DECARBONIZATION OF COMPRESSOR TRAINS, ELECTRICAL DRIVER CONSIDERATIONS FOR HIGH POWER SYSTEMS.

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Abstract - Driven by targets for CO2 reduction, Oil & Gas operators are increasingly investigating electrical solutions for their high-power compressor systems that have historically been powered by turbines and are also considering retrofitting electrical drives to existing compression trains.

Traditionally such very high power electrical variable frequency drive systems use current source, load commutated technology (LCI). However, recent developments in voltage source inverters (VSI) has made this technology available at increasingly higher powers. Current source LCI drives are well referenced but are viewed as complex by operators, whilst VSI is considered, overall, a simpler system but lacking in experience at very high ratings. This paper will compare both VSI and LCI drives above 25MW including availability, efficiency, footprint, weight, cooling, technology readiness, CAPEX and OPEX for a complete working system.

Index Terms — CSI, LCI, VSI, AFE, Availability, Adjustable Speed Drives, Variable Frequency Drives, Synchronous motor, Induction-Asynchronous motor, Network behaviour.

I. INTRODUCTION

Main components of an electric drive system.

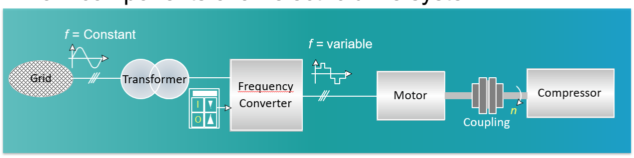

Fig. 1 Main elements of the drive system

Network

The network 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. Interaction between these components are evaluated during SSTI studies including load shedding and line disturbance immunity or support. The network is normally a national electrical grid but can be an island network.

Transformer

The VFD is most commonly connected to the network 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 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 12, 18, 24, 30, 36 pulse or more. If a harmonic filter is required, this is normally connected to an additional winding.

Variable Frequency Drive

This paper is predominantly considering the Variable Frequency (VFD) or Adjustable Speed Drive (ASD) characteristics for high power levels (30-100MW). So, the statements and considerations are for this high power range and not considering other requirements more applicable at lower power levels.

The VFD as its name suggests changes the frequency from the fixed line frequency to a variable frequency that in turn alters the speed and torque of the electrical motor driving the load. The drive is split into 3 main power parts rectifier-dc link-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, this can be from 0 to 50Hz, or in the case of high speed 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. The 2 families of drives are discussed in section II of this paper. CSI drives use thyristors in the switching sections of their rectifier and inverted sections which are uncontrolled switches. Whilst VSI drives have diodes in the rectifier section as standard. It is also possible to have Active Front End drives (AFE) with controlled switches in the rectifier which can provide some additional capability to the system that will be discussed later in the paper. The inverter section uses controlled switches such as IGBT's or IGCT's.

Motor

Considering the power level above 30MW the most common motor type is a synchronous motor, in the case of LCI this is mandatory as the motor provides the commutation to switch off the uncontrolled thyristor. The synchronous motor is most commonly used as it has higher efficiency and considerably more references, however, has some additional complexity in the excitation circuit, however this had almost on effect on the motor availability. Induction motors have a slightly lower cost. The motor the transition of electrical power into mechanical torque that is used to drive the load equipment.

Load

For loads in excess of 30MW the majority of cases are compressor applications although some fan and pump applications do exist. Normally these applications tend to be square law torque load profiles.

System Comparison

Whilst the main focus is on the VFD comparing LCI and VSI aspects such as availability, efficiency, opex, capex, TRL, safety, footprint, weight, cooling, AFE, harmonics, power factor and testing the impact on the network and load will also be considered.

II. OVERVIEW OF HIGH POWER DRIVE TOPLOGIES

Fig. 2 shows the main medium voltage drive topologies for high power ratings in industrial applications.

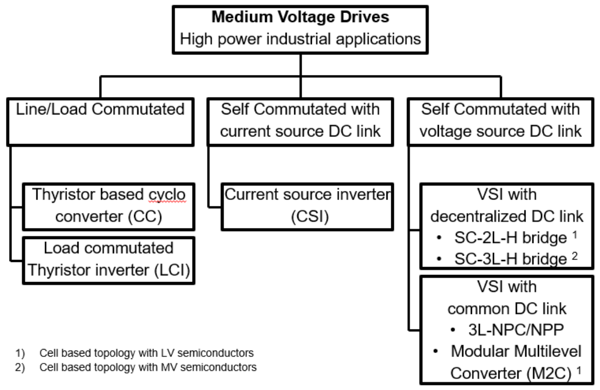

Fig. 2 Family tree of MV drive topologies.

CSI / LCI (Load Commutated Inverter) (figure 3) have been in operation since the 1970's, however today due to improvements in the VSI technology are rarely used below about 25MW. VSI came into the MV market in the 1990's most manufacturers use slightly different topologies, multi-level / multi-cell drives are the most common form of VSI VFD. Most manufacturers have a single thread VSI solution up to 25-35MW, these can be paralleled together to achieve higher power although paralleling more than 2 together increases complexity and impacts availability. Above 30MW there are only a handful of VSI references from any supplier.

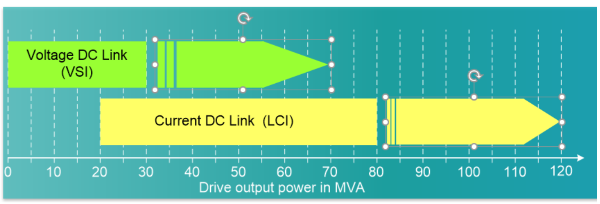

Fig. 3 Increasing power of VSI and LCI

Over the last few decades, the voltage source inverter (VSI) topologies have become the predominant converter technology. This paper will only focus on topologies capable of power above 20MW. Because of the various applications, the wide voltage and power range for medium voltage drives and the rapid development of the power semiconductor devices that are now available, numerous different voltage source inverter topologies have been developed for medium voltage applications in recent decades. Unlike the low voltage range, where the two level (2L) voltage source inverter has become the dominant concept, a large number of different converter topologies are available in the medium voltage drive market. The spectrum includes IGBT converters with low and high voltage IGBTs as well as IGCT-based converters including both 3-level, 5-level and multilevel drives with more than 9 levels.

The advantages of motor speed (frequency) control may be summarised as follows:

- Energy saving (compared to fixed speed operation and flow control via valves)
- Accuracy and speed of process control
- Reduced reactive power demand during motor starting – so called "soft start"
- Regeneration and energy recovery

A. Current Source Load Commutated Converter

CSI / LCI (Load Commutated Inverter) (figure 4) are very simple drives with high reliability and compact footprint. The main complication is they normally require a harmonic filter to comply with network standards such as IEEE 519. The technology is very well referenced and applied to power levels up to 100MW, in oil and gas the highest power level referenced is at about 80MW. All manufacturers use a similar topology of circuit

The base configuration is a 6-pulse rectifier and inverter, at high power the systems is normally a 12 pulse design at both the network and motor sides. The DC link reactor (inductor) is used to damp the DC ripple. The switching devices (Thyristors) naturally operate at a poor power factor and considering 12 pulse is normally not sufficient to comply with network harmonic requirements, a harmonic filter is required to absorb harmonics and correct the power factor to an acceptable level. Only synchronous motors can be powered by CLI drives as the thyristor is an uncontrolled switch it needs the back EMF of the motor to turn the thyristor off.

The LCI drive is naturally 4 quadrant as the rectifier thyristors can conduct in both directions, unlike a diode that can only conduct in 1 direction.

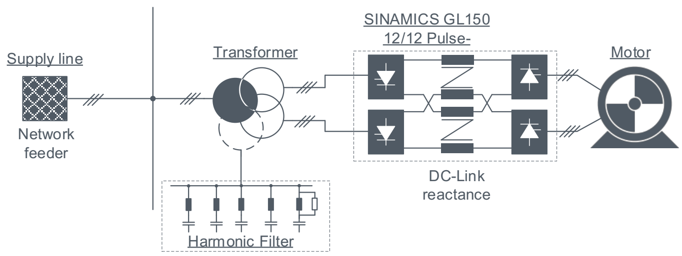

Fig. 4 Current Source Load Commutated Inverter.

B. Modular Multilevel Converter (M2C)

The modular multilevel converter (see Fig. 5) is the latest topology to enter the high-power medium voltage drive market. Depending on the motor voltage and the corresponding number of cells, the M2C is a 7-level up to 17-level drive. It uses simple, two terminal cells equipped with 1.7 kV IGBTs and state-of-the-art polypropylene film capacitors. These technologies are well established in the low voltage converter industry. Since the low voltage drives market is 80-90 % of the total drives market, these components are manufactured in very high quantities.

This ensures the highest possible quality at reasonable costs. Furthermore, all new technologies (e.g. new IGBT and diode generations, new module technologies with higher load cycling capabilities) are first introduced into the LV markets. All these developments are driven by

high volume applications, such as the wind power industry requiring very high-quality standards. Therefore, MV drives using LV technologies can benefit from these applications, leading to a long-term availability of spare parts, fast innovation cycles and high reliability.
On the line-side, the M2C can be connected to any conventional 12 to 36-pulse diode rectifier using press pack diodes and RC snubbers. This technology has been employed for many decades and has reached a very high quality standard.
Due to the modularity of the M2C topology, redundancy can easily be implemented in the motor-side inverter. By adding 6 (or 12) additional cells and bypass switches to all the cells an n+1 or n+2) redundancy can be realized.
This kind of redundancy covers a complete cell including semiconductors, capacitors, heat sinks, PCBs, and power supply. Having this type of redundancy, the drive voltage and current capability does not have to be reduced in case of a cell failure. One advantage of cell-based topologies that should be noted is that a cell bypass allows operation with reduced power that would allow the process to remain operational.

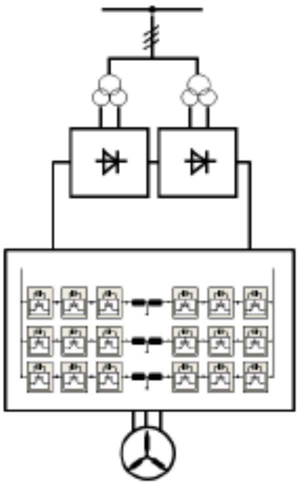

Fig. 5 Voltage Source Load M2C topology.

3L neutral point piloted converter (3L-NPP)
The 3L neutral point piloted converter (3L-NPP, Fig. 6) is derived from the conventional 3L neutral point clamped converter (3L-NPC, Fig. 6). Due to the high DC link voltages, this topology requires MV IGBTs connected in series [7]. Today 4.5 kV IGBTs offer the best compromise between the number of devices connected in series and semiconductor performance. Compared to the 3L-NPC topology, the IGBT switching losses can be reduced in the 3L-NPP concept as twice the number of IGBTs connected in series are employed for blocking half the DC link voltage during switching. This allows a higher power rating, which is the reason why the 3L-NPP topology was selected for the additional comparisons made in this paper.

MV IGBTs are available in either single-side cooled module packages or double-side cooled press pack packages. While IGBT modules are usually also used in other applications (e.g. traction drives), IGBT press pack devices are usually single-source devices and their usage is currently limited to fewer applications. The single source situation might result in problems regarding spare parts availability over the long term. Due to the low production quantities, innovation cycles take longer and the amount of feedback from problems in the field is limited as there is a lower number of devices in operation.

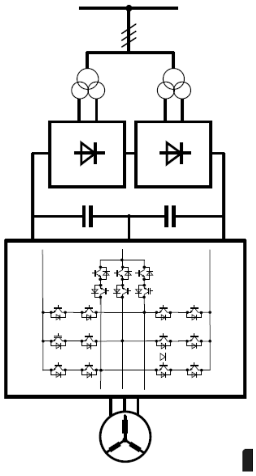

Fig. 6 3L-NPP (neutral point piloted) topology

Due to the centralized DC link capacitor, the amount of the total installed film capacitor energy of the 3L-NPP is lower than in the cell-based drives mentioned before. Even though the total capacitance is less, the value of the total capacitance, and therefore stored energy, in a single location, is many times greater than in topologies that are based on a distributed power architecture design. On the line-side, the 3L-NPP can also be connected to any conventional 12-pulse to 36-pulse diode rectifier using press-pack diodes and RC snubbers. The press-pack IGBTs and diodes in the 3L-NPP mean that devices can be simply connected in series without excessive stray inductances that would otherwise result in high switching losses. Furthermore, the conduct-on-fail capability of press pack devices is the deciding factor for this type of application.
By adding

- 12 (24) additional press pack IGBTs and
- 12 (24) additional press pack diodes

an n+1 or (n+2) redundancy can be realized with no decrease in voltage and current in case of a failure. The series-connected press pack IGBTs require isolated gate driver circuits connected to the emitter potential of the corresponding IGBT for controlling the gate-emitter voltage. In contrast to the LV cell-based topologies, gate driver failures cannot be covered by this kind of redundancy. This is because a failed driver does not necessarily result in a short-circuited IGBT, i.e. the IGBT gate drivers are still potential single points of failure and can cause a drive to be shut down.

The required off-state voltage of the power semiconductors directly depend on the DC link voltage. Therefore, continuous operation with reduced motor power without using additional hardware components (semiconductors, drivers) is not possible. This is different to the LV cell-based topologies where the cells that are still in operation are not affected by the bypassed cells in any way.

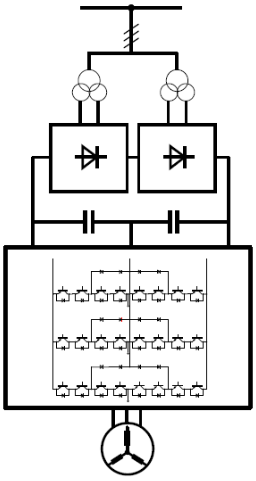

Fig. 7: 3L-NPC (neutral point clamped) topology

Series-connected (SC) 3L-H bridge converter
Regarding its cell-based design the series-connected 3L-H bridge converter is similar to the 2L-H bridge converter. The cells are individually fed by galvanically isolated transformer secondary windings. The required installed capacitor energy is higher than in concepts having a centralized DC link because of the single phase cell output.

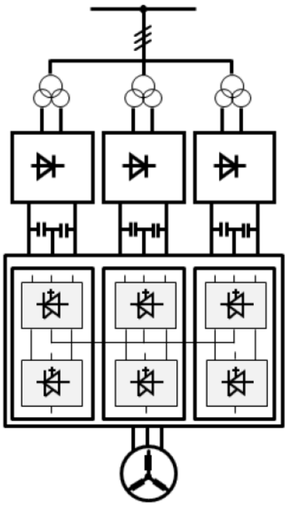

Fig. 8: 3L-H Bridge converter topology.

Commercially available converters use press pack semiconductors (4.5 kV IGBTs/IEGTs; 4.5 or 6 kV IGCTs/GCTs) with a maximum of two cells per phase, i.e. max. 6 cells in total. This results either in a 5-level (3 cells in total) or a 9-level drive (6 cells in total). Just the same as the press-pack IGBTs, the IGCTs are specifically designed to address certain applications. Due to the limited market, these kinds of devices are usually single-source components. On the line side, each cell can be equipped with a 12-pulse diode rectifier using press-pack diodes and RC snubbers, resulting in a 36-pulse line-side performance for 3-cell configuration. Due to the high number of additional devices a redundant operation of the SC-3L-H bridge topology is not reasonable, and therefore not available on the market.

III. LCI & VSI COMPARISON

The following criteria is used to evaluate both LCI and VSI systems.

1) Reliability MTBF

Transformer

The transformer is very similar to the topologies stated in section II, The LCI transformer will normally have 4 windings (primary, 2 secondaries and a 4^{th} winding for the harmonic filter) whilst VSI will be configured most likely in a 24 or 36 pulse arrangement, this will comprise of two 50% rated transformers in one tank, each having a primary and 2 or 3 secondaries to create either 24 or 36 pulse. Either can be connected to very high input voltages in excess of 100kV and will normally be oil cooled. MTBF and MTTR are comparable for each solution.

Harmonic filter

The harmonic filter normally only relevant to LCI, it is a passive system including container and HVAC system. Redundancy should be used for the cooling system. This is generally a very reliable system.

Variable speed drive

Including controls and cooling systems. LCI is a much simpler circuit and high reliability, all VSI circuits > about 30MW require parallel systems to achieve the required output power. The power circuits are more complex with a higher component count that impact the reliability, hence N=1 redundancy should be implemented to improve availability to a comparable level with LCI. The figure below are for a single thread system. See reference [1] and [4] for further details.

Motor (synchronous/induction)

Although induction motors are simpler in comparison to synchronous motors (fewer moving parts) and thus might have higher reliability/availability, this advantage is more than lost due to the far higher complexity/components of high power multi-parallel VSI.

	MTBF	MTBF
Component	**LCI**	**VSI**
Transformer	540y	540y
Harmonic Filter	95y	N/A
Motor	65y	65y
Excitation	140y	140y
VFD (N)	6.5y	5.3y
VFD (N+1)	11.5y	11.8y
VFD system (N+1)	**6.5y**	**6.5y**

2) Efficiency

The figures below are typical values, higher efficiency for the transformer and motor are possible with higher cost components.

Component	**LCI VFD system**	**VSI VFD system**
Transformer	99.2	99.0
Harmonic Filter	99.9	-N/A-
Motor	98.0	98.0
VFD	99.0	98.5
System Total	96.15%	95.56

3) CAPEX

Component	**LCI VFD system**	**VSI VFD system**
Transformer	100%	95%
Harmonic Filter	100%	0
Motor	100%	95%

Excitation	100%	100%
VFD	100%	125%
System Total	100%	90-95%
For > 50MW+ systems.		

These figures are typical and develop year by year.

Operational cost (OPEX) and maintenance is mainly driven by the cost of electrical power, hence efficiency is the most important factor. Maintenance cost differences between the topologies are minor.

4) TRL

Technology readiness level for LCI drives is proven at power levels about 80MW for compressor applications operating motors at speeds above 3000rpm. However extending this to powers of 100MW+ is simple to scale from lower powers as it means adding additional thyristors to increase the motor voltage level from about 11kV to about 13.8kV. A TRL process should be considered to understand the development required.

For VSI there are references for continuous duty up to about 27.5MW, above this higher motor voltage levels and/or paralleling of systems are required to achieve the power level to about 70MW. A TRL process should be considered to understand the development required at these higher power levels.

5) Footprint and Weight

	50MW m^2		70MW m^2	
Component	**LCI**	**VSI**	**LCI**	**VSI**
Transformer	29.4	25	37.4	32.4
Harmonic Filter	45	N/A	60	N/A
Motor 3600rpm	27.7	26.4	33.6	31.7
Excitation	0.24	0.24	0.24	0.24
VFD	19.2	33.2	27.2	39.4
System Total	**121.5**	**84.8**	**158.4**	**103.7**

	50MW kg		70MW kg	
Component	**LCI**	**VSI**	**LCI**	**VSI**
Transformer	85	80	104	97
Harmonic Filter	24	N/A	29	N/A
Motor (2 pole)	108	102	137	130
Excitation control	0.4	0.4	0.4	0.4
VFD	22	30	27	36.4
System Total	**239.4**	**212.4**	**279.4**	**260.8**

As can be seen the values are strongly influenced by the harmonic filter. However in most cases both the filter and the VFD are in containerized housing which means the complete system dimensions for both solutions tend to be very similar (+/-<10%) after the containerization is included.

6) Containerization

Considering the above dimensions, the larger VSI drive is still a smaller system due to the harmonic filter. However as both drives are large systems it is often more practical to use containerized systems to minimize site installation work. Containers can be supplied with HVAC and be pressurized depending on site environmental conditions. Overall, with all equipment in containers the difference in footprint is relatively small.

7) Safety

Most suppliers have capability to offer arc flash drives for operator safety, safe torque off SIL ratings are becoming an increased request. Suitability for different SIL rating are still being developed by suppliers.

8) Cooling

Variable speed drives have 2 possibilities of cooling either direct air cooled or direct liquid cooled. Losses (see above) are in the range 1-1.5% which at 50MW = 500-750kW of heat load.

Direct air

Forced air is drawn across the switching device heat sink fins to cool the drive, stray heat losses are also picked up by the cooling air flow and removed from the VFD. Redundancy for the fans is recommended for increased reliability. Air cooling presents a simple and highly reliable cooling system as managing cooling liquids is not required and often useful in very cold arctic locations, instant startup can be done without checks on the cooling system. However, if the heat load cannot be absorbed by the switchroom or directly blown outside an air-to-air or air-to-water heat exchanger can be provided.

Direct Water cooling

Cooling water is directly pumped through pipes to all the main heat loads within the VFD (switching devices, DC link components etc..) additional heat sinks can be placed in control cabinets and other hot spots to remove stray heal losses. As the water is directly passed through heatsinks clamped against the power electronics the water needs to be non-conductive (de-ionized). Redundant pumps, main heat exchangers are recommended for increased reliability. Serviceability of the cooling circuit during operation is recommended to avoid shutdown for maintenance on de-ionizer cartridges and pumps. The de-ionized cooling circuit is an internal closed loop. This can be cooled via a water-to-water heat exchanger, where ambient conditions fall below +5degC glycol is required in any cooling loop that is exposed to this temperature. If cooling raw water is not available a water-to-air fin-fan heat exchanger is required.

9) Harmonics

The rectification process of the variable speed drive creates non sinusoidal elements within the voltage and current waveforms. A single rectifier bridge across the 3 phases draws current or voltage in 6 distinct pulses which creates a square profile waveform. With two 6-pulse connections it is possible to phase displace the 2 waveforms to create a 12-pulse more sinusoidal connect to the line. With more rectifier bridges in parallel connections in excess of 36 pulse are possible. National electrical grids will have standards such as IEEE519 which have to be met to allow VFD's to be connected.

A current source drive is normally configured in a 12-pulse arrangement, this is unlikely to conform to the electrical grid requirement for harmonic limits. A harmonic filter in the form of an LC circuit is added to meet the harmonic limits. Designing a harmonic filter requires network information such as fault level and existing harmonic profile. If the network characteristics change over time the harmonic filter may need to be re-designed.

MV Voltage source drives are normally supplied as a minimum in an 18-pulse connection with 3 rectifier circuits to allow for compliance with the harmonic standards. The more pulses the more sinusoidal the waveform. Due to the higher number of rectifier bridges in a VSI drive harmonic filters are almost never used. Care should be taken that the harmonic pulse number does not excite a network resonance.

10) Power factor

Current source drives with thyristors naturally operate at power factor of about 0.82. This is undesirable as it causes higher currents and impacts on efficiency and results in voltage drops, causing the operator higher running costs. To correct the power factor the capacitance in the harmonic filter is used to improve the power factor to an acceptable level of about 0.95.

This is not a problem for voltage source drives with diode bridges as the diode operate at about 0.96 power factor. If the VSI drive has an active front end (AFE) see below then the drive can be used to provide leading VArs into the grid to correct the grid power factor.

11) Testing

Both topologies of drive are standard tested at full current and full voltage, but not both at the same time. If a load test is required then the complete systems needs to be assembled either in the form of a back-to-back test or a string test with the driven equipment (compressor).

For a back-to-back test [3] if there are 2 identical systems then the LCI systems can be connected together at the motor shaft with one motor in motoring mode and the other motor in generating mode. The power can be circulated through the 2 systems and loaded close to full power. However as VSI is not naturally 4 quadrant either a test bay drive/load is required or an AFE implemented on the rectifier circuit.

12) Active Front End

Active Front End drives (AFE) means the switching device in the rectifier if controllable. For a voltage source drive the standard solution is to use a diode in the rectifier, this is an uncontrolled switch and is a 2-quadrant drive, meaning the VFD can drive the motor clockwise or anticlockwise. By replacing the diode with an IGBT for example means that the drive can regenerate power from the motor (acting as a generator) to the electrical grid. This is also known as a 4-quadrant drive. Any spare capacity in the drive and transformer can be used to provide VAr's back into the grid for power factor correction. The drive can support the grid against voltage and frequency disturbance, grid code functionality needs to be investigated for requirements at site.

Whilst LCI Current source drives are naturally 4 quadrant this is not an active front end drive, as VAr compensation is not possible due to the limitation on switching the thyristor off, as it is not fully controllable. However, optimization of firing angles of the thyristor can help support the drive system through voltage disturbance by allowing continued operation and avoiding losing control of the motor for larger dips and longer durations of dips.

Further examples of AFE and 4 quadrant drives are discussed in the next chapter.

13) Interharmonics

Interharmonics [2] is a well understood issue where there can be interaction between rotating equipment on the electrical grid and driven equipment rotating equipment. Mitigation techniques are used for LCI drives, whilst VSI has not experienced problems due to the DC link design.

14) Load torsional vibrations

Non sinusoidal elements in the current waveform to the motor result in air gap torques that can cause problems for the mechanical train. Torsional vibrations in the motor-load shafts need to be evaluated to ensure there are no interactions with natural resonances and issues across the operating speed range of the system.

15) SSTI

Sub Synchronous Torsional Interactions of the complete system need to be evaluated for vary large power drive systems, this is particularly important for islanded networks where the motor power can be a high proportion of the generator power. The interaction between the generator is discussed above in interharmonic issues, however SSTI also includes the complete start up and operating philosophy of the plant including the commissioning phase that is likely different to normal operation conditions and also black start up of the island system. Load shedding needs to be carefully considered, under normal circumstances when there is a voltage dip the variable speed drive will try to maintain power to the load to prevent interruptions in the process. However for island system if a turbine generator were to trip causing a voltage dip and the VFD responded by drawing more current to maintain the process this will further exacerbate the other turbine generators from recovering and could cause the complete system to trip. Pre-programmed load shedding scenarios will ensure the network has the best chance of recovery. A team of process and grid experts will need to consider the response to each failure event.

16) Soft starter for fixed speed motors

The electronic soft starter device is one of the motor starting options, among others, that is selected when voltage drop constraints are fixed by the energy provider, or not to exceed limits are set for the adjacent bus bars. The LCI as well as the VSI allow reducing inrush current and voltage drop when starting large motors, offering a smooth start-up. In some cases the electronic soft starter is convenient to save space or additional equipment (e.g. versus an autotransformer starting method). The LCI and VSI device makes it possible that the starting current would not be more than the rated current of the large motor. This is also good for the motor and other electrical equipment associated with the plant as it lessens the stresses placed on them by the other types of starting methods.

The main inconvenient for the operations is the complexity of the equipment that requires specific skills in the maintenance and operations teams.

The choice of this solution is made on a case by case basis, more especially when it is supposed to be shared between two motors. Then the most appropriate technology and product may be selected taking into consideration the:

- type and reference with regard to the existing fleet,
- return of experience with products and suppliers,
- OEM's technical support in the geography,

- simplicity of the system,
- line current total harmonic distortion,
- input power factor,
- reliability (MTBF),
- equipment size,
- cooling system.

More broadly:

- The electronic soft starter should provide the motor accelerating torque, such that a minimum net accelerating torque of 10% should be available for the entire speed range up to pull-in speed. The soft starter control and acceleration rate should be programmed and commissioned, to give optimum compressor acceleration,
- the LCI or VSI system could produce negligible sidebands of the characteristic current harmonics on the source side, due to the operation of the load side bridge,
- the LCI or VSI system may be designed to minimize the motor ripple torque, due to interaction between the source and load-side converters,
- the design and construction of the soft starter output transformer could allow forced commutation starting at low frequency to accelerate the motor and connected inertia to pull-in speed using the compressor starting load torque shown on the compressor load torque curve. The design parameters of the transformer should be submitted the operator and soft starter vendor for approval,
- the LCI or VSI drive could provide its own referencing voltage for the load,
- the design of the LCI / VSI should be as independent as possible of Motor(s) and Motor Control Panel(s). After startup, it should be possible to disconnect the drive without impact on motors. If required, a Master PLC is to be used to make the interface between the drive, the MCP, the MV circuit breakers and the control system (BPCS and SIS).

IV. USE OF DRIVES AND CONVERTER-BASED POWER GENERATION

The global drive to reduce CO2 footprint increases the potential for electric VFDs compared to turbine drivers. Traditionally, island networks use local diesel or gas turbines as prime drivers for high power mechanical loads. This also includes sites such as offshore platforms. New platforms may be designed with power from shore or power supply from offshore wind farms or other local generators such as hydro-electric and solar, where electrical cables connect the offshore facility to the local power grid or power generation facility. Depending on the distance from shore and power demand, high voltage AC or DC power transmission systems can be used.

Operators are also investigating power from shore for existing platforms, where offshore power generation is removed and turbine driven loads converted to electric systems. There is the added complication of a mismatch of frequency, where for example the offshore platform is using 60Hz but the power from shore is at 50Hz, this means where an HV cable is used to deliver power offshore a frequency converter is required to operate the existing 60Hz loads. Industrial VFDs can be used as cost effective SFC's. Using an AFE means the SFC can deliver power in both directions, also VAr compensation can be provided to the grid, as well as support against voltage and frequency disturbance.

There is increasing penetration of grid-following renewable and other converter-based sources of power, such as battery energy storage systems, which rely upon VSC technology for connection to the power system. As the amount of converter-based equipment increases, effects not previously considered become more relevant especially the interaction of the power electronics / control of the converter-based equipment with other system components notably drive converters.

CIGRE has highlighted the issues to be considered when deploying large amounts of converter-based resources into systems [5]. Other than the general issues regarding the quantification of non-integer harmonics produced by many AFE VSCs [6] there is also the risk to system operation as unstable oscillations are identified within the frequency range of the VSC outer controls, which include dc-link voltage control (DVC), ac voltage control (AVC), and the frequency tracking phase-locked loop (PLL). It is reported that the PLL can lose stability under weak ac system (high impedance) conditions.

In general, the stability of a system formed by the ac power system and the power converter can be studied using frequency domain methods, such as the impedance-based Nyquist stability criterion. This requires detailed modelling and knowledge of controller dynamics, and so is difficult to do in early project phases. More simply, a screening analysis can be done per the advice in CIGRE TB671 – this is based on the ratio of the power system short circuit level to the MVA rating of the connected converter-based equipment at the point of coupling (referred to as the Short Circuit Ratio, which can confusing for those familiar with synchronous machines). While there are discussions about the exact details the calculation method, when this ratio (System MVA SCL / connected MVA) < 3, problems may be anticipated with control of converter-based resource and further study is needed in the early project phases, potentially leading to testing of controller hardware once equipment and suppliers have been chosen. The literature does indicate stability at lower levels of SCR, but this should be modelled and then demonstrated during project development.

As grid-forming converters become more standard where measurement and feedback loops are less susceptible to signal amplification by the power system impedance, it may be that the SCR values at 1 or below may be acceptable.

V. CONCLUSIONS

As a general rule owners and operators nearly always use VSI technology below 25MW and nearly always use LCI above 50MW. In the range 25 to 40MW the market is cautiously considering VSI technology and references are increasing year by year. In the range 40-60MW whilst VSI is technically possible, the lack of references in a conservative market means there needs to be a compelling reason to consider VSI over LCI.

VSI has several advantages over LCI, namely better waveform to the network and motor, so harmonic filters are almost never required. This makes the system simpler and slightly lower cost, however as power increases more and more components (series or parallel switching devices) are required, which impacts complexity and availability of the VSI drive, hence N+1 redundancy can be implemented to improve availability. VSI **can** have the required availability by offsetting the high component count with higher redundancy.

At high penetrations of converter-based equipment (both generation and motor drives), EMT modelling studies and controller testing are required to demonstrate controller stability and overall impact on the electrical grid.

VI. ACKNOWLEDGEMENTS

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