DECARBONIZING TURBINE POWERED OIL AND GAS PROCESSES WITH ELECTRICAL ADJUSTABLE SPEED DRIVE SYSTEMS

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Abstract — *The Oil & Gas (*O&G) industry operations account for 9 percent of all man-made greenhouse-gas emissions. CO_2 reduction paths 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 high-power compressor systems that have historically been powered by turbines.

Traditionally very high power electrical variable frequency drive systems use current source technology. However, recent developments in voltage source inverters have made this technology available at increasingly higher powers. Current source drives (LCI) 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-power ratings. This paper compares both VSI and LCI drives above 25MW including availability, efficiency, footprint, weight, cooling, technology readiness, AFE, CAPEX and OPEX for a complete working system. The paper compares impact of large VSI and LCI drives on the power supply system in terms of harmonics, and network impact on the drive. Future proofing of drive solutions due to changes in the power supply system, including the addition of other power users on the network during the lifetime of electric driven plant.

Index Terms —. ASD, VFD, AFE, MV Motor, LCI, VSI.

I. INTRODUCTION

Main components of an electric drive system:

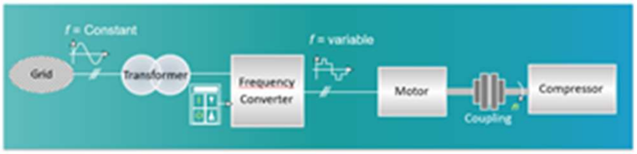


Fig. 1 Elements for complete drive system.

A. 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 is evaluated during Sub Synchronous Torsional Interactions SSTI studies which includes load shedding and line disturbance immunity or support. The network is normally a national electrical grid but can be an island network.

B. Transformer

The ASD is most commonly connected to the network via a transformer as the network voltage for high power drives is normally significantly higher than the ASD 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 ASD restricting short circuit currents. Additionally, it eliminates high frequency bearing currents that are a consequence of the current flow in the common mode circuit of the ASD and protects the motor against common mode voltages. 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 and are commonly known as multi-pulse configurations. If a harmonic filter is required, this is normally connected to an additional winding.

C. Adjustable Speed Drive

This paper is considering the adjustable speed drive ASD (or variable frequency drive -VFD) characteristics for high power levels (25-100MW). So, the statements and considerations are for this high-power range and do not consider other requirements more applicable at lower power levels.

The ASD 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 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, this can be from 0 to 50Hz or 60Hz, 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. CSI drives utilize inductors as the filtering component on the dc link while VSI drives employ capacitors. The two families of drives are discussed in section II of this paper. CSI drives use thyristors in the switching sections of their rectifier and inverter sections. 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 IGBTs or IGCTs.

D. Motor

The motor transforms the electrical power into mechanical torque that is used to drive the connected mechanical load. Considering the power level above 25MW 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 it has some additional complexity in the excitation circuit. However, this has almost no effect on the motor availability, Induction motor do have more complexity in the construction with many laminations and bars.

E. Load

For loads in excess of 25MW the majority of cases are compressor applications although some fan and pump applications do exist. Normally these applications tend to be square law torque loads with variable torque profiles.

F. System Comparison

Whilst the main focus is on the ASD comparing LCI and VSI aspects such as availability, efficiency, CAPEX, OPEX, Technology Readiness Level 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 VSI AND LCI AND MAIN TOPOLOGIES IN THE MARKET PLACE

A. Load Commutated Inverter (LCI) Drives

The LCIs are the most referenced drive found in high power applications with a power rating 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. A typical 12-pulse configuration of an LCI drive is shown in Fig. 2 [1]. There are two main variations in LCI drive configurations: one with a single winding synchronous motor with a 6-pulse inverter output, and the other for a dual winding synchronous motor with a 12-pulse inverter output. An LCI drive with 24 pulses can be built but is complex and not economically viable.

The cost difference from a 12-pulse drive to 24-pulse drive outweighs the cost of harmonic filters used with a 12-pulse drive to bring the harmonic levels to the ones achieved with a 24-pulse drive.

The drive presented in Fig. 2 shows the most common LCI fed synchronous motor drive topology for large compressor applications with 12 pulses at the inverter. The 6-pulse inverter would be simpler and would not require synchronous motors with a two-winding stator, but such a drive would generate high levels of harmonics and torque pulsations.

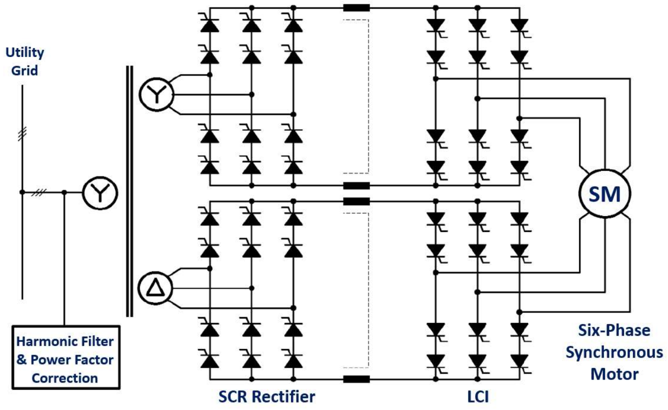


Fig. 2 An LCI drive system with 12-pulse input (rectifier) and 12-pulse output (inverter).

The drive shown in Fig. 2 uses a 12-pulse SCR rectifier with a DC link choke to provide a controllable DC current to the 12-pulse inverter. The number of series connected SCRs depends on the voltage ratings of the SCRs and the utility supply. SCR is a silicon-controlled rectifier, one of the first and simplest thyristor type devices used in ASD power electronics. It is the main building block of both rectifier and inverter section of the LCI drive.

The line current of the 12-pulse SCR rectifier has a large amount of 11th and 13th harmonics. Therefore, a harmonic filter is often required for the LCI drive. The filter is of an LC series resonant type, normally tuned at the 11th and 13th harmonics. By a proper selection of LC parameters, the tuned filter can also serve as a power factor compensator. 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.

Since the SCR devices are used in the LCI drive, it is important to understand the basic principle of SCR operation. SCRs belong to the thyristor family of power electronic devices. The thyristor device, the SCR, turns on with a small current injected into its gate. Reducing current in the device to zero through external voltage levels, devices, components, or circuit load characteristics can only turn off the SCR. For example, an SCR conducting in a phase-controlled rectifier circuit turns off when the applied utility AC sine wave voltage across it reverses polarity. At this time, the current through the device is zero and device is reverse biased. With an LCI drive, the synchronous motor itself, which is the load to the LCI drive, provides the needed switching and reversal of voltage for device turn-off. It is the key to LCI drives that they operate with synchronous motors, the motor that has its own excitation and controllable power factor. An LCI drive cannot work with an induction motor.

An LCI drive is inherently a four-quadrant drive. By adjusting firing angles of SCRs in the rectifier and the inverter section the drive can operate in motoring or generating (regenerative breaking) mode.

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. 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). Fig. 3 shows an example of three level NPC drive and other types are explained in detail in the reference [1].

1) Three level NPC drive is one of the technologies used for the high-power electric drive applications. By splitting the DC link capacitor into two sections and tapping the mid-point, a third source of voltage is available for the inverter. With this third source of voltage, a three-level, voltage-source PWM inverter is configured as shown in Fig. 3.

This configuration is called a neutral point clamped (NPC) inverter. The NPC design can either utilize medium-voltage IGBT or IGCT switching devices depending on the output power requirements. Higher output with less components can be achieved with an IGCT. Fig. 3 shows an IGCT configuration for illustration purposes. The NPC design references the output voltage levels to the neutral point connection at the center of series-connected DC link capacitors. This connection prevents large voltage shifts within the motor neutral and therefore reduces stresses on the motor insulation. The voltages obtained with a three-level inverter more closely approximates a sine waveform and accordingly are less stressful to the motor.

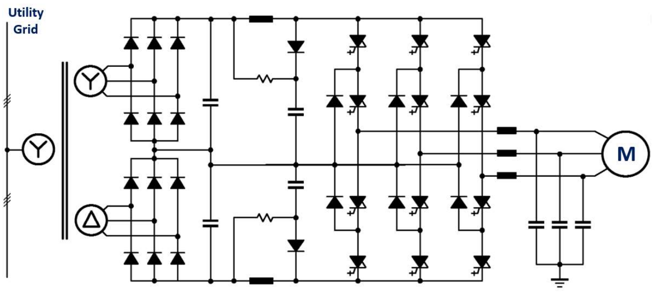


Fig. 3: Three level IGCT based NPC VSI drive

Advantages of NPC technology are:

- The waveform of the line-to-line voltages leads to lower THD and dv/dt in comparison to the two-level inverter operating at the same voltage rating and device switching frequency

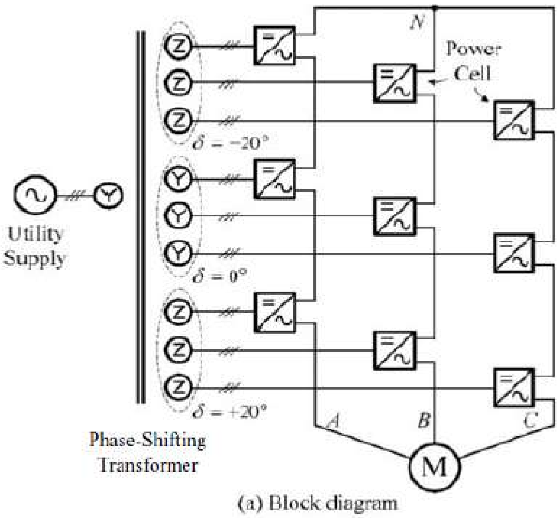
Disadvantages of NPC technology are:

- Additional clamping diodes
- Complicated PWM switching pattern design, and possible deviation of neutral point voltage
- Regenerative braking and four quadrant operation only available for NPC inverter if active front end (AFE) rectified is provided, which complicates the design

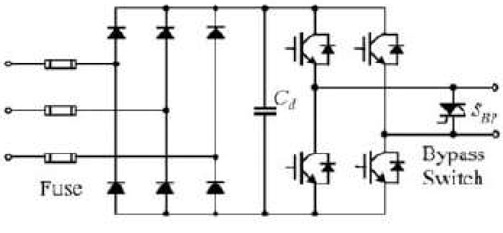
2) Multilevel Cascaded H-Bridge (CHB) Drive topology principles are shown in Fig. 4.

Advantages of CHB technology are:

- The low-voltage power cells can be mass-produced for the multilevel CHB inverters operating at various medium voltages. Defective power cells can be easily replaced, which minimizes downtime.
- The CHB inverter can produce ac voltage waveforms with small voltage steps. The inverter normally does not require any filters at its output. The motor is protected from high dv/dt stresses and has minimal harmonic power losses.
- Faulty power cells can be bypassed, and the drive can resume operation at reduced capacity with remaining cells.
- The drive system reliability can be improved by adding a redundant power cell to each of the inverter phase legs. When a power cell fails, it can be bypassed without causing reduction in the inverter output capacity.
- Nearly sinusoidal line current is mainly due to the use of the multi-pulse diode rectifier.



(a) Block diagram



(b) Power cell

Fig. 4: Typical configuration for VSI Cascaded H-Bridge topology with an 18-pulse diode rectifier

Disadvantages of CHB technology are:

- The multi-winding transformer is the most expensive device in a CHB drive. Its secondary windings should be specially designed such that the symmetry of leakage inductances is preserved for harmonic current cancellation.

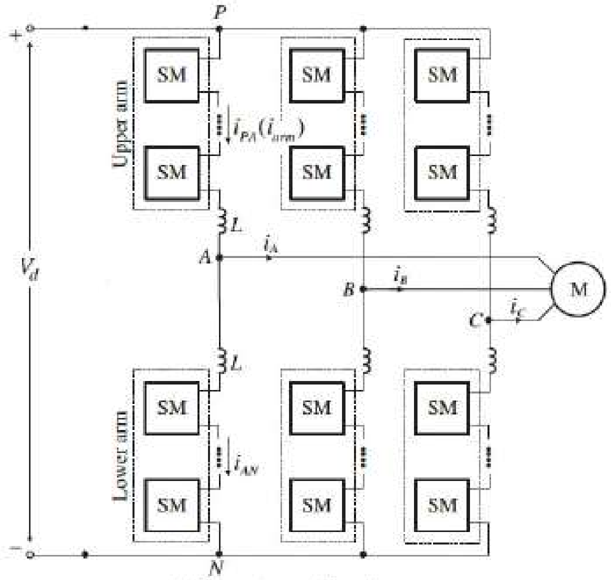
- The multilevel CHB inverter drive normally requires large number of cables to connect the power cells to the transformer.
- The CHB inverter drive uses large number of low-voltage components, which potentially reduces reliability of the system. But can be overcome with redundancy built in.

3) Modular Multilevel Converter (MMC/M2C) Drive topology was originally developed for HVDC transmission systems and is now being applied to the MV VSD systems. Industry demand for higher power range and superior performance provide a vast field for new converters which are a combination of conventional converters. [2] In MMC/M2C topology, the rectifier section is similar to VSI-NPC topology, but the inverter section consists of multiple sub-modules as depicted in Fig. 5.

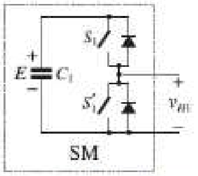
A modular concept similar to CHB topology is applied to the MMC/M2C topology except that power is supplied to the DC link differently. In CHB topology, each power cell contains diodes, DC capacitors, and IGBT devices; therefore, multi-secondary windings in the VSD transformer are essential. Each sub-module in MMC/M2C topology consists of a DC capacitor and IGBT devices. In some way, it may be considered as a hybrid design with the advantages of NPC (e.g., rectifier section) and CHB (e.g., inverter section) topologies.

Advantages of MMC/M2C technology are:

- The low-voltage sub-modules can be mass-produced for the modular multilevel converter (MMC/M2C) topology operating at various medium voltages. Defective sub-modules can be easily replaced, which minimizes downtime.
- With multiple sub-modules, the topology is able to produce ac voltage waveforms with low THD and dv/dt. Therefore, the MMC/M2C topology does not require filters at its output. The motor is protected from high dv/dt stresses and has minimal harmonic power losses.
- A faulty sub-module can be bypassed, and the drive can resume operation at reduced capacity with the remaining cells.
- The drive system reliability can be improved by adding a redundant sub-module to each of the inverter phase arms. When a sub-module fails, it can be bypassed without causing reduction in the inverter output capacity.
- The converter sub-modules do not require isolated DC power supplies when compared to CHB topology. The converter can operate with a single DC supply, so it is possible to have a transformer-less drive.



(a) Converter configuration



Switching states

S_1	S_1'	v_{H1}	SM status
1	0	E	On state
0	1	0	Bypass state

(b) Half-bridge submodule (SM)

Fig. 5: Typical configuration for VSI MMC/M2C topology with sub-module details

Disadvantage of MMC/M2C technology is:

- The capacitor voltage ripple is relatively high at low drive output frequency. The capacitor rating should be significantly increased to resolve this issue, which may be impractical for sub-module design. But the capacitor voltage ripple can be mitigated by injecting high frequency common mode voltage, which will cause additional common mode voltage stress on the motor stator winding.

In-depth explanation of drive technologies is given in [1].

III. ELECTRICAL SYSTEM CONSIDERATIONS

A. Harmonics and Power Factor

Variable frequency drives represent sources of harmonics, both at the input and at the output of the drive. Harmonics at the input of the drive impact the electrical network the drive is connected to. Harmonics at the output of the drive impact the motor and driven load. While harmonic levels on the output side of the drive are handled by design of the drive-motor system (e.g. number of output submodules, inverter levels, etc.), the input harmonics and their impact on the upstream grid is often more critical. If plant with large variable frequency drives is connected to an external power utility grid, the grid may mandate that harmonic levels should not exceed specified levels. Typical “not-to-exceed” harmonic level requirements at the point of grid interface, point of common coupling (PCC), are given in IEEE

519 [3] but some network utility companies may have their own, often more stringent requirements.

On a project with large variable frequency drives, harmonics study is required to determine and analyze filter sizing and filter design. The study requires actual equipment data, operating points, and accurate representation of the components of the electrical system being analyzed. The study should be done for many scenarios. It is important to realize that when plant is connected to electric power grid, existing and future capacitors and harmonic filters in the grid, the number of capacitor stages connected, short circuit equivalent of the grid, present and future, and grid configuration including changes over the lifetime of the plant, will affect harmonic filter performance. This means that detailed and not always readily available information about external power grid need to be collected in the filter design stage. Effectiveness of the harmonic filters can be greatly impacted by changes, so future-proofing of filter design is the key to harmonics analysis and filter sizing exercise. Final filter design shall include margins and provisions for future changes in the electrical system.

As discussed in previous sections, one of the key indicators of the drive impact on the grid is the number of pulses. Lower pulse drives have more severe impact by generating high content of low order harmonics. LCI drives in large electric drive applications consists of two 6-pulse drives on two input transformer secondaries phase shifted by 30 degrees, making it effectively a 12-pulse drive. VSI drives are typically higher pulse (24-pulse, 36-pulse or 48-pulse) with significantly lower harmonic impact than LCI drives. Harmonic studies are typically done for project with LCI drives. Even though harmonics with VSI drives are considerably lower than with LCI configurations, harmonic studies should be done for projects with VSI drives as well. Even if filter is not required to meet the requirements of IEEE 519, the filter may be needed to mitigate resonance in the local circuit where cable capacitance can cause resonance for high order harmonics [4]. Detailed model representation of drive and connecting cables should be used. Relatively small harmonic filters may be required in systems with VSI drives.

To do the modelling for the harmonic analysis studies it is important to determine sources of current harmonics, model components of the electrical system, select location of harmonic filter, and define criteria and scenarios for harmonic filter sizing. Fig. 6 shows an example of a 12-pulse LCI drive.

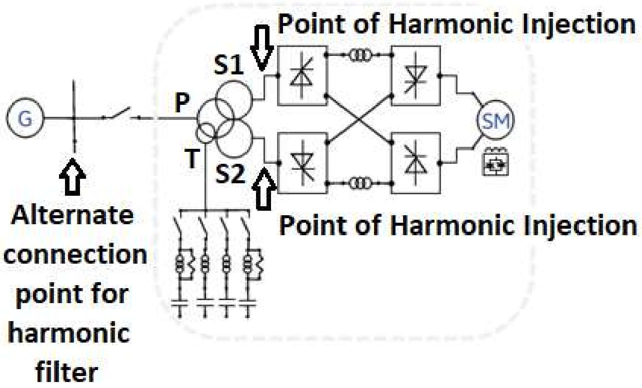


Fig. 6: Example of a 12-pulse LCI drive

The large LCI drive system in the example has a 4-winding input transformer with primary P connecting to a high voltage source bus. Two 6-pulse input rectifiers are connected to separate secondaries S1 and S2. Secondaries S1 and S2 are phase shifted by 30 degrees, making the system effectively a 12-pulse system. Harmonic filter is connected to the fourth winding of the input transformer, a dedicated tertiary T. The source of the current harmonics is the 6-pulse rectifier.

LCI drive has two 6-pulse rectifiers. It is necessary to obtain current harmonic content for the 6-pulse rectifier from the manufacturer. Example of current harmonic content is shown in Fig. 7. High harmonic content can be observed at 5th and 7th harmonic order which is typical for a 6-pulse rectifier.

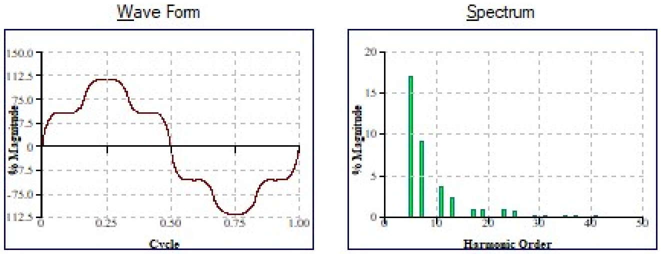


Fig. 7: Example of a 6-pulse rectifier current harmonics

Another component that requires due diligence in modeling is the input 4-winding transformer. Some modelling software do not have a library model for a 4-winding transformer, and for harmonic studies it is critical to represent the transformer adequately. When harmonic filter is connected to transformer tertiary T, and sources of harmonics are rectifiers on two secondary windings S1 and S2. Point of common coupling is upstream from the primary P. It is critical to understand that mutual impedances between the windings, and their adequate representation are key to how the filter will interact with sources of harmonics, and how the filtered harmonics will propagate to the primary side. Representing 4 winding transformer with two 3-winding transformers may be suitable for some calculations, like simple load flow, but such representation is completely inadequate for harmonic studies. If 4-winding transformer is not available in electrical simulation software library, equivalent model with 8-bus representation can be created as explained in [5]. If transformer percent impedances are given Z(P to S1) = Z12, Z(P to S2) = Z13, Z(P to T) = Z14, Z(S1 to S2) = Z23, Z(S1 to T) = Z24 and Z(S2 to T) = Z34, and they are all defined on the same MVA base, then according to [5]:

$$\text{K1} = \text{Z13} + \text{Z24} - \text{Z12} - \text{Z34} \tag{1}$$
$$\text{K2} = \text{Z13} + \text{Z24} - \text{Z14} - \text{Z23} \tag{2}$$
$$\text{Ze} = \text{SQRT}(\text{K1} \times \text{K2}) + \text{K1} \tag{3}$$
$$\text{Zf} = \text{SQRT}(\text{K1} \times \text{K2}) + \text{K2} \tag{4}$$
$$\text{K3} = \text{Ze} \times \text{Zf} \,/\, [2 \times (\text{Ze} + \text{Zf})] \tag{5}$$
$$\text{Za} = (\text{Z12} + \text{Z14} - \text{Z24}) / 2 - \text{K3} \tag{6}$$
$$\text{Zb} = (\text{Z12} + \text{Z23} - \text{Z13}) / 2 - \text{K3} \tag{7}$$
$$\text{Zc} = (\text{Z23} + \text{Z34} - \text{Z24}) / 2 - \text{K3} \tag{8}$$
$$\text{Zd} = (\text{Z34} + \text{Z14} - \text{Z13}) / 2 - \text{K3} \tag{9}$$

The 8-bus model of the equivalent impedance of a 4-winding transformer is given in Fig. 8.

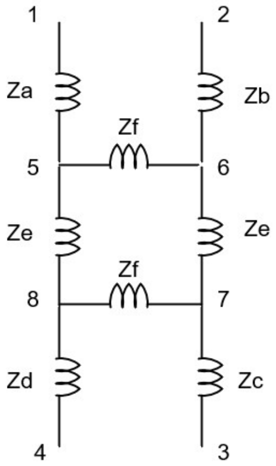


Fig. 8: 8-bus model of equivalent impedance of a 4-winding transformer

Base voltage can be selected as one of the windings' nameplate voltage, e.g. voltage Vp of the primary winding P. Then primary input to 4-winding transformer is connected to ideal transformer (zero, or "close to zero" impedance) with ratio Vp/Vp connected to bus 1 in Fig. 7. Secondary S1 output with nameplate voltage Vs1 is connected to ideal transformer with ratio Vp/Vs1 connected to bus 2. Secondary S2 output with nameplate voltage Vs2 is connected to ideal transformer with ratio Vp/Vs2 connected to bus 3. Tertiary T output with nameplate voltage Vt is connected to ideal transformer with ratio Vp/Vt connected to bus 4. Other buses in the equivalent scheme, buses 5, 6, 7 and 8 are internal buses of the transformer model and represent how the windings interact with each other in terms of mutual impedance. Primary input of 4-winding transformer, first leg of the drive input rectifier, second leg of the drive input rectifier, and harmonic filter are connected to their corresponding voltage levels Vp, Vs1, Vs2 and Vt respectively.

Instead of dedicated winding, one alternate connection point for the harmonic filter is the primary bus, as shown in Fig. 5. For a large ASD drive, typical primary bus voltage level is 132 kV or 138 kV. Harmonic filter, in that case, would be connected to a captive step-down transformer. Advantage of that solution is that dedicated 4th winding of drive input transformer wouldn't be needed, i.e. the drive input transformer would be a simpler 3-winding transformer, and also, in some configurations the filter can be physically located away from the equipment intensive area around the drive input transformer and variable frequency drive itself. The main disadvantage of the solution with filters connected to alternate connection point on the main primary bus is that the harmonic filter would electrically be "far away" from the sources of harmonics (drive input rectifiers), with drive input transformer and step-down transformer to the harmonic filters between the filters and the sources of harmonics, so the filter would be far less effective. Our findings are that connecting the filter to dedicated 4th winding of the input transformer is better and often the only effective option.

Another point that must be taken into consideration is the requirement to comply with not-to-exceed harmonic limits given in standards or required by power grid companies. As an example, voltage distortion limits from IEEE 519 [2] are shown in Table I. For Island grips the owner has flexibility in setting their own harmonic levels, generally they follow international standards to avoid any impact on other equipment connected to their network.

TABLE I
VOLTGE DISTORTION LIMITS PER IEEE 519

Bus Voltage V at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Plant system design engineer may specify to the ASD package vendor, who supplies the input transformer, the ASD and the filter, to limit harmonics at point of interface of the package to comply with Table I. The thinking may be that if all equipment packages individually within the plant comply with Table I, the plant, as the system, at its point of common coupling with the grid will comply with Table I. Such approach is incorrect and may lead to major rework in advanced stage of the project. First, the source of harmonics is current source, and voltage harmonics at the plant's point of common coupling depend on impedances external to the package, and how those impedances at different frequencies are excited by current harmonics. Second, the ASD package may connect to 132 kV bus for example, and per Table I the voltage THD at 132 kV is not to exceed 2.5%, but the plant's point of common coupling may be at different voltage level, for example 220 kV, and at 220 kV, per Table I, the THD is not to exceed 1.5%. In addition, as current harmonics propagate from lower voltage to higher voltage, the voltage harmonics may increase instead of decrease, they depend on impedance for specific harmonic frequency at a given point. It is important to consider harmonic analysis as overall and all-encompassing system analysis, rather than fragmentized calculation at isolated points.

When harmonic filter stages and configurations are selected for the project, the changes in the electrical system over the design life of the facility may affect operation of the filter. Some typical future-proofing measures are:

- oversizing the filter stages
- having resistors with taps to adjust damping factor
- having reactors with taps to adjust tuning points
- having capacitor sections with space to add more capacitors to increase MVAr rating and to adjust tuning point
- Flexibility in filter design to adjust tuning if filter stages are opposing each other
- Using oversized high pass filter stages with damping, or oversized C high pass filter stages with damping, tuned at lower order harmonics can ensure that if higher harmonics become present in the system, due to any future changes, those harmonics are handled by the existing filter. It should be noted that damping requires resistors as part of the filter design, and resistors take space and generate heat, so that may impact space requirements and HVAC requirements of the filter room.

When plant with large ASD s is connected to the Utility grid, the grid company usually requires minimum power factor at the PCC. This value depends on the grid, and it is typically 0.95 lagging, or higher. When harmonic filters are used, they are also contributing to power factor compensation. With LCI drives, this should be taken into consideration in deciding if any additional power factor compensation is required. When VSI drives are used, they may not have harmonic filters, or harmonic filters may be small. VSI drives with active front end can regulate the power factor at the input. The power factor with VSI drives with active front end can be unity. With VSI drives with diode front end, it should be analyzed if any additional power factor correction is needed to meet the power factor requirements.

B. Transients and Ride-Through Performance

Standard IEEE 1566 [6] specifies performance criteria for variable frequency drive systems. One of the criteria in the standard is that the drive system shall ride through and maintain control of the motor during an input power and/or control supply voltage sag down to 65% of nominal on one or more phases for a duration of 500 ms.

First, performance criteria need to be discussed with the ASD drive manufacturer to understand if the equipment complies with the standard, and to determine what disturbance the drive can withstand and achieve the ride through. Second, design engineer should perform transient simulations to determine upset conditions that may impact performance of the drive. Examples of upset conditions in the electrical system are faults on feeders supplying the facility (different types of faults, fault locations, fault durations), voltage sags, auto-reclosing, etc., and how those upset conditions are reflected on voltage at the input of the ASD. An ordinary lightning event that causes short duration self-extinguishable fault on the transmission line feeding the facility, followed by auto-reclosing, may be barely noticeable or un-noticeable to ordinary consumers, but it may cause trip of ASD s resulting shutdown of a multi-billion dollars facility.

Example of a single-phase fault on one of the two transmission lines feeding a large facility with ASD s, tripped after 100 ms, can cause voltage sag on the input bus to the ASD, as shown in Fig. 9.

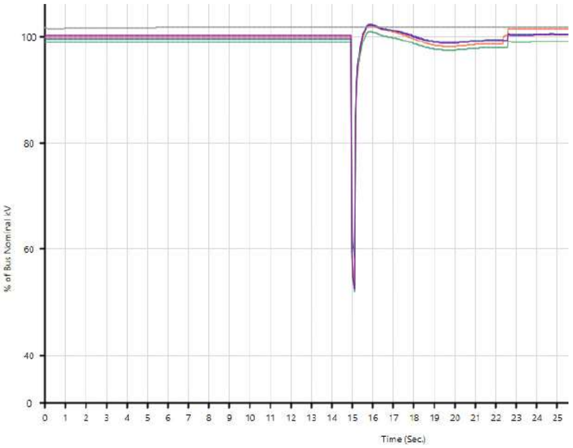


Fig. 9: Example of simulated voltage sag at the VFD input bus when one of the two parallel transmission lines experiences single phase to ground fault

Voltage drops to 54%, the trip of the faulted line occurs in 100 ms, after which the voltage recovers. If drive complies with IEEE 1566, it should maintain control of the motor during an input power and/or control supply voltage sag down to 65% of nominal on one or more phases for a duration of 500 ms. So, in this particular scenario, voltage dropped to 54% but for less than 500 ms. It is imperative to discuss with ASD drive manufacturers how the drive would perform and if it would survive such events.

An LCI drive in a motor-compressor drive application for example, would sense the voltage dip and adjust firing angles. The goal of the drive control is to keep DC link current constant and at the nominal value, as much as possible. So, the DC link current control and motor exciter control would try to keep sufficient torque to maintain the speed. The ultimate goal is to keep the speed high enough to avoid compressor surge. Drive manufacturers should perform simulations to determine if simulated voltage sag event would cause trip of the drive-motor-compressor train.

The ride-through will not be possible in all scenarios but understanding the boundary conditions sets the realistic expectations.

IV. COMPARISON OF VSI AND LCI TECHNOLOGY

A. 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 4th winding for the harmonic filter) whilst VSI (3-level and M2C) 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 is normally only relevant for an LCI ASD, is a passive system including container and HVAC system. Redundancy should be used for the cooling system. This is generally a very reliable system.

Adjustable speed drive

Including controls and cooling systems. LCI is a much simpler circuit and high reliability while all VSI circuits larger than 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 an LCI. Table II provides a comparison for a single thread system.

Motor (synchronous/induction)

Although induction motors IM are considered simpler in comparison to synchronous motors, IM have thousands of laminations and many bars the reliability and availability is very similar. This advantage is more than lost due to the far higher complexity and count of components of high power multi-parallel VSI. In Table III the LCI driven motor efficiency is lower due to higher harmonic content of the current waveform.

TABLE II

MTBF COMPARISON

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

B. Efficiency

Table III provides typical efficiency values. Higher efficiency for the transformer and motor are possible with higher cost components.

TABLE III
EFFICIENCY COMPARISON

Component	**LCI**	**VSI**
Transformer	99.2%	99.0%
Harmonic Filter	99.9%	-N/A-
Motor (sync)	97.9%	98.1%
ASD	99.0%	98.8%
System Total	96.05%	95.95%

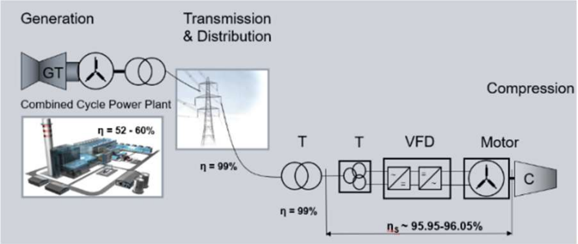


Fig. 9: Total generation to compression efficiency

Typical mechanical drive efficiency ~31%
Typical aeroderivative drive efficiency ~40%

C. CAPEX & OPEX

TABLE IV
CAPEX COMPARISON

Component	**LCI**	**VSI**
Transformer	100%	95%
Harmonic Filter	100%	0%
Motor	100%	95%
Excitation	100%	100%
ASD	100%	125%
System Total	100%	90-95%
For > 50MW+ systems.		

These values are typical and may vary 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.

D. EMISSIONS CALCULATION

	Eff'cy	Total Eff'cy	Power cost $/year	CO2 /day	CO2 Tax/y
Gas Turbine single cycle	39-43%	39-43%	$15M	+345t	$2.3M
Gas CCPP	54-63%	49-59%	$11M	+250t	$1.6M
Distribution	94-98%				
ASDS	96%				
Hydro electric	98%	89-93%		Base line	
Distribution	94.98%				
ASD S	96%				

Electric power cost	$50/MWh
Natural Gas CO2 emissions	0.413kg/kWh*
Carbon Tax (California)	$18t

*Based on US Energy Information Administration published emissions [8], other governments have different values.

E. FOOTPRINT & WEIGHT

TABLE V
FOOTPRINT COMPARISON

	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
ASD	19.2	33.2	27.2	39.4
System Total	**121.5**	**84.8**	**158.4**	**103.7**

TABLE VI
WEIGHT COMPARISON

	50MW (T)		70MW (T)	
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
ASD	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 ASD are in containerized housing which means the complete system dimensions for both solutions tend to be very similar (less than 10% difference) after the containerization is included.

Considering the above dimensions, the larger VSI drive is still a smaller system due to the elimination of a 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.

F. Safety

Most ASD manufacturers have capability to offer arc flash safe drives and safe torque off. SIL (Safety Integrity Level) ratings are becoming an increased request from the end users. Suitability for different SIL ratings is still being developed by suppliers.

G. Cooling

ASD's have two possibilities of cooling; either air cooled, or liquid cooled. Air cooled ASD's utilize either direct air cooling or indirect air cooling. Losses are in the range 1-1.5% which at 50MW = 500 - 750kW of heat load.

Direct air cooling

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 ASD. Fans are utilized to force the air through the designed air paths and plenums. Redundancy for the fans is recommended for increased reliability and availability. [7] 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. Typically, the hot air gets exhausted into the electrical room. Air-conditioning units may be required to absorb the heat from the room in order to maintain the room temperature within the required range. Alternatively, the hot air can be exhausted directly to the outside environment. In this case, it is essential to ensure that the housing room is capable of supplying clean air at the required air flow rating. However, if the heat load cannot be absorbed by the electrical room or directly blown outside air cooling system can be used. Direct air cooling is more suitable for low power or starting duty high power applications.

Indirect air cooling

Indirect air-cooling provides closed loop air cooling feature and requires an air-to-air or air-to-water heat-exchanger (A-A HEX or A-W HEX). An A-A HEX includes two separate air pathways known as loops. The internal loop accepts hot air out of ASD enclosure and returns cooled air back to the enclosure. The external loop absorbs cool air from the outside ambient and exhausst air after it absorbs heat from the internal loop. The ASD and the A-A HEX are typically installed back-to-back configuration in which the ASD sits inside the electrical room while the A-A HEX is installed outside. This cooling system is suitable for high power continuous duty applications in which the outside ambient environment does not reach very high temperatures.

An A-W HEX includes an air pathway as well as a water pathway. Water absorbs heat from the ASD's hot air when the air travels around the water pipes. The cooled air returns back to the ASD. This cooling method is suitable for continuous duty applications in which the process is capable of providing the cooling water.

Direct Water cooling

Cooling water is directly pumped through pipes to all the main heat loads within the ASD (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 shut down 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 +5ºC 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.

Manufacturers of LCI and VSI ASD's offer a variety of cooling options. Advantages and disadvantages of each option may be evaluated during the system design phase. The optimized solution may differ from a project to project due to variation of required power rating and site environmental conditions. Various methods of heat-load management of ASD's is discussed in [7].

H. Immunity to Unknowns in the Electrical System

With regards to immunity to the unknowns in the electrical system, this can be summarized as follows:

LCI drives

The line current of the 12-pulse rectifier does not contain the 5th or 7th harmonics, but it does contain the 11th and 13th harmonics, therefore a tuned LC series-resonant type filter is required, tuned to the 11th and 13th harmonics. External electrical network characteristics must also be considered in the filter tuning/design, and this may be affected by significant unknowns on future changes in the network.

VSI drives

Typically consist of multiple sub-modules (multi-level inverters) fed from multi-level/multi secondary transformer with phase shifts to mitigate any line side harmonics. Harmonic filters are generally not required for VSI drives, or in some cases a relatively small harmonic filter may be required, therefore impact from external network characteristics is limited.

V. SPECIAL APPLICATIONS

A. Starting applications

Starting of large AC motors is a practical challenge and requires total system design evaluation and implementation. Starting of AC motors across the line (also known as direct on -line) is the simplest method. However, at and during startup when the motor speed is zero or close to zero, there is little back EMF and high current is allowed to flow. This current, which is typically 6 to 8 times of the full load current, is known as inrush current and can last for several seconds. The inrush current results in various issues both mechanical and electrical. From mechanical point of view, the high inrush current generates high accelerating torque which stresses the motor shaft, drivetrain and connected load. From electrical standpoint, the high inrush current results in high power loss and thermal stress in motor winding and connecting grid cables. Additionally, the high current demand can result in voltage drop at the plant. This becomes a critical issue with large AC motors since the voltage drop may interfere with the required voltage regulation and impact other connected loads at the plant or nearby plants.

Various methods can be implemented to reduce the starting inrush current. Electromechanical starters (Wye-Delta starters) and autotransformers reduce the motor voltage during startup and limit the inrush current. However, the switching between different voltage levels results in transient current and torque that may exceed the direct on-line inrush current and torque. Solid-state reduced voltage soft starters (RVSS in short) can be utilized to increase the connected voltage gradually during startup. A soft starter eliminates transient current and torque. However, they can limit the starting inrush current to two or three times of the full load current.

To fully eliminate the starting current and thermal stress, ASD's can be used. A ASD controls both voltage and frequency and therefore, it can adjust the V/Hz ratio which determines torque. When connected to a ASD, an AC motor and connected load are not exposed to the sudden starting torque. Additionally, other electrical equipment connected to the line are not exposed to the voltage drop. When used as a starter, a ASD is utilized in a synchronized transfer configuration. Since the ASD remain in circuit only during startup, it can be sized in accordance with the required starting load which can be a fraction of the full load power, most technologies of drive should transfer from ASD start to fixed line operation in a bump-less torsion free connection. Additionally, the system can be configured for use of single ASD – multiple motor operation in which the ASD is used for starting of motors one by one. It, also, can be used for full operation and control of the last motor. This configuration is common when there is a large and a much smaller motors in the plant.

B. High speed applications

Advancements in design and manufacturing of high-speed electrical motors have made them a desirable driver for large compressors [11].

Traditionally, steam or gas turbines were considered as the driver. This industry trend, commonly referred to as turbine electrification, requires ASD's that can supply AC power at frequencies higher than nominal 50 or 60Hz. Operating an AC motor at higher speeds eliminates the need for gearbox. Overall, an electrically driven system has a higher efficiency and ensures higher reliability and availability. Additionally, the delivery lead-time is shorter for a ASD-motor package compared to a turbine. More importantly, electrical drivers eliminate the CO_2 and NO_x emissions at the plant. This advantage alone, may become a determining factor in assessing the feasibility of an operation.

The global drive to reduce CO_2 footprint increases the potential for electric ASD's 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 ASD's can be used as cost effective static frequency converters (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 voltage source converter (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, and control of the converter-based equipment with respect to other system components notably drive converters.

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 [9] – 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 PCC which is referred to as the short circuit ratio (SCR). While there are discussions about the exact details of 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.

VI. EXPERIENCE OF HIGH-POWER DRIVES

VII. CONCLUSIONS

By using electric drivers rather than gas turbines a significant reduction in CO_2 emissions can be achieved, with benefits in both operating costs and increased availability. The exact CO_2 gain is very heavily dependent on how green the power generation source is that powers the drive.

As a general rule owners and operators nearly always use VSI technology below 25MW and nearly always use LCI above 50MW. In the range of 25-40MW however 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. A 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), Electromagnetic Transient Modelling studies and controller testing are required to demonstrate controller stability and overall impact on the electrical grid.

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IX. VITAE

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