SUPPORTING DECARBONISATION – AN INTRODUCTION TO ELECTRO-MECHANICAL ASD

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Abstract - Electrification of energy plants is an evolving trend as operators look to decarbonise facilities. This paper focuses on electro-mechanical ASD which can be an effective solution to turbine driver replacement or new plant versus large power electronic ASD, for speed regulation of driven equipment up to 20MW.

Electro-mechanical ASD utilize the power split principle which can result in efficiency gains of up to 2.5% versus a full-scale power electronic ASD. The drive consists of a fixed speed motor, two smaller servomotors connected to a regenerative ASD providing control power and the main planetary gearbox which connects to the driven equipment.

The paper evaluates the underlying theory behind the technology, benefits in comparison to full-scale ASD, starting performance, reliability and availability. Assessment of TOTEX including lifecycle energy consumption and carbon dioxide emissions savings of the hybrid electro-mechanical ASD in comparison to the alternative traditional full-scale ASD are included. Finally, a case study is presented detailing a 5MW pump drive train upgrade.

Index Terms — Adjustable Speed Drive (ASD) also known as Variable Frequency Drive (VFD), this paper uses ASD according to IEC 61800 series [1] and NEMA ICS7 terminology [2]

I. INTRODUCTION

The energy sector has historically been a significant contributor to individual country green house gas emissions. Annual reporting as part of the United Nations Framework Convention on Climate Change (UNFCCC) Nationally Determined Contributions (NDCs) [3] as part of the Paris Agreement detail work at country level to reduce national CO_2 emissions and adjust to the effect of climate change. Ultimately this effort demonstrates individual nation`s policies to progressively reduce their CO_2 emissions over time. Regional incentives such as EU Emissions Trading System (ETS) [4] provide a cap and trade system to encourage polluters in energy intensive industries to reduce their emissions over time through provision of a fiscal mechanism to offset individual installation CO_2 by trading of carbon credits.

Within the energy sector, high-power compressor and pump drive trains are typically deployed on critical process applications. As the energy sector works to reduce its CO_2 emissions impact in the context of more aggressive forward reducing NDCs and more widespread adoption of ETS, more energy efficient drive train solutions are needed to reduce OPEX exposure to both emissions and prime energy usage costs.

Traditionally steam or gas turbine variable speed drive train solutions have been adopted due to the availability of gas or steam for driver power, perceived flexibility, technical simplicity and footprint considerations but are challenged in terms of their overall energy efficiency, reliability and hence CO_2 emissions.

As process plant operators in the energy sector look to replace these installations using more energy efficient solutions for drive trains in order to and reduce their emissions intensity through electrification of existing installations or base case electrification of new plants, motor driven variable speed solutions become more attractive.

A. Requirements for electric motor driven variable speed drive trains

When selecting technology for the variable speed trains in replacement applications or new projects the following requirements are often considered as supplemented by IEEE 958 [5]:

1) The torque speed characteristic of the motor and driven equipment.

2) Operating speed range: Expected duration of operation at upper and lower speed limits, critical speed bands and mode of operation at these points for the variable speed drive train.

3) Electric supply grid: Expected short circuit level and power quality at the point of common coupling for the variable speed solution during expected process plant operating scenarios including start-up and controlled shutdown.

4) Reliability and Availability: Mean time between failure (MTBF) and mean time to repair (MTTR) of the drive train and associated sub-components is in line with the user ranking of the criticality of the associated process equipment and the expected process plant planned maintenance frequency.

5) Safety: The process safety aspect of the drive train implementation leads to an overall reduction in the risks associated with operation of the process equipment. This can include redundancy in drive train topology design and identification single points of failure. Subsequent failure of drive train sub-components allows for a controlled ramp-down or controlled process shutdown.

6) Efficiency of the variable speed drive train: Higher efficiency means that losses are reduced, typically this is a reduction in thermal losses from energy conversion from electricity to motive power. This implies minimization of operating losses effectively reducing CO_2e emissions. This has a direct impact on OPEX in terms of direct energy costs and as ancillary equipment count and complexity is reduced, then maintenance costs also fall.

7) Total expenditure (TOTEX): Consideration of initial CAPEX investment and OPEX lifecycle expenditure in determining the total cost ownership of the variable speed solution and associated ancillary equipment needed. OPEX in this instance is both energy and component maintenance/replacement.

8) Footprint / weight: Both on-plant for the drive train and electrical rooms are important either on new facilities where for example plot allocation may be limited or on brownfield developments

9) Maintenance: Improvements in process plant internal inspections through adoption of technology solutions have progressively increased the running periods between turnarounds and reduced the duration of the turnarounds themselves. This places an increased emphasis on the reliability of the variable speed solution and the need for enhanced digitized condition monitoring techniques for the variable speed solution to ensure that its maintenance is not the critical path item determining turnaround frequency or duration.

B. *Electric motor driven variable speed solutions*

There are various electric motor driven variable speed solutions available, a selection are summarized below. Often a variable speed drive is selected based on the specific project scenario and the requirements listed previously may be ordered by priority, which can differ project to project, as per Fig. 1a and Fig. 1b.

1) Constant speed electric motor driven hydrodynamic fluid couplings: optionally including gear stages(s)
2) Constant speed electric motor driven hydrodynamically controlled superimposing planetary gear
3) Full-scale ASD with gear box
4) Full-scale ASD without gear box (high speed motor)

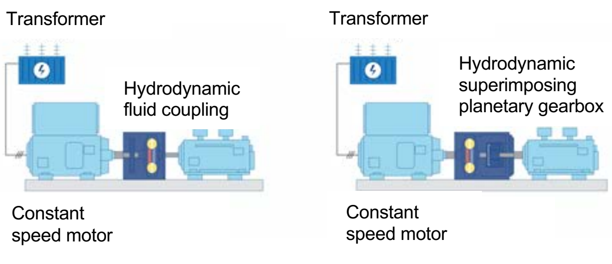


Fig. 1a Constant speed electric motor driven variable speed solutions

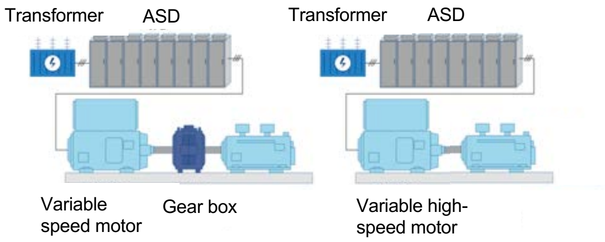


Fig. 1b Full-scale ASD solutions

Therefore, electro-mechanical ASDs offer a further solution, with the aim of supporting the requirements for variable speed drives previously described with a focus of improving efficiencies across operating speed ranges of the driven equipment. Full-scale ASDs with gearboxes to step up the motor speed are often used where the motor is controlled by the ASD, placed in line, and designed to full power. This paper will focus and draw comparison to such full-scale ASD solutions.

C. *Technology evolutions for electrical driven equipment*

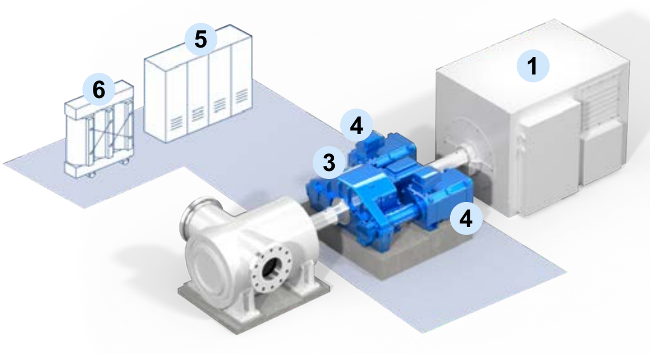
Electrical ASDs are based on semi-conductors that have evolved through the years. In the 1950's diodes have been the first type of semi-conductors used for ASDs to convert AC to DC. Then the evolution of semi-conductors to the thyristors family allowed to have the first Current Source Inverter (CSI) AC to AC ASDs as the Load Commutated Inverter (LCI) or Cycloconverters in the 1970's. These ASDs can drive only synchronous motors and are capable to reach high power levels. In the late 1980's Insulated Gate Bipolar Transistor (IGBT) have been developed allowing to have Voltage Source Inverters (VSI) AC to AC ASDs driving synchronous or induction motors. Over the years the VSIs were capable to reach higher voltages and currents and drive high power motors thanks to the development of the MV IGBTs. Motors as well have been evolving from DC motors to Synchronous motors or Induction Motors. The evolution of ASDs towards VSIs have pushed the evolution of the induction motors to higher power and speed allowing to reach on some cases load operating points without gear box (high speed motors).

The different evolution of components in the system have led to different system improvements either on power, quality, efficiency, etc. At the same time, system re-arrangement of existing components can lead to a system improvement as for the electro-mechanical ASDs

II. INTRODUCTION TO ELECTRO-MECHANICAL ASD

Electro-mechanical ASD can provide variable speed regulation for pumps and compressors up to a 20MW rating and 15,000 rpm rated output speed, operating typical pump operating ranges of 50-100% and compressor operating ranges of 70-105%. The solution (Fig. 2) consists of a constant speed main motor (typically a four-pole induction motor connected to a medium voltage grid) which drives a superimposing planetary gearbox, which is connected to the driven machine.

Two control servomotors controlled by a regenerative ASD are connected either side of the superimposing planetary gearbox which creates an (electro-mechanical) superimposing planetary gearbox (ESPG). The servomotors are specified to a low percentage of rated power, which means only a small percentage of power is used as control power by the servomotors and ASD. The driven machine`s speed can then be achieved and regulated by a combination of constant input speed from the main motor and regulation speed provided by the ESPG.



(1) Constant speed main motor (2) Driven machine (3) (Electro-mechanical) superimposing planetary gearbox (4) Servomotors (5) ASD (6) Transformer

Fig. 2 Electro-mechanical ASD layout

A. *Evolution towards electro-mechanical ASD*

Electro-mechanical ASD, as previously noted, is based on the rearrangement of improved single components within the system to improve the full system. It consists of using proven and widely used main components, already referenced in the energy industries. Table I highlights a breakdown and compliance with Industry standards. The one partial deviation in electro-mechanical ASD is the gearbox, parallel shaft gearboxes are considered as standard with superimposing planetary gearboxes being widely used in the energy industry.

TABLE I
Using proven & widely used main components

Main component	Industry Standards i.e., IOGP JIP 33	Industry References Proven
ASD Transformer	✓	✓
ASD	✓	✓
Main Motor	✓	✓
Gearbox	✗	✓
Servomotors	✓	✓

The innovation with the electro-mechanical ASD allows to have significant power and size reduction of the electrical components when comparing to full-scale ASD (Fig.3). As per the power-split principle (described in section IIC), all powers are added together. The result is reducing the electrical ASD and its transformer to ~15% of the total power, and the main motor to ~85% of the total power while adding two servomotors of a total power of ~15% to reach a total of 100% on the load side. The reduction of power allows footprint and weight savings to be made and auxiliaries can also be reduced such as cooling needed for the ASD.

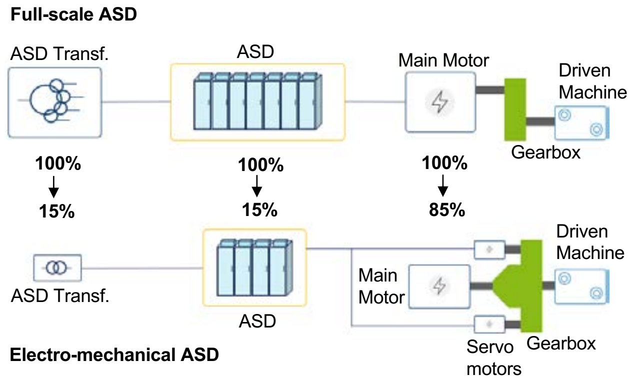


Fig.3 Electrical power reduction of electro-mechanical ASD

B. *Theory behind the technology – bringing electrical and mechanical together*

Reference to Fig.4 the ring gear (3) of the superimposing planetary gearbox is connected to the main motor (1) by the input shaft (2) and is driven at the motors constant speed. The sun gear (4) is connected to the output shaft (6) which provides the variable speed to the driven machine. The sun gear is then orbited by the planet gears (5) which are housed in a planet carrier (8) and then enclosed by the ring gear. The two control servomotors (7) are indirectly connected to the planet gear via the planet carrier. The servomotors are operating in a bi-directional way which changes the direction and speed of the planet carrier, therefore providing variable speed regulation to the driven machine.

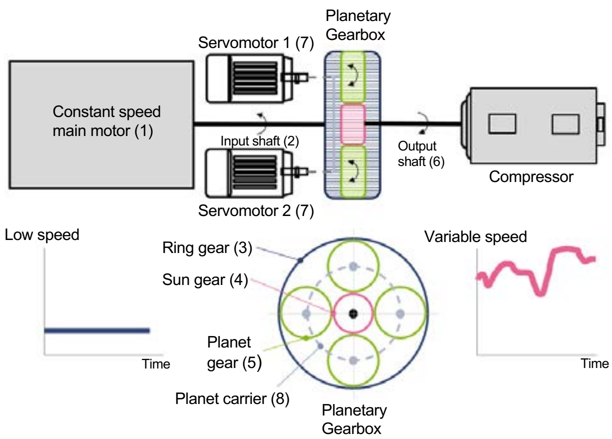
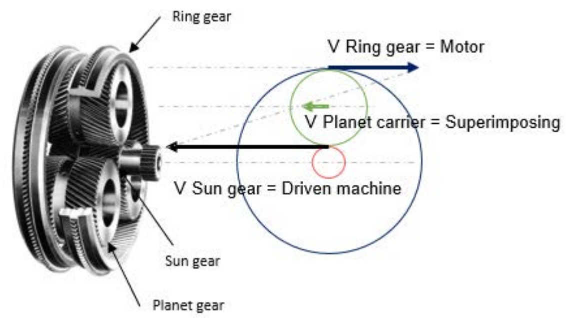


Fig.4 Theory behind electro-mechanical ASD

To increase the output speed the planet carrier is driven by the servomotors in the same direction as the sun gear, and to reduce the output speed the planet carrier must rotate in the opposite direction to the sun gear (Fig.5)



$V = \omega * r$

$V = \pi * n * r / 30$

where

V	Circumferencial speed (m/s)
ω	Angular frequency (1/s)
r	Radius (m)
n	Speed (rpm)

Fig.5 Speed diagram of the ESPG [6]

C. The power splitting principle (at rated point)

Electro-mechanical ASD utilizes two power flows to provide the desired output power for the driven machine. When the driven machine operates at rated point, as an example, the main motor will typically provide 85% of power to the driven machine and the remaining 15% power would be provided by the ASD and servomotors, this is called the power splitting principle. When comparing to full-scale ASD, 100% full power is provided by the main variable speed motor and ASD, which are installed inline. (Fig.6)

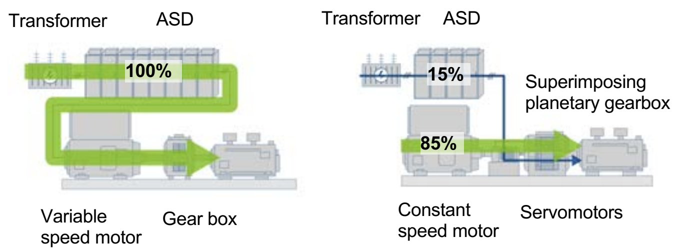


Fig.6 Full-scale ASD vs Power splitting principal

III. EFFICIENCY COMPARISON WITH FULL SCALE ASD

A. Main drive train equipment

An efficiency comparison can be made between electro-mechanical ASD and full-scale ASD with gearbox (Fig. 1b)

As previously discussed at rated point, an electro-mechanical ASD uses 15% as control power for providing variable speed, this means the ASD losses are proportional to 15% of power. In full-scale ASD due to the inline arrangement the losses are subjected and proportional to the full (100%) power flow (Fig.6)

Here the power splitting principle supports increased efficiencies due to only a small portion of power flowing through the ASD line and the majority of power transmitted purely mechanically. Therefore, the following equation (1) can be used to describe the underlying theory at rated point:

$$\eta_{Train} = (0.15 \times \eta_{Tr} \times \eta_{ASD} \times \eta_{SM} + 0.85 \times \eta_{MM}) \times \eta_{PG} \times 100\% \qquad (1)$$

At rated point the following equation (2) can be used to define the full scale ASD efficiency:

$$\eta_{Train} = \eta_{Tr} \times \eta_{ASD} \times \eta_{MM} \times \eta_{PSG} \times 100\% \qquad (2)$$

where

η_{Train}	Drive train efficiency
η_{Tr}	Transformer efficiency
η_{ASD}	ASD efficiency
η_{SM}	Servomotor efficiency
η_{MM}	Main motor efficiency
η_{PG}	Superimposing planetary gear efficiency
η_{PSG}	Parallel shaft gear efficiency

Table II shows an efficiency comparison between the two technologies considering the main drive train equipment and using the principles and equations described previously, which results in an increased efficiency at rated point for the electro-mechanical ASD.

Harmonic filters are not considered necessary as electro-mechanical ASD reduces harmonic impact on the grid as only 15% of power is using a nonlinear load and the ASD uses Active Front End (AFE) regenerative topology which has a lower harmonic content. Modern full-scale ASDs within the discussed power range and by using a multi-winding input transformer may not need harmonic filters on grid or motor side. For higher power range applications a harmonic filter might be required for full-scale ASD. Requirements will however be application specific to the electrical network.

TABLE II

Efficiency comparison vs full-scale ASD

Main component	Full-scale ASD	Electro-mechanical ASD
ASD Transformer	99.0%	99.0%
Harmonic filter	-	-
ASD	98.0%	97.2%
Main Motor	97.4%	97.6%
Gearbox	98.5%	98.1%
Servomotors	-	96.5%
Rated point	**93.1%**	**95.0%**

It must be noted that the individual component efficiencies are dependent on the original equipment manufacturer (OEM), however for the comparison with full-scale ASD its references are taken from: ASD Transformer [7], full-scale ASD [8], main motor (see acknowledgements), full-scale gearbox [9]

Improved efficiencies can be achieved across the driven machine operating speed range of a typical compressor operating range 70-100% (Fig.7)

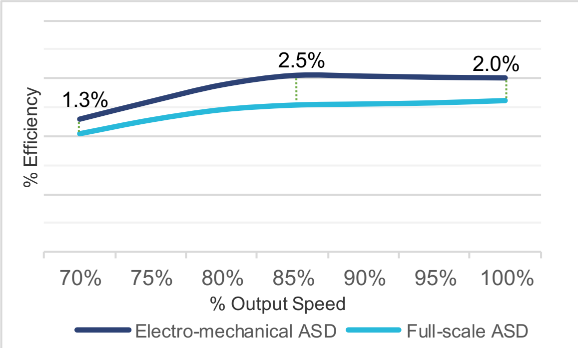


Fig.7 Main drive train efficiency comparison between electro-mechanical ASD and full-scale ASD

B. The impact of auxiliaries

Aside from the main drive train equipment auxiliaries are needed in both solutions and have an influence on efficiencies due to a degree of power consumption, therefore the efficiency comparison can be expanded beyond the drive train equipment itself. Main auxiliaries that could be considered for both solutions include main motor cooling, cooling for the e-room, ASD cooling, and the lube oil pumps (lube oil system itself is not considered as seen as similar for both solutions).

Power consumption for auxiliaries can change depending on the project environment which can be seen in the specific project example later in the paper. For general discussion in this section two differing scenarios described are a Central European climate or a Middle East climate with higher ambient temperatures. The previously mentioned drive equipment efficiency comparison is generalized up to driven equipment of 20MW power however for the auxiliary comparison we choose a specific ~15MW scenario. Therefore, the following will be considered, summarized in Table III

1) *Electro-mechanical ASD*: Cooling is needed for the ASD however due to 15% of control power being used this allows an air cooled ASD to be considered, which has an impact on the electrical room (e-room) HVAC system and its power consumption. For both solutions the main motor cooling could be water cooled where a water-cooling pump is required, or air cooled. Power consumption is slightly less for the constant speed motor due to 85% power contribution. A lube oil pump will be needed therefore a mechanical driven pump is assembled onto the electro-mechanical ASD but considered as a separate auxiliary.

2) *Full-scale ASD:* Typically, air or water cooled ASD would be used but for this power scenario a water cooled ASD will be considered [10] and a liquid-to-liquid system (Fig.8). Loop A is a closed loop circuit with deionized liquid and Loop B is external providing the plant cooling water (sourced from either sea water or cooling towers) which removes the heat. If however their isn`t local cooling water available a specific chiller system may be required which includes a chiller unit and pumping skid that can also include redundancy [11]. Around 10% of the ASD heat loss is dissipated into the e-room so this must also be considered in HVAC power consumption [10]. A lube oil pump is again required which will be considered as a separate power consumption.

TABLE III
Auxiliaries required for both solutions

Auxiliary	Full-scale ASD	Electro-mechanical ASD
Main motor water or air cooled	✓	✓
e-room HVAC	✓	✓
ASD water cooled system	✓	✗
Lube oil pump	✓	✓

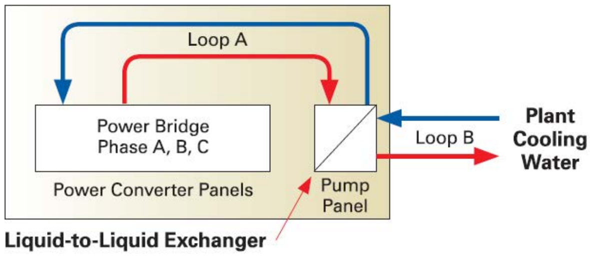


Fig.8 Liquid-to-Liquid ASD cooling system [10]

The auxiliary efficiencies can therefore be calculated using the following equation (3)

$$\eta_{Aux} = (P_{Load} / (P_{Load} + P_{Aux})) \times 100\% \quad (3)$$

where

η_{Aux} Auxiliaries relative efficiency
P_{Load} Driven equipment power
P_{Aux} Auxiliaries power consumption

The two scenarios can now be discussed so that the impact of auxiliaries and therefore total efficiency and energy costs can be observed.

Scenario 1; Central European climate, ambient conditions up to 40°C where cooling water is available within the plant infrastructure. Main motors would be water cooled. The total efficiency comparison is detailed in Table IV and expanded over a compressor operating range (Fig.9)

TABLE IV
Scenario 1 – Total Efficiency comparison of Central European climate

Main System	Full-scale ASD	Electro-mechanical ASD
Main drive train equipment	93.1%	95.0%
Auxiliaries	99.5%	99.6%
Rated point	**92.6%**	**94.7%**

Scenario 2; Middle East environment, ambient conditions up to 55°C, cooling water is not available, and a specific chiller package system is needed (using compressors and pumps). Power consumption would be increased on the e-room HVAC system due to warmer ambient conditions. Main motors would be air cooled.

The total efficiency comparison is detailed in Table V and expanded over a compressor operator range (Fig.10)

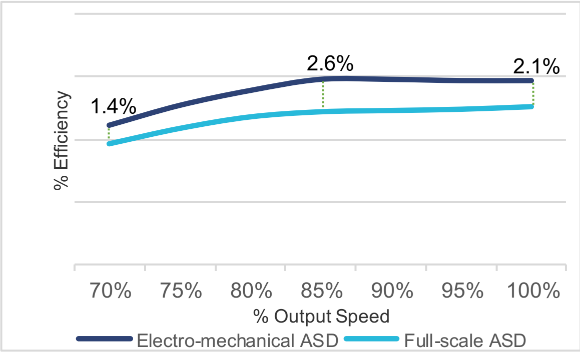


Fig.9 Scenario 1 - Main drive train efficiency plus auxiliaries comparison between electro-mechanical ASD and full-scale ASD

TABLE V
Scenario 2 – Total Efficiency comparison of Middle East Environment

Main System	Full-scale ASD	Electro-mechanical ASD
Main drive train equipment	93.1%	95.0%
Auxiliaries	98.0%	99.5%
Rated point	**91.2%**	**94.5%**

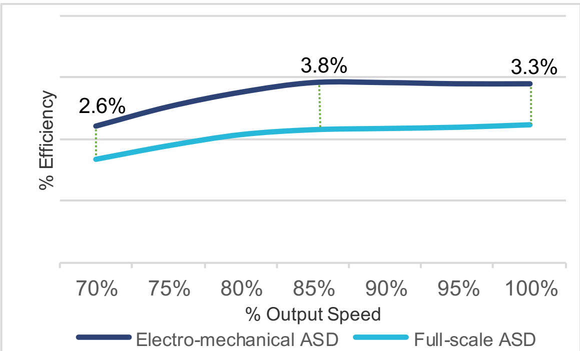


Fig.10 Scenario 2 - Main drive train efficiency plus auxiliaries comparison between electro-mechanical ASD and full-scale ASD

IV. CONSIDERATION TO THE ELECTRIC SUPPLY GRID

When starting high-power variable speed drive trains, the impact to the electrical grid must be considered, here the full-scale ASD has minimal impact to the grid.

Electro-mechanical ASD has two start up possibilities, the first when the main motor is started directly on-line (DOL). Together, the two servomotors increase the speed of the driven equipment smoothly ensuring a short start up time and reduced main motor load. The second and an alternative to DOL start, is a main motor assisted start option, using the servomotors as soft starters, which allows the main motor to be connected to the grid under controlled conditions and large voltage fluctuations are avoided. This is particularly required when large drives are connected to a weak grid [12]

A. Motor Assisted Start

The ESPG when supporting motor assisted start has additional mechanical hydraulic shifting clutches which are engaged at start up. This connects the servomotors with the input shaft of the main motor. The superimposing element of the planetary gear is able to turn with a fixed ratio to the servomotors. (Fig.11).

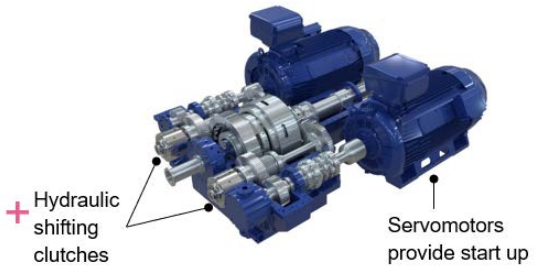


Fig.11 ESPG hydraulic shifting clutches

On startup (Fig.12) the two servomotors accelerate the main motor (Area 1) while being switched off. Once the main motor reaches its 100% speed the driven machine (i.e compressor) will be typically running at 50% speed (Point 2). The main motor is then switched on and connected to the grid.

If an induction motor is used the rotor will magnetize with a minimal effect to the electrical grid (Fig. 13). After the motor is connected to the grid the servomotors hand over the torque to the main motor and then the hydraulic shifting clutches are disengaged (Point 2). This leads to a direct connection between servomotors and superimposing elements of the gearbox and a disconnection between servomotors and main motor. The servomotors then accelerate the compressor via the planetary gearbox to the desired start up speed (Area 3).

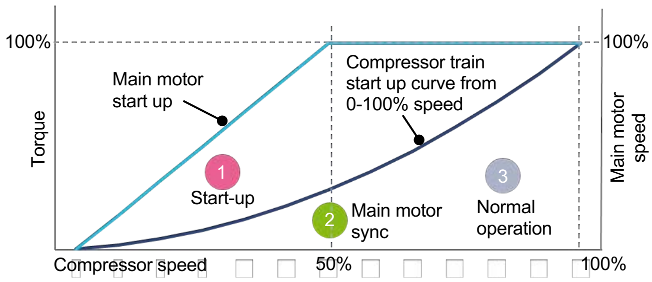


Fig.12 Electro-mechanical ASD main motor assisted start

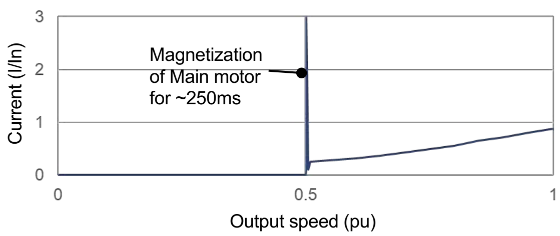


Fig.13 Electro-mechanical ASD induction main motor assisted start showing magnetization

Electro-mechanical ASD motor assisted start therefore reduces the thermal stress of the main motor and power cables, has a short current peak on motor magnetization with a short time ~250ms and the voltage dip observed achieves a tolerable value.

V. RELIABIITY & AVAILABILITY

Full-scale ASD is an established design whilst electro-mechanical ASD uses standard, tried and tested components. MTBF of the individual components in both solutions can be different from manufacturer to manufacturer, as a consequence Table VI can be used to highlight a generalized comparison of MTBF between the two solutions rather than a numerical comparison.

TABLE VI
MTBF Comparison

Main component	Advantage full-scale ASD & gearbox	Advantage electro-mechanical ASD
Transformer		
ASD		
Main motor		
Gearbox		
Servomotors		

When using ASDs in full-scale or electro-mechanical solutions MTBF can be increased and MTTR reduced by implementing redundancy (such as n+1 on power electronics). Additional redundancy is available for electro-mechanical ASD due to the use the two ASDs and two servomotors. If there is a failure of one ASD or servomotor, the electro-mechanical ASD can operate with a reduced power (~80% of rated power) and speed range, which allows for a planned stoppage of the drive train.

Availability illustrates the relationship between system total uptime (MTBF) and unplanned downtime (MTTR), equation (4).

$$\text{Availability} = \text{MTBF} / (\text{MTBF}+\text{MTTR}) \qquad (4)$$

Both solutions use existing and well proven components and therefore both benefit from a well-designed overall service concept. Service and maintenance can be optimized to minimize downtime. However, the electro-mechanical ASD solution provides increased availability when compared to full-scale ASD. Both have similar components with equivalent reliability data but the electro-mechanical ASD has the option to operate in a de-rated mode if there is a loss of power to or from one of the servomotors.

VI. TOTEX OVERVIEW

Traditionally projects would only consider operating (OPEX) and capital equipment investment costs (CAPEX) in isolation. Assessment of CAPEX considered the net present value of the project and internal rate of return to gauge a projects individual ranking. OPEX by comparison would largely focus on running costs including periodic planned shutdown maintenance. CAPEX and OPEX budgets are traditionally generated by different parts of an organization reflecting different business drivers and associated behaviors.

The TOTEX by comparison is a more accurate valuation of the life-cycle cost as it considers the weighted average cost of capital (WACC) across the equipment lifetime to provide an annualized CAPEX charge in a given period in addition to the totalized OPEX expenditure, where WACC is effectively the required return to satisfy both debt and equity requirements on the organization allowing for the implicit tax rate. The TOTEX methodology is discussed in more detail by Brosig, Waffenschmidt and Strmpler [13]. Varying parameters within the TOTEX calculation enables a project to understand the sensitivity and relative importance of a parameter on the lifecycle cost and hence a better understanding of the risk for a given commercial scenario.

A. Project Scenario

A gas turbine currently driving a centrifugal compressor with varying operating points has been considered for replacement by an electric motor driven ASD. Energy savings and decarbonization are considered as key reasons to replace the gas turbine. The compressor rated at 6MW with an output speed of 7200rpm (variable speed range down to 5900rpm) is installed in the United Kingdom on a process application, the project scenario will be of a brownfield type. Plant power supply is available 11kV at 50Hz and average ambient operation temperatures are 9°C rising to a peak of 30°C in the summer months. There is limited space for additional electrical equipment in the existing motor control center (MCC) therefore a new e-room is considered. The distance for cabling between the e-room and motors ~100m. The drive train equipment is installed in a hazardous area with ATEX explosion protection required.

Electro-mechanical ASD is compared with full-scale ASD including gearbox with the conceptual solutions defined as follows:

1) *Electro-mechanical ASD (for this section abbreviated EM ASD)*: The drive train consists of a constant speed induction type main motor rated at 6.1 MW 1490rpm IC81W, connected to the existing 11kV 50Hz electrical grid. This is directly connected to the EM ASD superimposing planetary gearbox. A low voltage regenerative ASD controls the two servomotors each rated at 399kW, 690V IC71W. Therefore, the control power for this project is 15% (Fig.3) with specific motor assisted start not required. The ASD has a used power of ~875kW and provides redundancy with independent motor invertors and one infeed system. A separate transformer is installed in the e-room (Fig.14)

2) *Full-scale ASD (for this section abbreviated FS ASD):* The drive train consists of a variable speed induction type main motor rated at 7.5MW IC81W 6.6kV 50Hz connected to a parallel shaft gearbox. This is driven by an air cooled hi-pulse ASD 6.6kV complete with integrated transformer. The cooling was covered by the e-room HVAC system however in the summer months a chiller system is required running for an estimated 500 hours per year, together with the HVAC system.

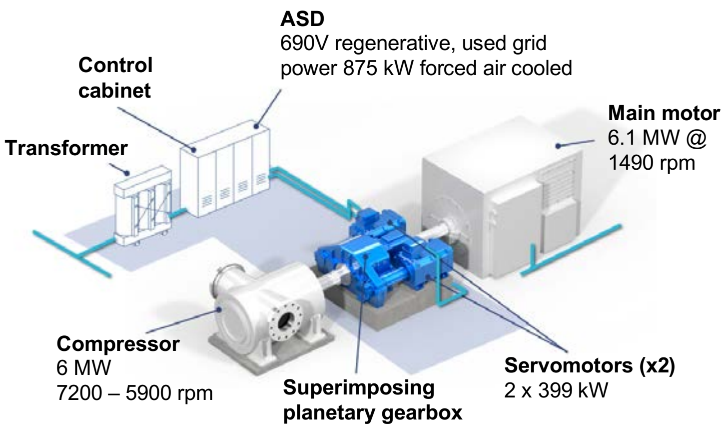


Fig.14 Electro-mechanical ASD 6MW compressor layout

B. CAPEX Comparison

The CAPEX inputs consider all main drive train equipment, auxiliaries and civils required to implement the project and are split into eleven categories, with a final summary of the total noted. General engineering concept to implementation hasn't been considered. Rationale for the main CAPEX inputs (Fig 15 and 16) can be described as follows:

- Main electric motor: EM ASD uses a more economical 6.1MW constant speed motor (85% of compressor output power), FS ASD uses a 7.5MW for variable speed duty, both water-cooled
- Substation: The FS ASD will take the site provided 11kV and with an integral transformer drop the voltage to the required ASD/Motor voltages. The EM ASD will need a transformer to generate the required 690 V for the servomotors. EM ASD require 2 switch-gears, 1 for the fixed speed motor and 1 for the ASD while FS ASD would require only 1 switch-gear for the full system
- Variable speed (VS) main system: Included in EM ASD are all components for the drive package such as ASD, transformer, gearbox (blue highlighted area Fig.14) whereas FS ASD comprises of the ASD and transformer
- Soft starting option: already included in the FS ASD not required for EM ASD
- Gearbox and coupling: Parallel shaft gearbox required for FS ASD and oil free diaphragm couplings for input and high-speed drive shaft connections for both solutions. Planetary gearbox for EM ASD is already included in VS Main System
- Lube oil (LO) system and oil cooler: lube oil system similar for both solutions however overhead run-down oil tank selected for FS ASD while not needed for EM ASD due to the integrated mechanical pump
- Harmonic / grid filters: not required for this project for both solutions
- e-room; For both solutions e-room and auxiliaries are included such as HVAC system. As described previously, the reduction of power on the main electrical equipment for EM ASD allows a reduction on footprint and weight. Therefore, the e-room would have an area of ~22m^2 and volume of ~52m^3 in comparison to the FS ASD with an e-room area of ~80m^2 and volume of ~320m^3. On the drive train skid, for EM ASD the planetary gear with its two servomotors increases the footprint by ~15% and weight by ~10% of the skid, even if on the main motor side a slight reduction is there due to the ~85% power of the main motor
- Cabling; Cables are mainly defined by current and voltage with a great impact of current on the cable section size. With FS ASD system, motor voltages are limited to the ASD output voltage (3kV to 6kV in this case) which is usually lower than the grid input voltage (11kV in this case). For EM ASD, the fixed speed motor is designed for 85% of power and 11kV voltage which result in ~60% less cables. However, EM ASD requires additional cables between its 15% ASD and the servomotors. In total, the FS ASD still requires ~35% more cables compared to EM ASD
- Chiller package: required for FS ASD to cover periodic warmer ambient temperatures, the system works by pump exchanging the heat in the room with a water-to-air cooler. The water is subsequently chilled to below atmospheric temperature using a refrigeration package
- Engineering and Construction: Outside of the core package there is considerable engineering design works to ensure the final package meets site requirements and is safe to operate within the plant. In addition, there is a requirement to complete construction work, isolating and making safe existing gas line, connecting to electrical and control networks, altering civil and structural aspects on site, and managing and planning the entire process

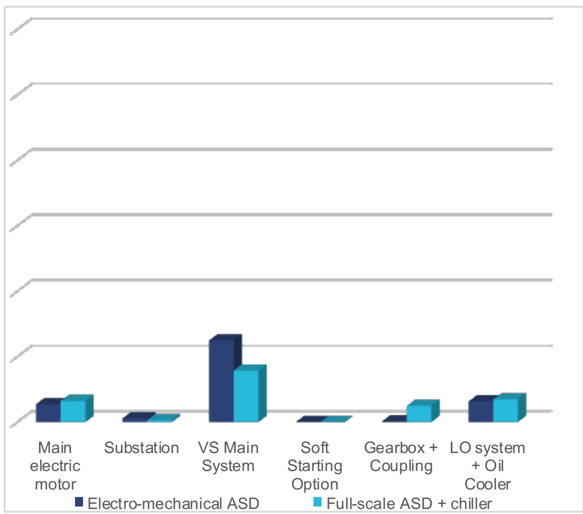


Fig.15 CAPEX comparison of drive train components (first part)

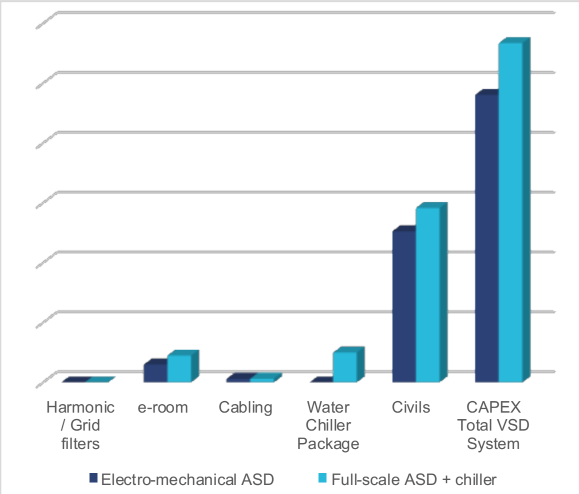


Fig.16 CAPEX comparison of drive train components (second part)

C. *Energy and CO_2 savings*

To calculate energy and CO_2 differences between the two technologies the project efficiencies need to be derived. The main drive train equipment efficiencies are taken from Table II given this project is within the 20MW power range. As noted previously auxiliaries are project specific therefore for this project, FS ASD is utilizing an air cooled ASD with a chiller package being used for 500 hours. The auxiliaries considered are detailed in Table VII, and the efficiencies used are detailed in Table VIII. As the chiller package is being utilized for only 500 hours an additional auxiliary percentage "Auxiliaries (including chiller operating)", 96.5%, is derived for FS ASD.

TABLE VII
Auxiliaries required for both solutions

Auxiliary	Full-scale ASD	Electro-mechanical ASD
Main motor water cooled	✓	✓
e-room HVAC	✓	✓
Chiller package	✓	✗
Lube oil pump	✓	✓

TABLE VIII
Total rated point efficiency comparison

	FS ASD	EM ASD
Main drive train equipment	93.1%	95.0%
Auxiliaries (w/o chiller)	98.5%	99.3%
Total rated point efficiency (w/o chiller)	**91.7%**	**94.4%**
Auxiliaries (including chiller operating)	96.5%	-
Total rated point efficiency (chiller)	**89.8%**	**-**

Dividing the compressor load power (6000 kW) by the total rated point efficiency of the main drive equipment and auxiliaries equates to the total power consumption (kW) of each solution, equation (5). For FS ASD total power consumption is considered with the periodic usage of the chiller package and then without.

$$TPC = P_{Load} / \eta_{Rated} \quad (5)$$

where

TPC Total power consumption
P_{Load} Driven equipment power
η_{Rated} Total rated point efficiency

This study focuses on energy losses per year (MWh/a) not the total energy used, equation (6), therefore for EM ASD 8000 hours are considered and for FS ASD 7500 hours without chiller and 500 hours with chiller is considered.

$$TLO = (TPC - P_{Load}) \times OP / 1000 \quad (6)$$

where

TLO Energy losses per year
OP Operating hours

The energy cost per year is calculated using 0.15 €/kWh [14] as an appropriate UK electricity price at the time of writing this paper multiplying by the calculated TLO. FS ASD considers TLO as the total energy losses with and without chiller operation.

CO_2 emissions and tax on losses can also be calculated using 0.21 kg/kWh [15] and a tax of 53.45 (€/Ton) [16] (Table IX)

The energy savings per year comparing EM ASD with FS ASD are ~235,000 EUR with a saving of 7.4M EUR on energy losses, possible over 25 years including a 2% yearly inflation (Fig. 17). The CO_2 reduction per year comparing EM ASD with FS ASD is 323 Tons with ~440,000 EUR of CO_2 taxes saved over 25 years.

TABLE IX
Energy and CO2 summary*

	FS ASD	EM ASD
Total power consumption (kW)	6543	6356
Total power consumption inc chiller (kW)	6682	-
Energy losses p.a. 7500 & 8000hrs (MWh/a)	4073	2848
Energy losses p.a. inc chiller 500hrs (MWh/a)	341	-
Energy cost p.a (€)	662,100	427,200
CO_2 e Emissions p.a. due to losses (Tons)	926	603
CO_2 tax p.a. due to losses (€/Ton)	49,500	32,000

*all figures rounded

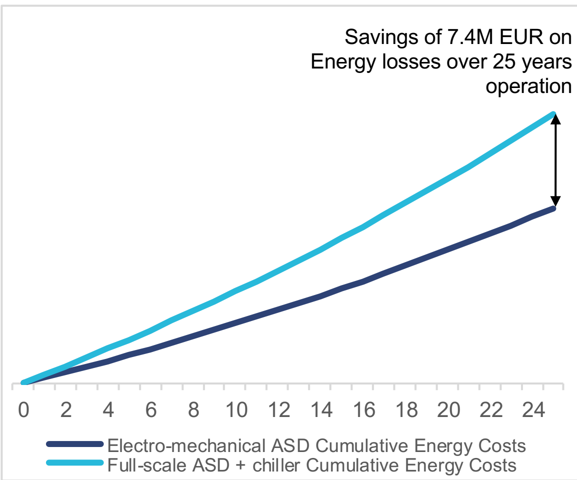


Fig.17 Cumulative energy savings comparison

D. TOTEX (Capital Expenditure + Operational Expenditure)

As previously introduced TOTEX over a 25-year period can be summarized for both solutions (Fig. 18) which includes the CAPEX inputs (Fig. 15 and 16), installation, commissioning and initial project spares, yearly and major maintenance at ~5-year intervals (as a base case) and finally energy costs (Fig.17) per year and CO_2 taxes. In this project scenario EM ASD has a lower initial total project CAPEX input with savings increasing over a 25-year period.

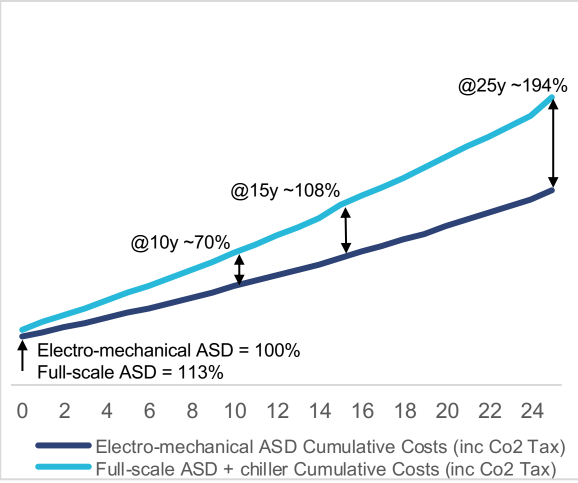


Fig.18 TOTEX comparison

VII. CASE STUDY 5MW PUMP APPLICATION

Electro-mechanical ASDs have been successfully installed and commissioned in 2020 on two boiler water feed pumps at a coal fired power plant in China which were upgrades to the existing variable speed solutions in operation, constant speed electric motor driven hydrodynamic fluid couplings (Fig. 1a). The rated power for each drive is ~4.5MW with output speed of ~5300rpm. The electro-mechanical ASD included a low voltage regenerative ASD with two 500kW servomotors providing the control power (Fig.19). This supported the main aims of the plant to improve overall efficiency long term, reduce energy consumption and greenhouse gas emissions [17]

Fig.19 Electro-mechanical ASD installed on a 4.5MW boiler water feed pump

VIII. CONCLUSIONS

From this paper we established the global and regional context for emissions reductions associated with large mechanical equipment drive trains. The technical requirements of motor drive trains were discussed with the available technologies and their evolution.

A detailed introduction of the electro-mechanical ASD technology was provided, highlighting the principle components, the underlying theory behind the planetary gear box and the power split principle identifying a potential reduction in system complexity for ASD solutions up to 20MW rating.

A comparison of efficiencies between traditional full scale ASD and the electro-mechanical alternative was provided, highlighting efficiency improvements for the electro-mechanical solution of the order of 2.5%. This efficiency gain was complemented by a review of the reduced complexity of ASD auxiliaries associated with the electro-mechanical solution where demands on cooling systems were less. A comparison of the implications of this simplification for both Central European and Middle-East climatic environment was given, reinforcing the advantage of the electromechanical solution over a larger full scale ASD solution.

An assessment of the starting performance requirements for the electromechanical ASD was given, this showed that use of servo motors for an assisted start significantly reduced the magnetizing current impact over a DOL alternative.

The reduction in complexity of the electro-mechanical ASD compared with a full-scale ASD highlighted earlier was seen to have a positive impact on the reliability and availability of the drive train due to greater flexibility to operate under de-rated mode due to loss of a single servomotor.

A detailed evaluation of the TOTEX across the installation lifecycle was provided through evaluation of changing a gas turbine driven centrifugal compressor with an equivalent rated electro-mechanical ASD and full scale ASD. A comparison of CAPEX costs found in favor of the electro-mechanical ASD at the 6MW reference case for the UK. From OPEX perspective energy and CO_2e emissions were evaluated, again showing significant savings for the electro-mechanical ASD. TOTEX comparison was plotted across a 25 year life of installation, integrating CAPEX, OPEX in terms of energy and emissions and OPEX in terms of maintenance charges. Overall, for the reference case a electro-mechanical ASD proved to be significantly more cost effective.

Finally, a real life application of an 4.5MW electro-mechanical ASD retrofit solutions in China on a pump drive train was provided, demonstrating confidence in the technology for the specified application.

In conclusion electro-mechanical ASD can provide a more effective solution to traditional full scale ASD in the power range up to 20MW, particularly when lifecycle benefits are considered. Detailed evaluation on a case-by-case project basis is needed to establish the optimum technology solution, early appraisal of the alternatives is recommended.

IX. ACKNOWLEDGEMENTS

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X. REFERENCES

[1] IEC 61800 series, *Adjustable speed electrical power drive systems*, IEC – SC 22G Dashboard > Projects / Publications: Work programme, Publications, Stability Dates, Project files, accessed 13 December 2021.

[2] NEMA ICS 7 (2020), *Industrial Control and Systems: Adjustable-Speed Drives*, NEMA ICS 7 – Industrial Control and Systems: Adjustable-Speed Drives | Engineering360 (globalspec.com), accessed 13 December 2021.

[3] UNFCCC (2021), *Nationally Determined Contributions*, Nationally Determined Contributions (NDCs) | UNFCCC accessed 03 December 2021.

[4] European Commission (n.d.), *EU Emissions Trading System (EU ETS)*, EU Emissions Trading System (EU ETS) (europa.eu), accessed 03 December 2021.

[5] IEEE Std 958 (2003), IEEE GUIDE FOR THE APPLICATION OF AC ADJUSTABLE-SPEED DRIVES, accessed 10 December 2021

[6] Tilscher, M., Lauter, B., Lindenmaier, J. (2017) "Superimposing planetary gears as variable speed drives for rotating equipment", *46th Turbomachinery & 33rd Pump Symposia 2017*, accessed 08 December 2021

[7] Durantay, L., Van Gemert, D., Lava, J., Spannagel, D. (2021) "A Success Story Of Steam Turbine Replacement By High Speed Electric System Driven Compressor" PCIC paper EUR21_08 Shell & GE, pg2, accessed 31 January 2022

[8] Siemens Perfect Harmony GH180 brochure (2018), *Watercooled-perfectharmony-brochure-june-2018_original.pdf* Siemens | Downloads | Information & Download pg 4, accessed 31 January 2022

[9] RENK high-speed gear units. *Parallel offset and coaxial concepts Renk high speed gear units brochure 2021* RENK | Product & Service, accessed 31 January 2022

[10] TMEIC Application Edge Volume 1, Issue 4 (2019) *Cooling Large Variable frequency drives* TMEIC | Library *accessed* 1 February 2022.

[11] Bacchetti, L., Batistoni Ferrara, A., Benedini, P., Ramundo, G. (ABB) *Environmental challenges in variable speed drive system (VSDs) applications: design and construction of a water cooling unit facing extreme temperatures and continuous critical duty* World Gas Conference 2012 ABB Library, accessed 1 February 2022.

[12] Voith website (2021) Voith | Variable speed drive | VECO-Drive, accessed 08 December 2021

[13] Brosig, C., Waffenschmidt, E., Strmpler, F., (2018) "Future Economic Efficiency of Gas Distribution Grids," *2018 7th International Energy and Sustainability Conference (IESC)*, 2018, pp. 1-7, doi: 10.1109/IESC.2018.8439977., accessed 3rd February 2022.

[14] Business Electricity Prices (2021) Business *What are the average business electricity prices per kWh in 2021* Electricity Prices | Cost per kWh, accessed 7th February 2022

[15] Greenhouse gas reporting: conversion factors 2021 Business *Conversion factors 2021*, retrieved 7th March 2022, accessed from Greenhouse gas reporting: conversion factors 2021 - GOV.UK (www.gov.uk)

[16] Reuters. S. Twidale (2021) *Britain's carbon market begins trading at higher prices than EU* Reuters | Business | Sustainable Business, accessed 7th February 2022

[17] Voith website, R. Wankerl (2018) Voith | News room, accessed 08 December 2021

XI. VITA

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