CHALLENGES OF ELECTRIFICATION FOR DECARBONISATION

Paper No. PCIC energy EUR23_27

Jeremy Andrews
Siemens
UK
jeremy.andrews@siemens.com

Troy Salazar
Siemens
USA
troy.salazar@siemens.com

Abstract – The drive to electrify processes traditionally power by turbines is currently driven by the commitment of both National and International oil companies to meet CO_2 targets set by governments and the international Paris treaty of 2015, however this is not the only advantage of electrification.

The use of electric motors and variable frequency drivers brings benefits of energy saving, efficiency, and availability as well as decarbonisation that are all attractive to the bottom line of operators. This paper outlines the benefits of VFD's and motors and highlights how systems should be optimized to perform better than their turbine alternatives.

Index Terms: VFD - Variable Frequency Converter, ASD - Adjustable Speed Drive, Electrification, Active Front End AFE, Static Frequency Converter SFC.

I. INTRODUCTION

The Oil & Gas (O&G) industry operations account for 9 percent of all man-made greenhouse-gas emissions. Driven by international commitments defined in the 2015 UN Paris Agreement both International Oil Companies IOC and National Oil Companies NOC are working on CO_2 reduction paths.

The types of measures being engineered include improved efficiency, carbon capture, and process optimization; however, the greatest impact is to change the power source. O&G operators are increasingly investigating electrical solutions for their pumping and compressor applications that have historically been powered by turbines.

The electrical alternative to turbines are motors and variable speed drives. This paper will concentrate on the use of both fixed speed (Direct On Line, DOL) motors and electric variable frequency drive systems. VFDs have other names such as variable speed drives, adjustable speed drives or AC drives. VFD systems historically have been implemented for process and or efficiency optimization. However, as drives have developed over the years additional operator benefits have been identified.

II. ELECTRIC ALTERNATIVE

As an alternative to gas or steam turbines as a driver for pumps, fans and compressors and other loads it is necessary to have an electrical power source. This can be from a National grid network or an Islanded power generation system. Depending on the site location power cables may need to be laid over long distances including subsea for offshore operations.

A. Grid

The network or Grid includes the electrical grid at the point of common coupling (PCC) where the harmonics and power factor are normally defined, together with the network fault level, where other large loads and generation are connected.

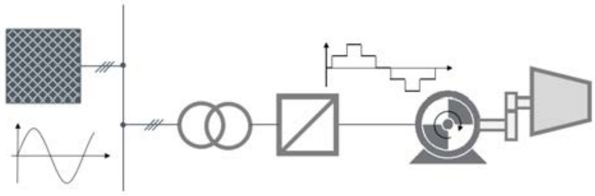

Fig. 1 Elements for complete drive system.

B. Grid

The network or Grid includes the electrical grid at the point of common coupling (PCC) where the harmonics and power factor are normally defined, together with the network fault level, where other large loads and generation are connected.

C. Transformer

The VFD is most commonly connected to the grid via a transformer as the network voltage for high power drives is normally significantly higher than the VFD operating voltage level. There will be switchgear connecting the network to the transformer, normally GIS (Gas Insulated Switchgear) type for protection and isolation. The transformer also provides galvanic isolation for the VFD restricting short circuit currents. The base solution is a single primary and single secondary winding in a 6-pulse configuration, however, to reduce harmonics normally additional phase displaced secondary windings are used to connect to the rectifier bridges. This can be up to 48 pulse. If a harmonic filter is required, this is normally connected to an additional winding.

D. Variable Frequency Drive

The VFD as its name suggests changes the frequency from the fixed line frequency to a variable frequency (and variable Volts/Amps amplitude) that in turn alters the speed and torque of the electrical motor driving the load.

E. Motor

The motor transforms the electrical power into mechanical torque that is used to drive the connected mechanical load.

Induction motors are the most common type of motor, but at higher powers (>30MW) the most common motor type is a synchronous motor as it has higher efficiency and considerably more references, however it has some additional complexity in the excitation circuit. This has almost no effect on the motor availability, Induction motor do have more complexity in the construction with many laminations and bars.

F. Load

Most loads in O&G are pump, fan and compressor applications. Normally these tend to be square law torque loads with variable torque profiles. Some constant torque loads are required in downstream applications such as extruders.

For high-speed loads either a high speed motor can be used or a gearbox to match the motor and load speeds.

III. BASICS OF A MOTOR & VFD

Motor

An electric motor connected to the power grid will rotate at a speed proportional to the grid frequency and the number of pole pairs of the motor. For example, on a 50Hz grid a 2 pole motor will rotate 3000rpm, a 4 pole motor at 1500rpm and so on.

The line frequency creates a moving magnetic field in the stator which is followed by the rotating rotor. There is some small difference between an induction motor and a synchronous motor as the induction motor has slip, hence rotates at a slightly slower speed (e.g.,1494rpm for a 4-pole motor) whilst the synchronous motor exactly synchronizes with the line frequency.

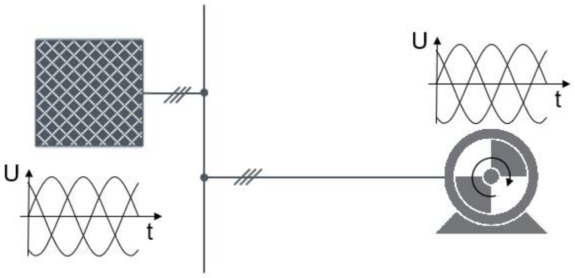

Fig. 2 Fixed speed DOL motor

A DOL motor when started has full grid voltage and frequency applied from the start, hence a stationary rotor effectively behaves like a transformer with shorted secondary windings so there is no back electromotive force (emf) to counter the emf in the windings so a very high current flows (e.g. typically 5-6 x FLC). A more detailed explanation of motors can be found in References [8], [9] and [10].

Any grid transient in voltage or frequency impacts on the fixed speed motor torque and speed output. The fault contribution of high-power motors needs to be considered as part of the system and switchgear design.

Variable Frequency Drive

The VFD as the name suggests is used to vary the output frequency from the fixed grid to create the desired operating speed of the motor, also at variable voltage and current amplitude depending on the technology type.

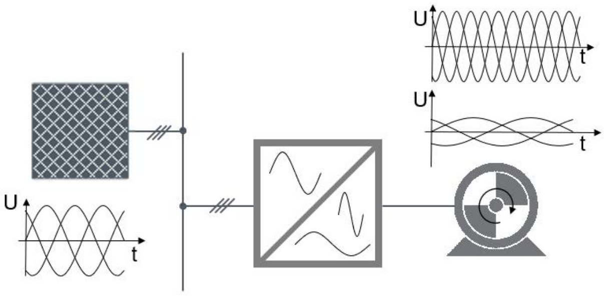

Fig. 3 Variable speed motor with VFD.

The drive is split into three main power parts including rectifier, dc link, and inverter. The rectifier rectifies the AC waveform into DC, the DC link smooths the DC and finally the inverter converts the DC back into AC at the desired frequency and voltage or current amplitude, this can be from 0 to 50Hz or 60Hz, or in the case of high speed motors the frequency can be several hundred Hz. Other major parts of the drive include the controls and the cooling system.

Current Source Inverter (CSI) drives as their name suggest control the current, whilst Voltage Source Inverter (VSI) drives control the voltage.

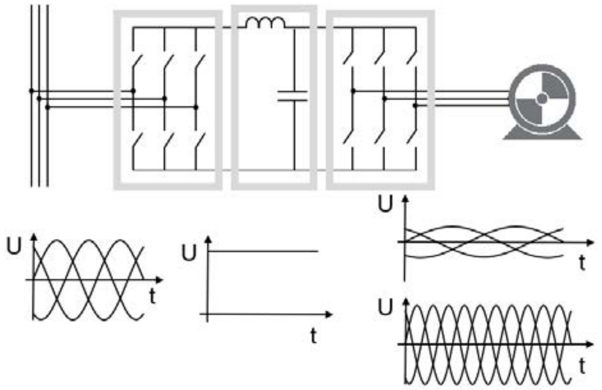

Fig. 4 VFD power circuit and waveforms. Fixed input frequency, variable output frequency and with varying amplitude.

In reality it's not simple to recreate a sinus waveform to the motor. There are technical challenges at each stage of the VFD.

In the rectifier circuit the rectifier switches are diodes for VSI and thryistors for LCI. These switches cut the AC waveforms near the peak of the 3 phases to create a DC. However as shown in the diagram below the DC is not a flat line, it contains the peak of each waveform that looks like a ripple.

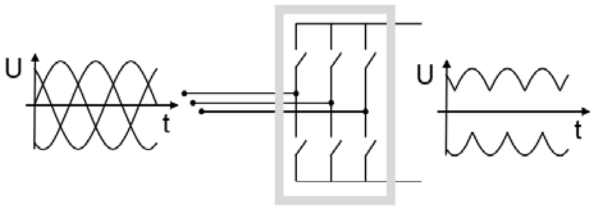

Fig. 5 Rectifier circuit

The DC Link then smooth's out the ripple of the DC, for VSI capacitors are used and for CSI reactors are used to achieve a DC closer to a flat line.

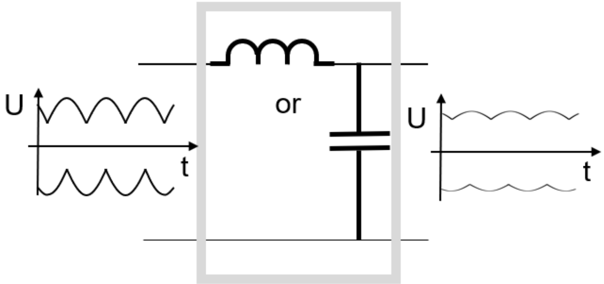

Fig. 6 DC Link circuit.

The inverter then uses switches to chop the DC up into a square wave at the required frequency to change the motor speed. For VSI IGBTs or IGCTs are used as the switch, for CSI again thyristors are used. The below diagram shows a flat DC but in reality, there is a small amount of ripple content remaining that will appear in the final square wave output.

The volume of current in the square wave represents the current amps, so the current to the motor is also controlable.

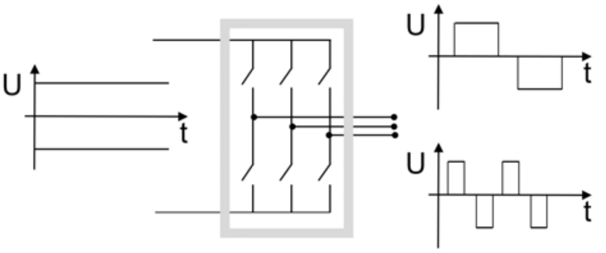

Fig. 7 Inverter circuit.

For VSI drives it is possible to have very fast switching, hence rather than a crude square waveform it is possible to create a series of pulses that better represent a sinus waveform. Below is a 3-level waveform (+ve, zero and -ve). The voltage to the motor is also controlled as the volume of volts in the pulses can be varied to alter the motor voltage level from 0 – 100% volts.

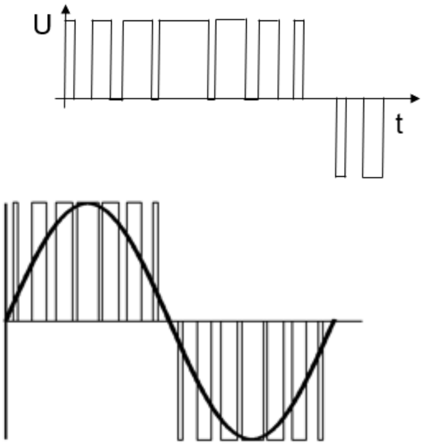

Fig. 8 Inverter output waveform with PWM switching.

For VSI it is possible to configure the inverter section by splitting the DC or putting the switches in series to create multiple levels of PWM waveforms that better represent a sinus waveform.

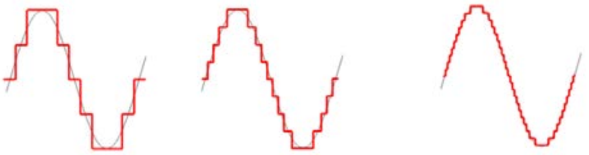

Fig. 9 Multi-level inverter output waveform.

Overview of VSI and LCI

A. Load Commutated Inverter (LCI) Drives

The LCIs are the most referenced drive found in high power applications with power ratings up to 100 MW, driving synchronous motors. The LCI drive uses low-cost silicon-controlled rectifier (SCR) thyristors in the rectifier and inverter, leading to cost optimization in the drive technology.

Most typically is configured as a 12-pulse rectifier with a DC link choke to provide a controllable DC current to the 12-pulse inverter which powers the motor.

The line current of the 12-pulse SCR rectifier has a large amount of 11th and 13th harmonics. Therefore, a harmonic filter with power factor correction is often required for the LCI drive to meet local codes and standards.

The main features of the LCI-fed synchronous drive include low cost, high efficiency, reliable operation, and inherent regenerative braking capability, if needed. The main drawbacks are high torque pulsation, slow transient response, variable input power factor and high harmonic content, all of which can be mitigated.

B. Voltage Source Inverter (VSI) Drives

A VSI converts constant DC voltage to AC voltage with a variable frequency related to rotor speed of the motor. Since switching timing of the self-commutated power devices can be controlled by its controller, fundamental frequency of the voltage is controlled precisely using pulse width modulation (PWM) techniques normally in multiple levels, lower-level design's may use a filter to clean up the waveform to make it more sinusoidal. Large capacity VSIs are available now because large capacity self-commutated power devices such as insulated gate bipolar transistors (IGBTs) and integrated gate-commutated turn-off thyristors (IGCTs) have been developed. VSI systems have been applied to many applications in a wide power capacity range because of their low harmonics. The capability now exists to drive large motors with VSI drives. VSI drives are built in different configurations: Neutral Point Clamped (NPC), Multilevel Cascade H Bridge (CHB), Modular Multi Level Converter (MMC/M2C). explained in detail in Reference [1] and [6].

IV. BENIFITS OF ELECTRIFICATION

Reduction of on-site CO_2

Compared to a gas turbine where gas is consumed by the turbine to generate power to the load, or in the case of a steam turbine where a boiler is used to generate steam an electric system does not have any onsite CO_2 footprint. This means the operator has no CO_2 tax for their processes allowing for a carbon free solution. An example of the CO_2 load for a 10MW load is detailed below.

	Efficiency	Total Efficiency	CO_2 (tons/day)	CO_2 Tax ($/year)
Gas Turbine SC	39-43%	39-43%	+140 tons	$1M
Gas CCPP	54-63%	49-59%	+100 tons	$0.7M
Distribution	94-98%			
ASD System	96%			
Hydro Electric	98%	89-93%	Baseline	
Distribution	94-98%			
ASD System	96%			

Fig. 10 10MW CO2 calculation, at California $18/t

This of course only eliminates CO_2 if the electrical power source is from carbon neutral generation such as hydro, wind or solar. Most national power grids are a combination of power sources such as gas, oil, coal, nuclear and renewable generation. The data for some example grids on of different CO_2 from fossil fuel levels for different grid mixes shown below Reference [5] and [11].

Emissions CO_2	Natural gas	Oil	Coal	Unit
France	0.42	0.78	0.99	kg/kWh
UK	0.47	0.73	1.00	kg/kWh
USA	0.42	1.1	1.02	kg/kWh

Fig. 11 CO_2 emissions, USA power generation plants.

Reference sites [11]

	Natural gas	Oil	Coal	Nuclear	Renewable	Other
Italy	43%	32%	4%	-	18%	4%
UK	34%	-	0.1	14%	38.5%	13%#
Netherlands	63.3% (fossil)			-	33.2%	3.5%
USA	39.8%	0.6%	19.5%	18.2%	21.5%	0.4%

Fig. 12 Examples of different grid generation mixes.

Imported.

Note if a grid is powered only by coal power stations, then using a gas turbine would have a lower CO_2 footprint than an electric system connected to the coal fed grid.

Where a national grid is not available an island electrical power grid with GTG including a heat recovery cycle can still operate at a lower CO_2 footprint than a traditional GT, having lower numbers of GTG makes for lower OPEX.

Power from shore has started to be implemented to reduce offshore platform carbon emissions. Gas turbines and GTG can be replaced with electrical cables from shore. The load can then be driven electrically either DOL motor or VFDS, in the case of a mismatch of frequency a static frequency converter (SFC) can be used to feed the existing load.

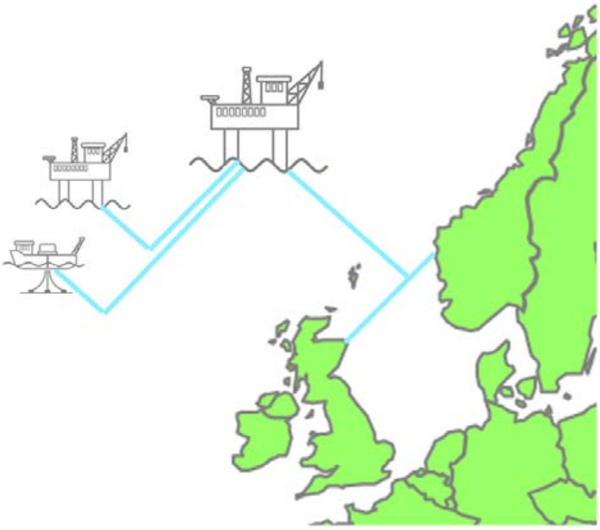

Fig. 13 Power from shore example with hubs.

An example is given in figures 13 and 15. Power hubs can be used to transfer power to nearby assets. In figure 15 the offshore 60Hz operating frequency fed from a 50Hz onshore grid requires a grid forming SFC to replace the GTG. Fig 14 shows a typical GT and GTG offshore configuration that is suitable for electrification.

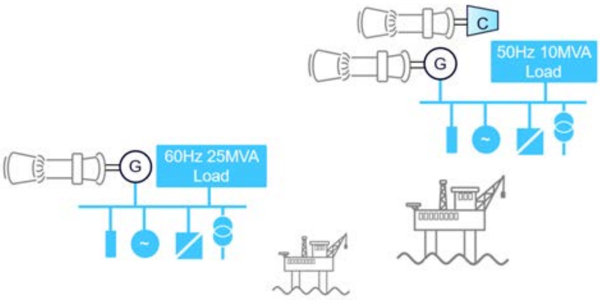

Fig. 14 Existing turbine driven loads and GTG.

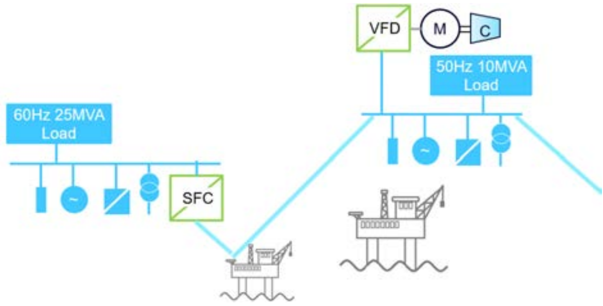

Fig. 15 Power from shore with subsea cable for VFDs and SFC.

If power from shore is connected to a grid such as in Norway where the power is generated by hydro-electric, then CO2 is eliminated from the production processes.

Efficiency improvement

Gas turbines operate at efficiencies of about 31-40% depending on the type. It is possible to improve the efficiency by adding a heat recovery system, however the use of multiple GTs across a plant at varying powers makes this difficult and with much increased footprint.

By connecting to a national power grid with combined cycle power generation the overall system efficiency will improve by 10-25%, see figure 16. A similar figure can be obtained on island grids with their own power GTG plant. Simplification of power generation with heat recovery saves space even with the addition of distribution switchgear, transformers and VFD motors making a case for platform and FPSO locations. In these cases, the transmission losses are higher via subsea cables.

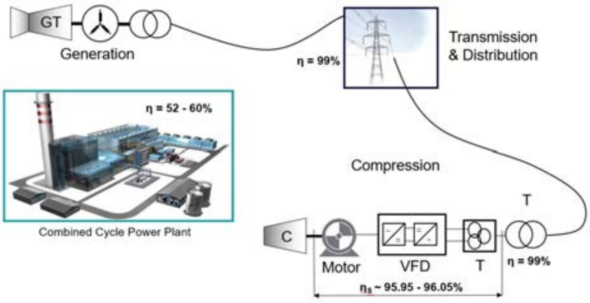

Fig. 16 Complete system efficiency comparison.

Electrical efficiency generation to motor **48.8 – 56.3 %**
Typical mechanical GT efficiency ~31%
Typical aeroderivative GT efficiency ~40%

The cost to the operator of the gas, or lack of gas sales revenue can be calculated to show the financial improvement of the plant with a highly efficient electrical system.

In addition to electrification where a gearbox may be required for compressors or pumps a high-speed motor can be used to avoid the gearbox. The motor can be operated in excess of grid frequency with a VFD to speeds of 250Hz+ (15,000rpm+). Reference [2] and [7] active magnetic bearings (AMB) for the motor and compressor can also be implemented to improve performance such as reduced maintenance, increased operational speed range and improved availability.

Maintaining and improving availability

Existing turbine systems particularly steam turbine have good operational availability. Whilst the gas turbine does have good availability, it does require constant maintenance to maintain the high availability.

Replacing a turbine system with an electrical system is attractive in both terms of CO2 and efficiency improvement, however this needs to balanced by a system of equal or improved availability. There are many papers written on VFD systems availability Reference [1], [3], [4] and [7] demonstrating high system availability using variable speed drive systems.

Most drive systems on the market have the option to implement redundancy concepts to both the main power circuit and the cooling systems to further improve availability or increase maintenance intervals.

However, this is only part of the story, the gas and steam feed to turbines is also reliable, so there needs to be a comparison of grid electrical power feed stability performance and the capability of the electrical equipment to perform against transient disturbance events.

The operator needs to provide details of typical voltage and frequency transient events, so the electrical equipment can be checked to see under which circumstances the drive might trip or cause the load or process to trip. Different processes have different susceptibility to tripping and also re-start time, some process can re-start immediately whilst others could cause a plant to be out of production for several days.

The drive system on the grid (rectifier) side for VSI is an uncontrolled switch diode, grid disturbance support is in the form of dynamic breaking (taking energy from the load to support the DC link). In the simulation shown in figure 17 the voltage dips from 100% to 10% (1), which is a significant drop of 90%, due to the missing voltage the DC link current (2) starts decreasing and the stored DC link capacitor (3) voltage reduces. In the first 11mS full output torque is available (4) after which the drive will re-generate a small amount of torque from the load to keep the DC link constantly at the lower limit threshold (6). Upon the voltage recovery (7) the DC link current (8) will recover, after which torque will be reestablished in the motor which has remained magnetized during the transient and under VFD control.

Decentralized DC links such as are found in multi-cell based topologies are more line friendly due to the decoupled DC link capacitors.

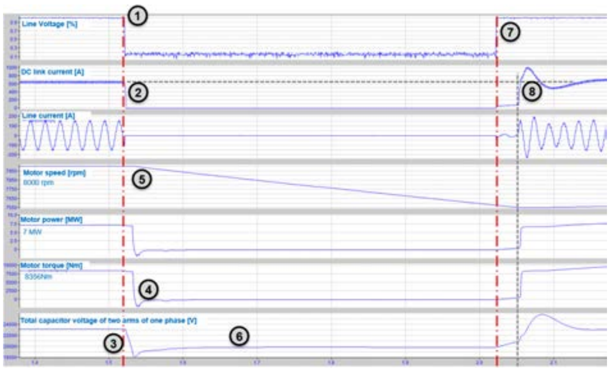

Fig. 17 Voltage dip simulation.

The downside of dynamic breaking is that the process will reduce in speed, and this can be a problematic. The diode bridge does not allow for active performance on transients, however if it is replaced with active switches like IGBTs the drive can now allow for power flow both from the grid to the load and from the load back to the grid, this is called an active front end (AFE) drive, with 4 quadrant control. The AFE can also correct power factor on the grid as well as survive greater voltage disturbances as the DC link voltage is maintained from the grid rather than the load.

The CSI already has thyristors in both the rectifier and inverter sections, the drive can be adapted to allow for improved DC link performance to maintain power to the load under different transients.

There is of course a difference of national grid and island networks performance, as the island grid is local it does not suffer from transmission interference, however island grid present their own challenges with hunting loops, Sub Synchronous Torsional Interactions SSTI between these components is evaluated which includes load shedding and line disturbance immunity or support potential.

Other benefits

Project costs in terms of OPEX and CAPEX are improved with electrification, note different global locations have different CO2 tax and power costs so it is difficult to make general statements Reference [1].

Process Optimization With fixed or variable speed system there are much faster start and stop times which can benefit some processes such as gas storage where gas is stored or exported based on cost of gas. Variation of demand on a minute by minute or year by year basis is possible with VFD systems giving the operator ultimate flexibility Reference [2] rather than controlling flow with a value which wastes energy.

Project funding is easier to obtain for electrification and de-carbonization initiatives, also including in some cases government grants or tax breaks.

Permit time can be shorter for electrification as local emissions of gas turbines are commonly an issue.

Digitalization for electrical systems and online condition monitoring with digital twin HIL and SIL systems makes for improved availability and reduced OPEX as the data pool of analysis grows.

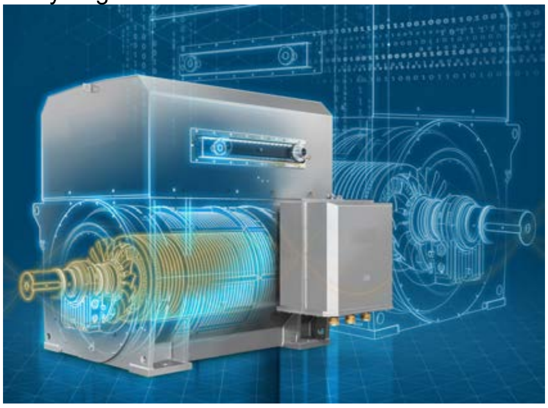

Fig. 18 Digitalization for motors and drives.

New applications

Grid forming SFC are the cutting-edge solution in power from shore locations where there is a mismatch between the onshore and offshore frequency. The AFE connection can be used to improve power factor and allow grid support in event of disturbance, power from either a national grid or an offshore windfarm can be converted to meet the grid operational frequency. The AFE SFC can deliver power in either direction and in the event of grid or load disturbance events the power management system can direct the SFC to support the grid to avoid worsening interruptions or equipment tripping and at the same time ensure the load is prioritized where applicable. Detailed priority of both grid and load loading will allow a pre-determined operation response to balance all necessary equipment and systems. With the aid of HIL and SIL modeling the different fault conditions can be examined and pre-determined for the survivability of both grid and loads.

This advanced operational optimization for the highest of system availability is driving the electrification wave.

Air storage systems acting as a battery storage, a motor driven compressor compresses air into underground storage reservoirs (such as salt caverns), during low power use, for example during the night. Then during peak demand the compressed can power an expander connected to a generate to feed power back to the grid. With a double ended shaft, the motor and generator can be the same machine.

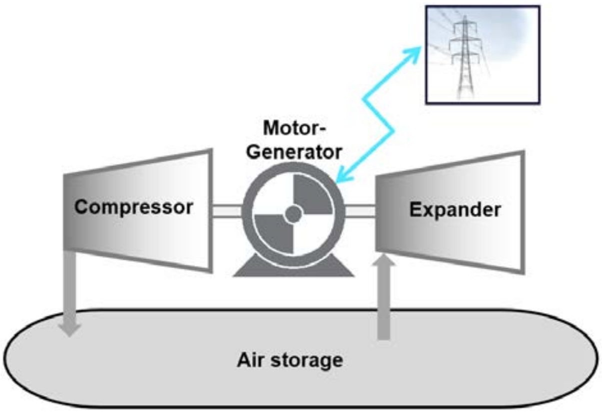

Fig. 19 Air storage system.

All Electric LNG eLNG for refrigeration trains has been around for some time but with limited implementation recently the trend for systems at very high power is to use an electric VFD system, the main motivation historically has been improved availability with increased production now with the drive to low emissions eLNG is becoming the base case solution for most projects, Reference [1].

Plant operational feedback has demonstrated high availability with increased production compared to traditional GT plants.

Synchronous Condensers where GTG are replaced with electric systems the generator can remain as part of the electrical network to provide grid inertia, this is important where large renewables are connected as the generator spinning rotor will improve the reliability and stability of the grid. Examples are offshore platforms that are electrified, and significant power is coming from offshore wind farms.

V. CONCLUSIONS

Electrification of oil & gas systems is a proven easy win to reduce CO2 emissions, however increased availability leading to increased production, operational efficiency and process optimization make electrical solutions the best financial solution.

The drive towards electrification will only improve the digitalization of systems further improving their availability and OPEX as more operational data is modeled.

Digital twins with HIL and SIL for concept and optimization verification leads to continuous improvement of the electrification pushing the boundaries within a controlled environment. The active front end solutions including grid forming capability are the new catalyst to push the boundaries of electrification possibility into even higher operational improvements.

VI. REFERENCES

[1] Decarbonizing turbine powered oil and gas applications with electrical ASDS. PCIC Denver 2022 J. Andrews (siemens), D Ristanovic (Bechtel) F Arias (Bechtel), N. Binesh (Abb).

[2] CO2 Emission reduction in chemical and petrochemical plants by steam turbine and gas turbine replacement with electrical drives. PCIC Denver 2022 H. Walter, B. Sauer, T Tyer, J. Kitchel

[3] MTBF comparison of cutting edge MV drive topologies for oil and gas applications PCIC London 2015. S. Busse, Dr M. Hiller, P Himmelmann, Dr K. Kahlen - Siemens.

[4] Managing Technology Step-outs and Optimizing Process Performance of Starter-Helper-Generator VFDs on Gas-Turbine Driven LNG Trains, *2014 Petroleum and Chemical Industry Conference Europe (PCIC-Europe)*, Amsterdam, Netherlands, 2014. Deacon K., Lanier S., Kubik J., Harshman M.,

[5] US Energy Information Administration website of emissions data: Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)

[6] Adjustable Speed Drives system comparison VSI and LCI for high power applications PCIC-2018-16. P. Bakker (Shell) A. Rauber (ABB).

[7] PCIC Europe (EUR17_56) VFD Operational performance of high speed motors on active magnetic bearings. Paul Donnellan (Shell) Rien Luchtenberg (Shell) Jeremy Andrews (Siemens) Dr. Horst Kuemmlee (Siemens).

[8] Min. terminal voltage on running sync motors during large motor starting PCIC Europe 2022 A. Alameer, Rami Dabbousi, H. Al-Marzoug, Z. T Balkhyour (Saudi Aramco).

[9] IEEE 1349-2021 Electrical machines in hazardous locations worldwide PCIC Denver 2022 P Hammer, L Padden, B Lockley, B. Misrty (IEEE).

[10] The effect of air gap on electric motor performance PCIC USA 2018 C. Yung, J Travis Griffith IEEE.

[11] Reference sites for emissions
Italian emissions / USA emissions / Dutch emissions

VI. VITA

Jeremy Andrews graduated from Sussex University in the UK with an honors degree in Engineering. He has worked with medium voltage drive systems in the oil & gas industry for 30 years and is currently employed at Siemens Large Drives as global business development and strategic account management. He has been a member of PCIC Energy Europe for over 10 years and is part of the committee as Secretary, Executive Committee Vice-Chair. He has presented many papers globally on VFD systems.
Jeremy.andrews@siemens.com

Troy Salazar graduated with a bachelor's degree in industrial Distribution at the University of Houston. He started his career with TECO-Westinghouse as a motor Application Engineer, he subsequently worked at Alstom and ABB expanding his experience into Power Conversion and Distribution systems in sales and account management roles. Since 2005 has worked for Siemens in various positions covering Power Conversion, Power Distribution, Automation systems and is currently Global Head of O&G Vertical O&G Sales.
troy.salazar@siemens.com