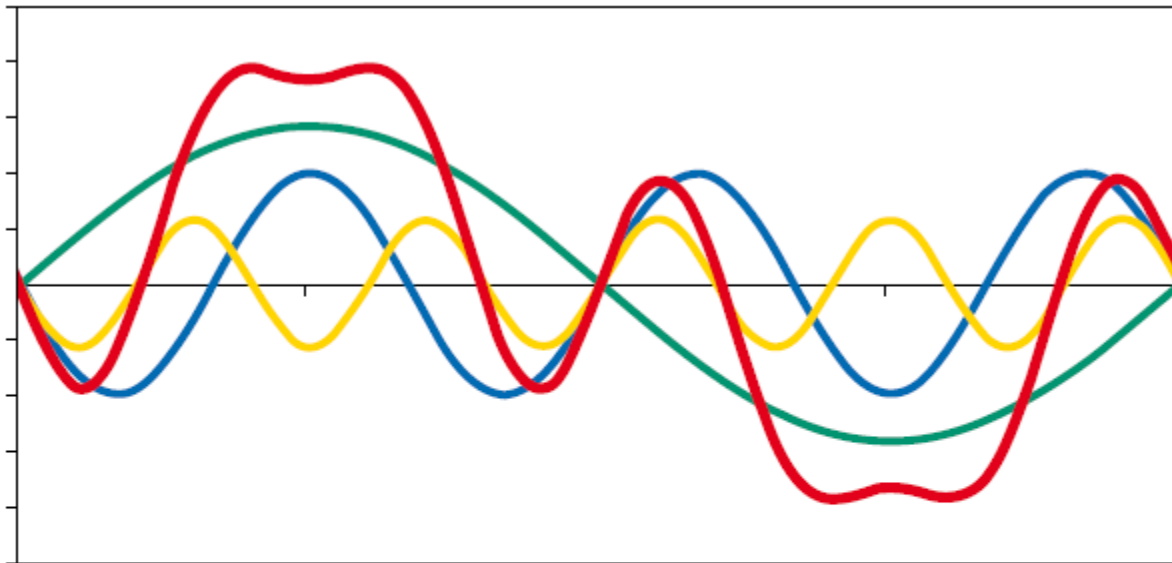
Figure 20 – Comparison of thyristor rectifier current FFT (fast Fourier transform) (a) and an IGBT current FFT (b)

It was decided in the paper that thyristor rectifier was preferable in their application due to their improved reliability and lower cost.

3.6.2 HARMONICS

When a signal is broken down into its frequency components using a Fourier analysis, the lowest frequency waveform is known as the fundamental frequency. Any frequency of an integer multiple is known as its harmonic [31].

Harmonics of a wave can distort the waveform to have undesirable characteristics. Figure 21 shows an example of how harmonic components combine to form a non-sinusoidal waveform.



Caption:

- nonsinusoidal waveform
- first harmonic (fundamental)
- third harmonic
- fifth harmonic

Figure 21 – Example of harmonic distortion [35]

Harmonics are caused in power systems by non-linear loads. For example, a rectifier circuit can generate harmonic currents when the supply voltage is greater than the voltage of the DC link. It is clear from Figure 22 which shows the output current of the supply that the pulses are much greater than the fundamental (dotted line). Figure 23 a Fourier transform of the current waveform in Figure 22 and it is clear to see the harmonics of the fundamental [36].

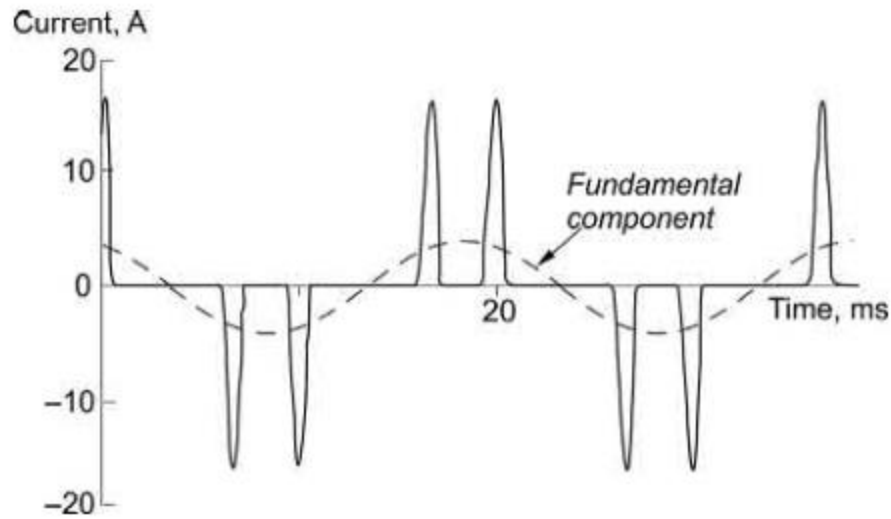


Figure 22 – Current Supply from 3 phase rectifier [36].

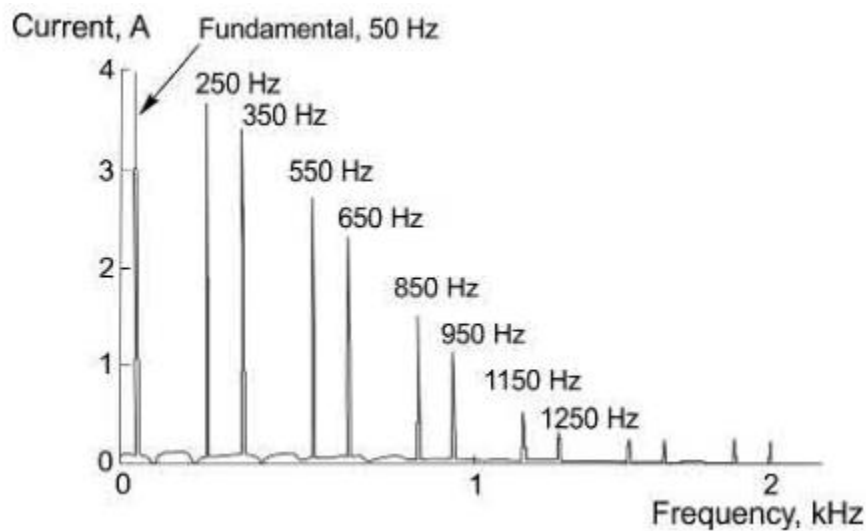


Figure 23 – Fourier transform showing harmonics of 3 phase rectifier [36].

3.7 HARMONIC MITIGATION BY RECTIFIERS DESIGN

One strategy that can be used to reduce harmonic content within a rectified signal is to increase the number of pulses within the output signal. This can be achieved by using a second three phase supply which is on the same transformer to the first. The first 3 phase supply will be connector in a star configuration and the second a delta configuration. This will cause the two to be shifted 30° out of phase. This is useful as the 30° shift in phase is the same as 180° at the 5th and 7th harmonic, which will cause current there to cancel out, producing a more sinusoidal outputs [36]. This circuit is shown in Figure 24.

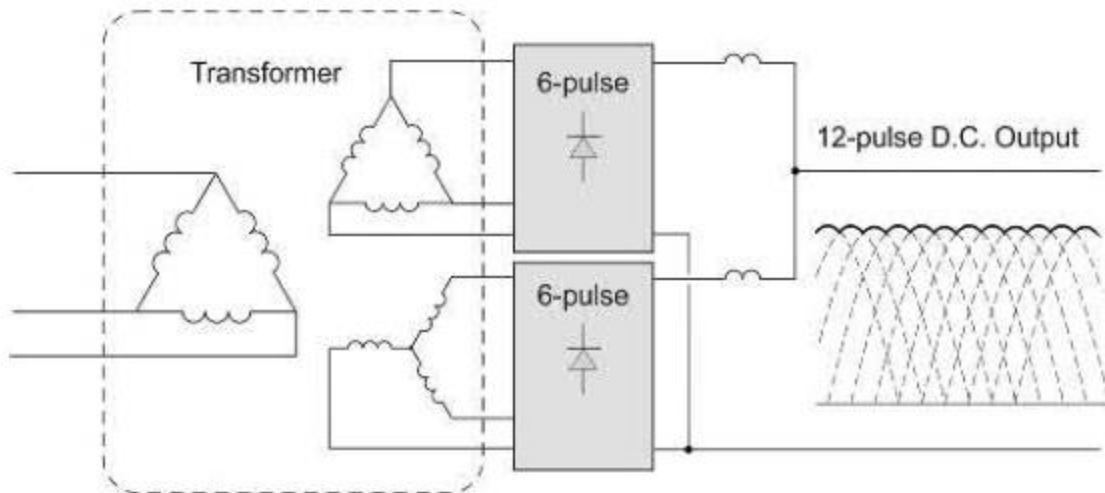


Figure 24 – 12 Pulse rectifier circuit [36].

3.8 HARMONICS AND POWER FACTOR

True power factor comprises of two components. The first of which is the displacement power factor, and the second component is the total harmonic distortion of the circuit.

There are a few different equations to calculate displacement power factor, shown in Equation 2. Active power is used by resistive components in the circuit and apparent power is the sum of active and reactive powers. Reactive power is used by reactive components such as capacitors and inductors.

$$PF_D = \frac{P}{S} = \cos(\delta_1 - \theta_1) = \cos(\varphi)$$

Equation 2 – Displacement power factor calculation [37]

A low displacement power factor indicates wasted energy in reactive elements.

The distortion power factor is a variable that is required to calculate the total power factor.

$$DPF = \frac{1}{\sqrt{1 + THD^2}}$$

Equation 3 – Distortion power factor calculation [37]

The total power factor (PF_T) is calculated using the following equation:

$$PF_T = PF_D \times DPF$$

Equation 4 – Total power factor calculation [37]

This shows that the greater the harmonic distortion, the lower the power factor [37].

3.9 CONCLUSION

There are numerous options available when it comes to rectifier designs, each with their own benefits. The design options should be weighed based on the use case to ensure the most suitable parts have been selected.

Harmonics are a key factor that should be considered when designing circuits. As shown, they can lower power factor, causing systems to operate in ways that are not as efficient, and they would otherwise be and could be more expensive to run. They can also reduce the lifespan of equipment if they are exposed regularly to harmonics.

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