ADJUSTABLE SPEED DRIVE SYSTEM COMPARISON VSI AND LCI FOR HIGH POWER APPLICATIONS

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Abstract – The current development of adjustable speed drives has made voltage source inverter technology available to high power applications such as large axial compressors. Hence, the comparison of voltage source inverter technology to the traditional way of controlling large rotating equipment with load-commutated inverters is of interest. This paper compares the adjustable speed drive systems for shaft powers of 20 MW and more. A drive system includes the drive, the supply network connection and the motor behavior. System reliability and availability are the main drivers, while system efficiency and costs are an additional motivation for the technology positioning. In general, the simple scalability of the load-commutated inverter leads to maximum reliability, especially for very high power. Voltage source inverter technology comes with a higher degree of flexibility in terms of possible output frequencies, cable lengths and type of motor.

Index Terms — Adjustable Speed Drive System, VSI, LCI, High Power Application, Availability, Efficiency, Supply Network Behavior, Motor Behavior

I. INTRODUCTION

Since the adjustable speed drive (ASD) technology heavily influences system design, this comparison considers all of the relevant system components, which are shown in Fig. 1.

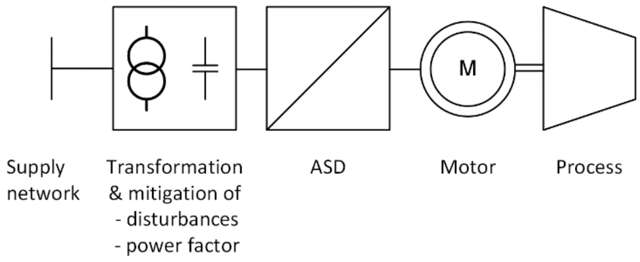

Fig. 1 Adjustable speed drive system

A. Supply Network

The supply network represents the network impedance as a function of frequency, which includes short-circuit capability as well as requirements regarding harmonic distortion and power factor.

B. Transformation and Mitigation

Each ASD system has a building block called transformation and mitigation as shown in Fig. 1. This block contains a dedicated input transformer, which is used to adapt the network supply voltage to the adjustable speed drive input voltage. The transformer also isolates the drive from the feeding network and restricts short-circuit currents. For higher-pulse applications, the 6-pulse bridges are combined with phase-shifted transformer windings for harmonic mitigation. Depending on the project and technology, the block contains a filter system to reduce network harmonic distortion and/or to improve the power factor.

C. Adjustable Speed Drive

Key selection criteria for high power ASD technology are safety, reliability, availability and maintainability at a low price. Safety and reliability are defined by the design of the product. For the highest level of safety and reliability, high voltage thyristor-based semiconductors are chosen. For voltage source inverters (VSI) and load-commutated inverters (LCI), high voltage integrated gate-commutating thyristors (IGCT) and phase-controlled thyristor (PCT) are the respective state-of-the-art technologies. Both of these power semiconductors are press-pack (hockey puck) type devices that provide arc flash safety due to their robust, ceramic housing and installation in a stack under pressure. These semiconductors enable the highest power per single device, which results in a low component count and high reliability. A further benefit is low conduction losses, which result in high efficiency. Injection-enhanced gate transistor (IEGT), which are high voltage semiconductors, are also used in the same applications as IGCTs. Furthermore, low-voltage IGBT module based topologies *i.e.* modular multi-level converter (MMC) are proposed for the highest power segment (above 20 MW).

The basic LCI topology is similar for all manufacturers as presented in Fig. 2, which shows a 6-pulse system; however, other configurations are common and are available. A system always has a DC-reactor to decouple the network from the motor side. Only synchronous motors can be driven by an LCI since the back-electromotive force (EMF) is used to commutate the inverter. Drive vendors are able to replace foreign brand LCIs and continue using the existing input transformer, power cable and motor, which is very difficult for VSIs due to the variety of different topologies. This is an advantage for the LCI,

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keeping in mind the shorter life cycle of the ASD compared to the other system components.

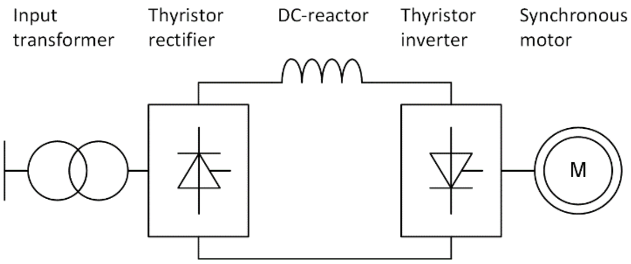

Fig. 2 Basic LCI topology (6-pulse system shown)

For more information on the most commonly used VSI drive system topologies see [1] and [2]. Many characteristics of a VSI are common, regardless of the topology, *e.g.* each VSI is self-commutated, *i.e.*, uses power semiconductors that can be turned off, and can drive both synchronous and induction motors. Furthermore, the decoupling between the line and motor sides is done via a DC-link capacitor, which is charged by a diode rectifier.

D. Motor

Depending on requirements like shaft power, speed and efficiency together with the capability of the motor supplier a synchronous or induction motor can be chosen. Both types of motors can be used in high power ASD applications. In general, synchronous motors are selected due to better efficiency, whereas induction motors are the simpler solution with a lower investment cost.

In this paper, high power positioning of technologies is derived as shown in Fig. 3.

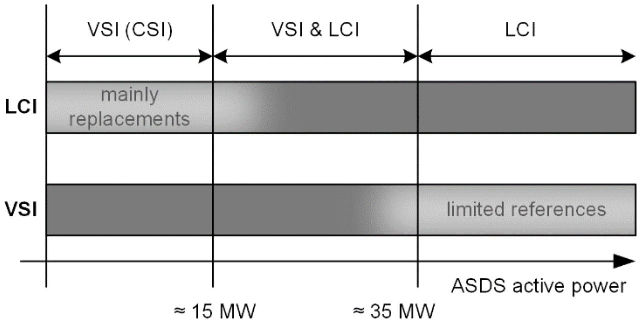

Fig. 3 General positioning of technologies for high power ASD applications

For an extensive power range, both technologies are available. The motivation for the technology positioning is reliability, which also assumes experience and available reference projects. In addition, the project cost and the unavailability or unprofitability of induction motors for very high power are considered.

II. COMPARISON OF LCI AND VSI SYSTEM

A. Supply Network Related

Performance item	**LCI**	**VSI**
Line side harmonics	Engineered solution	
Supply power loss ride-through	++	+
Power factor correction	Required	Not required

1) Power factor: For high power ASD applications, a diode bridge is considered for most VSI topologies. For a diode rectifier, the power factor is given by the inductive direct voltage regulation that depends on the commutation time, which in turn depends on the actual commutation voltage, load current and commutation impedance. A small network/transformer impedance, high voltage level and small currents lead to a better power factor. The power factor also depends on the pulse-number of the rectifier since the impedances are changing. The higher the pulse-number the better the power factor. In general, the power factor is higher than 0.95 for diode rectifiers in a properly designed system for any operating point. Active rectifiers can also be used on the network side for VSI drive systems. Active rectifiers are needed in case the process requires regenerative operation. With active rectifiers, the power factor can be controlled to any value but its reference is usually set to unity. In this paper, VSI with an active frontend is not considered, assuming that for the target applications regenerative capability is not needed (*e.g.* large compressors). Typically, power factor correction equipment is not required for VSI systems. More information can be found in IEC/TR 60146-1-2 [3].

For LCI drives, the power factor is dependent on the operation point and the way the system is designed. The network power factor is proportional to the ratio of motor and network voltage. The motor voltage increases proportionally to the speed and the network power factor increases accordingly. Due to network power factor requirements and speed range, a compensation system is often required for the LCI. Measurements of a LCI compressor system in commercial operation using modern control algorithms show massive improvements compared to traditional methods. With 92% speed, 82% torque and 100% network voltage, a power factor improvement from 0.83 to 0.93 was achieved. More details can be found in [4].

Motor speed and load torque also influence the power factor when a compensation system is used. For the LCI and LCI with power factor compensation areas indicated in Fig. 4, a quadratic load curve was assumed.

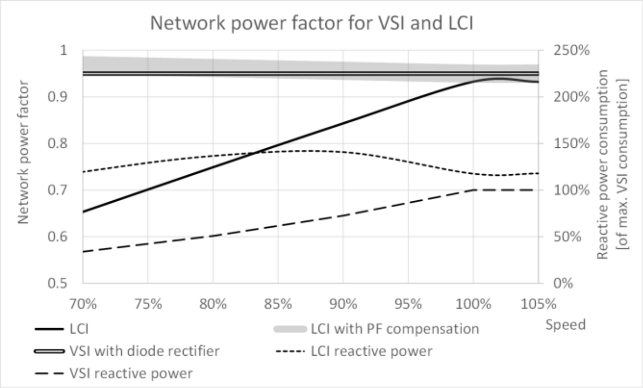

Fig. 4 Comparison of network power factor VSI / LCI

2) *Harmonic distortion:* In general, ASDs are non-linear loads that create current harmonic distortion. This distortion depends on the inductive direct voltage regulation for VSI and LCI. It also depends on the firing angle of the rectifier, which can be considered as zero (α = 0°) for diode bridges. Current harmonics are calculated as defined in IEC/TR 60146-1-2 [3]. It can be seen in [3] that there is no linear relationship between the firing angle and amplitude of the harmonic current. Nevertheless, the amplitudes tend to get bigger by increasing the firing angle. These calculations are supplier independent.

Irrespective of VSI or LCI technology, the harmonic distortion can be decreased to a certain extent by using a higher pulse number for the rectifier. Practically, a 24-pulse or 36-pulse solution is feasible but depends on the accuracy of the transformer phase shift (half a winding cannot be done). Higher pulse numbers are not practical because the transformer vector group cannot be realized with the required tolerances. In addition, the impact of the higher frequency harmonics can be neglected at one point.

Fig. 5 shows the total current demand distortion [TDD(i)]. The current harmonic distortion is then compared to the full load current (100%).

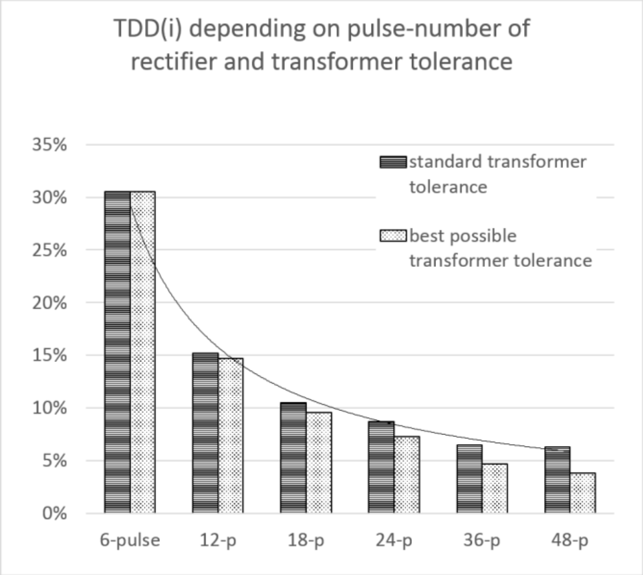

Fig. 5 Current harmonic distortion depending on rectifier pulse number and transformer tolerance

The values in Fig. 5 are considered the worst case for diode or thyristor rectifiers and are more acceptable depending on the inductive direct voltage regulation (see section II. A. on power factor and [3]).

For VSI and LCI, pulse numbers of 24 and higher are possible. In order to reduce complexity, 24 and 36-pulse rectifiers are preferred. Fig. 6 shows common network configurations. Configuration 1 represents the solution when harmonic filtering and power factor compensation are not required. This configuration is used for both VSIs and LCIs. For LCIs, the operation range must be small and close to the nominal speed or the power factor is compensated by other means. With regard to harmonic distortion, the performance of a 24-pulse solution in a standard environment is sufficient to comply with international standards (*e.g.* IEEE 519-2014 [5], IEC 61000-2-4 [6]).

If power factor compensation for the LCI is required, the filter system can also be used to mitigate harmonic distortion. In this case, a 12-pulse solution is preferred in order to reduce complexity. The size of the filter (Mvar rating) is determined by the required network power factor and the operation points of the process. This filter can easily cope with the harmonic distortion that is created by a 12-pulse rectifier to ensure compliance with the previously discussed grid standards. Configuration 2 or 3 as shown in Fig.6 can be used to compensate the power factor and reduce harmonics for an LCI system.

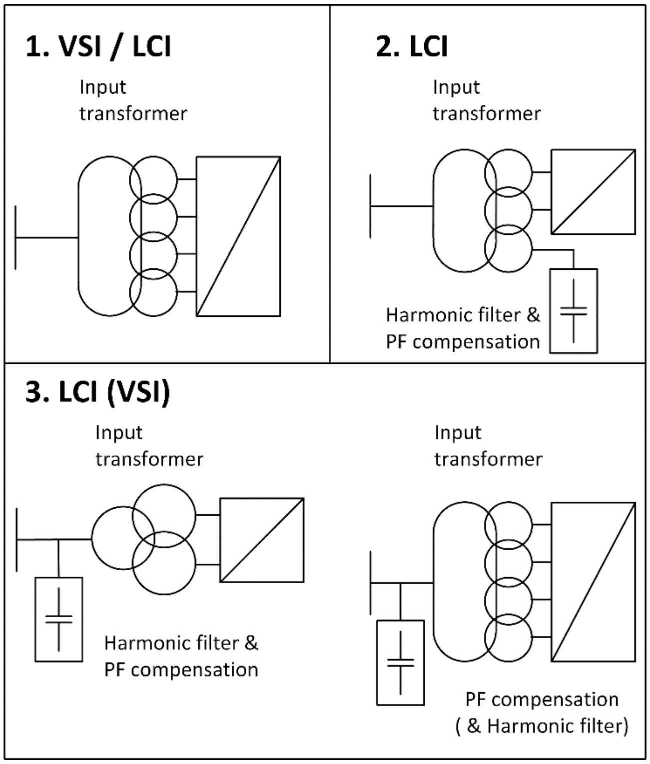

Fig. 6 Network configurations of VSI and LCI in order to reduce harmonic distortion and compensate the network power factor of the rectifier

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A general recommendation for the best configuration cannot be given as all three have advantages. In terms of simplicity, easy system integration and robustness, configuration 2 is preferred. In this case, the filter is decoupled from the network. This means a protection against overvoltage, which is achieved by the additional impedance and the earthed screen between the primary and secondary/tertiary winding of the input transformer for capacitive decoupling. Some transformers are equipped with dedicated overvoltage protection, *e.g.* varistors. Connection of the filter system to the tertiary winding makes this configuration very robust against changes of the network:

a. *Short-circuit capability:* A decoupled filter system de-tuned only very slightly in case the short-circuit capability is changed.
b. *Additional harmonic sources:* Later installation of other non-linear loads cannot overload the filter system if it is decoupled
c. *Network configuration:* In general, other changes such as introducing more transformers, motors, replacement of high voltage cable and others lead to a change in the network impedance and de-tune a filter system in case it is not decoupled.

In addition, the harmonic filter and power factor compensation system is controlled/switched depending on the ASD operation only. The rated voltage of the filter components can be chosen independently of the supply network voltage. As previously indicated the interacting system is small and does not include the network. A disadvantage is that the filter system of configuration 2 cannot be used to damp a possible network parallel resonance, which can be done with configuration 3. Configuration 3 can also lead to a simple and robust system when the network configuration is stable and the network voltage is not too high (*e.g.* < 22 kV). Configuration 3 is also an interesting option if several ASD systems are running at the same operation point. In such a case, a quasi-system can be created by phase shifting the input transformers, which can be used to simplify the filter.

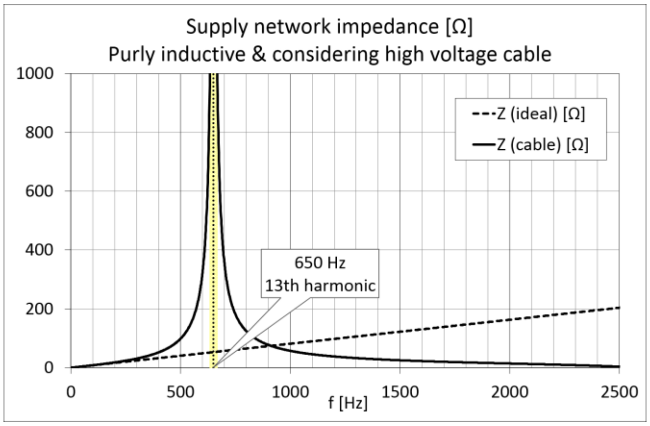

Fig. 7 Example of supply network impedance on 33 kV and the possible impact of high voltage cable

Regardless of the topology or the pulse number of the input section, the harmonic distortion must not be neglected for high power applications. As previously mentioned, the ASD is a source for current harmonics. The voltage harmonic distortion is the product of current harmonics and the network impedance that is frequency dependent. The voltage distortion (V_n) can be calculated using (1):

$$V_n = I_n \cdot \left|Z(j\omega)\right| \tag{1}$$

where

$Z(j\omega)$	Complex network impedance
V_n	Voltage harmonic distortion of the order n
I_n	Current harmonic distortion of the order n
n	Harmonic of the order n

It is not sufficient to calculate the voltage harmonic distortion based on a purely inductive network [Z (ideal)] as shown in Fig. 7. If a high voltage cable is used, the parallel resonance of the supply network can shift to low frequencies. In the example that is presented in Fig. 7 (Liquid Natural Gas (LNG) project with island grid), the first resonance frequency is located at 650 Hz, which is the 13th harmonic. The 13th current harmonic is injected by any ASD that uses diode or thyristor rectifiers. In such a case, even a small 13th harmonic current, which complies with any standard, can lead to a significant voltage distortion. Fig. 8 shows a measurement where the network was assumed purely inductive despite the installation of several hundred meters of high voltage cable.

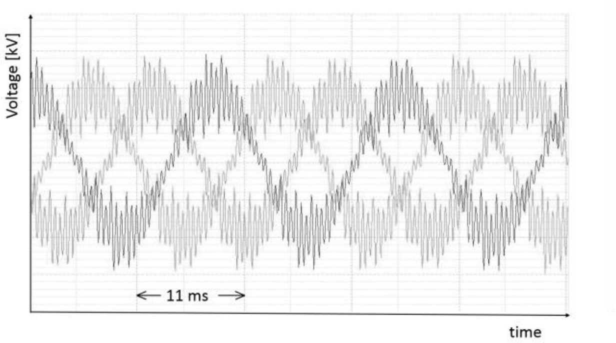

Fig. 8 Measured phase-to-phase voltages on a 33 kV bus with an undamped parallel resonance

In this example, a parallel resonance was located at 2350 Hz (47th harmonic), which is a characteristic harmonic for a 12, 24 or 48-pulse system regardless of the ASD topology. The 47th harmonic current is injected and led to a voltage distortion of > 50% for the 47th harmonic. The system was not sufficiently damped for the network configuration. These problems must be solved irrespective of the type of drive, for example, by installing an un-tuned capacitor bank or by reconfiguring the network.

3) *Supply power loss ride-through:* Both VSI and LCI based ASDs can ride-through supply voltage disturbances using different methods.

A drive shut-down can be prevented even during main power outages of multiple seconds by implementing advanced drive control software. The maximum sustainable duration of a power outage depends on the load system, the machine and the actual operating point before the power outage. A VSI can provide partial torque when the network voltage level is at 70-80%. When the DC bus voltage becomes too low, the drive enters the ride-through mode in which the motor is used as a generator to compensate for converter internal losses. The energy stored in the rotating system of the motor and the load is used to keep the DC bus charged. Fig. 9 shows the ride-through behavior. Additional information can be found in [7]. For synchronous motors an operational excitation system is assumed.

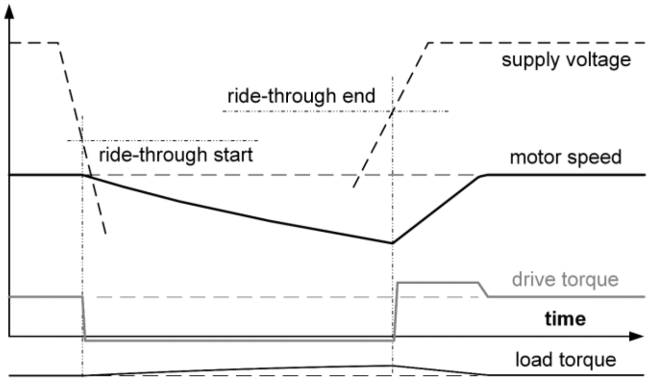

Fig. 9 VSI drive system behavior when entering and leaving ride-through mode

The ride-through capability of an LCI is superior to that of the VSI. It is more robust due to its active-frontend and because the decoupling of the motor side does not rely on a capacitor bank. An LCI can provide partial torque down to a network voltage level below 50% using state-of-the-art control methods. Model Predictive Control, which is an optimization-based control method, keeps the driven equipment in a healthy operation range even longer. An estimation of residual power during main supply power dips of a 41.2 MW export compressor system driven by an LCI is presented in [8], Fig. 10, [9] and [10]. Network configuration 2 from Fig. 6 with a network voltage of 132 kV is used.

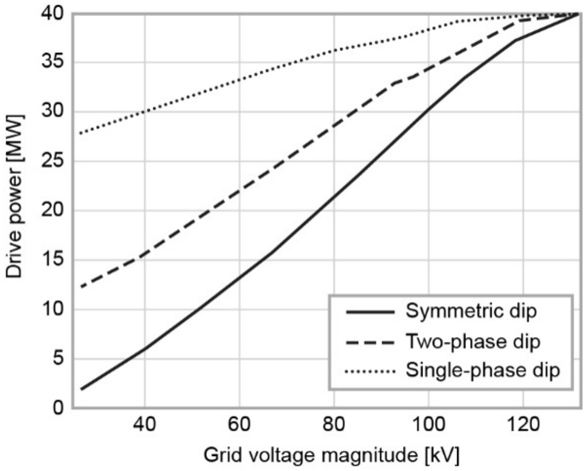

Fig. 10 Estimate of the residual power during voltage dips

In case the network voltage drops below approximately 50%, the current, power and torque are reduced to zero. It does not need energy from the rotating equipment. The LCI measures the network voltage continuously and reaccelerates the load in case the supply recovers.

B. Motor and Load Related

Performance item	LCI	VSI
Additional temperature rise due to current harmonics	Yes	Yes (except multilevel)
Torque excitation	Possible (system design required)	
Damping of mechanical resonances	First mode	Yes
Dv/dt & common mode to be considered	Yes	Yes

1) Current harmonics: Current harmonics produced by the ASD create extra losses in the motor, which result in an increased temperature rise. For LCI operation standard motors are normally not used. Traditionally, a synchronous motor with two, 30° electrically phase-shifted stator windings, is fed by a 12-pulse LCI. The stator windings must be designed for 6-pulse operation, which means a TDD(i) > 25%. The VSI creates current harmonics as well. The total leakage reactance for an induction machine or the subtransient reactances of a synchronous motor have a significant influence on the resulting motor TDD(i).

$$X_\sigma = X_{\sigma s} + X'_{\sigma r} \qquad (2)$$

$$X'' = \frac{1}{2}\left(X''_d + X''_q\right) \qquad (3)$$

where

X_σ	induction machine total leakage reactance
X''	synchronous motor subtransient reactance

Different VSI topologies influence the additional temperature rise. The impact of the reactance and VSI topology on the heating at the motor field-weakening point are presented in Table I. Note: abbreviations in Table I are, Cascaded H-Bridge (CHB), 3-level-neutral point clamp (3L-NPC), and Modular multi-level converter (MMC):

TABLE I
TYPICAL IMPACT OF MOTOR REACTANCE AND VSI TOPOLOGY ON THE HEATING AT FIELD-WEAKENING POINT

Topology	CHB	3L-NPC	MMC
Reactance > 23%	0 K		
20% ≤ Reactance < 23%	2 K	5 K	0 K
18% ≤ Reactance < 20%	5 K	10 K	0 K
Reactance < 18%	> 5 K	> 10 K	0 K

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The numbers in Table I do not consider an output sine filter. Sine filters are normally not used for high power applications because the motors are built for operation with a specific VSI and during the design process, the possible current harmonics are considered. In case a sine filter is used, there is no additional temperature rise. A sine filter is considered for very long power cable (*e.g.* 10 km) between ASD and motor.

2) *Pulsating torques:* Torsional oscillation of the driven shaft has always been a concern with ASD for both LCI and VSI. Although the amplitudes of such pulsating torques may be small compared to the driving torque, they can excite resonances when their frequency coincides with the natural frequency of the shafting (crossing). Literature is available for both LCI [11], [12], [13] and VSI [14], [15] and topology independent [16].

Demanding systems with high torsional stress on the shaft may require an advanced design process. Technical risk can be eliminated by designing mechanical and electrical components as a string. The output of such an electro-mechanical control system design is:

a. Control philosophy (start-up, overspeed, etc)
b. ASD parametrization and commissioning
c. Detailed torsional data for the selected control philosophy, maybe models

State of the art tools to optimize large mechanical trains and mitigation measures like torsionally resilient couplings are available. Modern modelling and simulation give new insight. Based on that, torsional optimized ASD control is developed. The following kind of mechanical excitations are to be considered:

a) Direct excitation due to converter switching: The converters are different in the way in which they produce harmonics and how they directly excite resonances. In general, VSI has smaller amplitudes of 6th and 12th harmonic than the LCI, but they are still present and have to be dealt with. In order to reduce the pulsating torques for LCI driven equipment, a motor with two winding systems has been used since the beginning of ASD development. The pulsating torques can be of different types. The integer pulsating torques have frequencies, which are integer multiples of the machine frequency and which are caused by the machine-side inverter

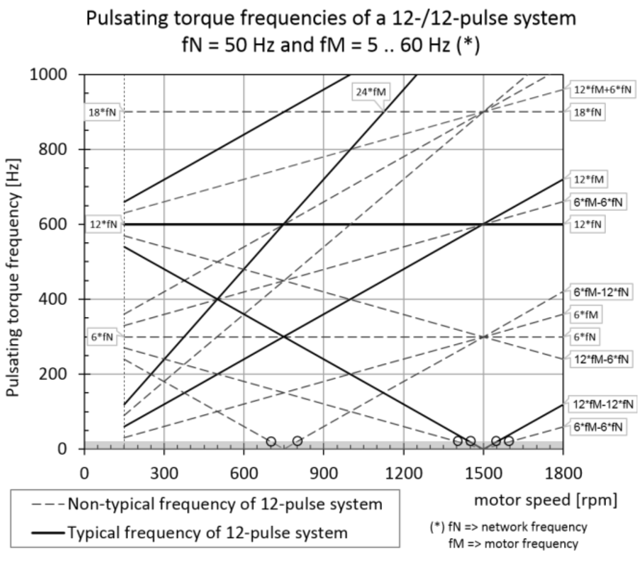

Fig. 11 Pulsating torque frequencies for an LCI driven 4-pole motor with network and motor frequency of 50 Hz

The non-integer pulsating torques have frequencies that are non-integer multiples of the machine frequency. They are generated by the rectifier and are transferred via the DC link to the machine side. The frequencies of the pulsating torques are predictable and can be presented in a Campbell diagram as shown in Fig. 11 and [17]. Different pulse numbers for the input and output converter can help when the line and motor frequency are identical. The gray area in Fig. 11 indicates frequencies below 20 Hz, where the first mode of large compressors is expected. In the past, torsional interaction was avoided by skipping critical speeds with crossings (indicated with circles). Control algorithms (*e.g.* sequence control for the LCI) can help to avoid crossings as well. For VSI, a general statement cannot be given as the pulsating torques are heavily dependent on topology and control method.

b) Closed loop stability: The converters dynamic capabilities (*i.e.* their control bandwidth) are different. LCI has approximately 30 Hz linear bandwidth for a 2-pole / 60 Hz motor. The bandwidth of a VSI is much higher, which is good, but needs to be managed accordingly. In order to damp the first mode, a control bandwidth of 20 Hz is sufficient. VSI and LCI have different critical speeds, but both must be considered equally in a closed-loop.

c) *Strong control modulation:* Control action can also be interpreted as pulsating torque. This phenomenon has not been fully addressed scientifically. It is independent of ASD topology and is caused by the control algorithm and settings.

2) *High change in voltage over time (dv/dt):* High dv/dt can exist even though the harmonic content in the current is low. The high dv/dt is a stress for the insulation system of the motor, irrespective of whether it is driven by VSI or LCI. The motor insulation system must be designed to meet the maximum dv/dt and peak voltage requirements. Depending on the VSI manufacturer, the switching frequency of a single power semiconductor is 200 Hz and higher, whereas the switching frequency for the LCI is given by the electrical frequency of the motor driven (*e.g.* 50 or 60 Hz). Thus, the stress on the insulation is smaller when using LCI technology due to lower switching frequency. Common mode voltages are present in VSI based systems. Its magnitude is depending on the grounding concept and the output filter configuration. The common mode voltage for LCI systems is insignificant because the output voltage is defined by the synchronous motor. This also applies to the line side. Anyway, mitigation is standard for large motors (e.g. insulated bearing and shaft grounding).

3) *Synchronous motor power factor:* Because a VSI is self-commutated, the motor power factor is controllable to unity or other values. Motor operation with the unity power factor is not possible when it is driven by an LCI. The motor power factor [PF(mot)] is usually > 0.9 (over excited), depending on the operating point and motor characteristic. State-of-the-art control algorithms helped to increase the power factor from 0.83 to 0.97 for the system mentioned in section II. A. and [4]. In general, line and motor side power factors are independent due to the DC link, which decouples both.

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C. ASD Scalability

Performance item	**LCI**	**VSI**
Series connection of semiconductors	**Yes**	(Yes)
Series connection of inverters	Yes	Yes
Parallel connection of inverters	No	Yes
Parallel connection of ASD systems	Yes	Yes

In order to reach high power, upscaling is necessary. In general, there are four directions to upscale an ASD. Series or parallel connection of the following components is required:

1) Semiconductors: Series connection of semiconductors means that there are no changes in the topology or in the control scheme of the ASD. Special, one-of-a-kind systems are avoided for secured maintainability and serviceability. Redundancy on the component level is possible. In order to increase the power and voltage for an LCI, semiconductors (thyristors) are connected in series. Thyristors are extremely robust and therefore an “n + 1” redundancy is not required, but can easily be provided.

2) & 3) Inverter: Series or parallel connection of inverters means that the topology is changed. A multilevel inverter is introduced for series connection, which requires complex input transformers. However, the output waveform can be optimized by using control schemes with higher complexity. VSI based topologies use parallel connected inverters to increase the power and current rating of the ASD.

4) ASD system: Parallel connection of ASD systems means that standard size products can be used. However, it increases the complexity of the installation, control and protection scheme. Such a system can offer redundancy on an ASD system level, which is only useful when the systems are oversized or the process tolerates reduced power. LCI and VSI based topologies use parallel-connected ASD systems to increase power.

D. Cost and efficiency

Performance item	**20 MW**		**50 MW**	
	LCI	**VSI**	**LCI**	**VSI**
Cost	+	++	++	+
Efficiency	**neutral**		++	+

Cost and efficiency are comparable for VSI and LCI. For LCI, many measurements of efficiency are available as a result of back-to-back testing. For VSI test results with lower power, the results have been scaled for a 50 MW comparison. The evaluation of the efficiency is performed in accordance with [18], which refers its efficiency evaluation to the mechanical output power of the drive system.

$$\eta_{tot}\left[\%\right] = \frac{P_{sh}}{P_{sh} + L_{tot}} * 100\% \qquad (4)$$

where

η_{tot}	efficiency of the ASD system
L_{tot}	total losses of the ASD system
P_{sh}	mechanical output power

Table II compares ASD systems that use synchronous motors. The presented values are based on full load back-to-back or string tests, which were performed as part of system projects between 2005 and 2015. For some of the projects, system efficiency has been guaranteed. The system components are:

a. ASD transformer
b. Harmonic filter and power factor correction for LCI (very small impact – approximately 0.05% of shaft power – and therefore included in the transformer)
c. ASD (LCI is by definition a four-quadrant ASD. It can be used for regenerative operation and therefore the back-to-back testing possibility is inherited. VSI is available for four-quadrant operation, but is not considered in this comparison because it is normally not required for high power applications. The VSI efficiency for four-quadrant operation would be significantly worse and have an increased complexity.)
d. Synchronous motor
e. Auxiliaries (cooling pumps, control power and excitation supply …)

TABLE II
COMPARISON OF SYSTEM LOSSES – VSI & LCI FOR 20 AND 50 MW

Shaft power	P_{sh}	20 MW		50 MW	
VSD topology	-	VSI	LCI	VSI	LCI
Transformer efficiency (incl. filter)	η_T	99.0%	99.0%	99.4%	99.4%
VSD efficiency	η_{ASD}	99.0%	99.2%	99.0%	99.3%
Synchronous motor efficiency	η_M	97.4%	97.4%	97.6%	97.6%
Auxiliary consumption	P_{aux}	20 kW	20 kW	50 kW	50 kW
VSDS efficiency	η_{ASDS}	95.4%	95.5%	96.0%	96.2%

For the 20 MW system efficiency, the higher switching losses of a VSI are balanced with additional LCI losses due to the non-unity power factor and harmonic filter. For the 50 MW system, the LCI has the advantage, as it is simply scalable on semiconductor level. The power increase is achieved by an increase of system voltage; parallel connection of converters is not required. The system currents are stable compared to a 20 MW solution.

E. Physical size

Performance item	20 MW		50 MW	
	LCI	**VSI**	**LCI**	**VSI**
Physical size	**neutral**		**++**	**+**

A general comparison of VSI and LCI that is independent of the supplier and arrangement of system components is not possible. Some suppliers only optimize the footprint to a certain extent for a high power ASD. Simplicity and therefore reliability has the highest priority and must be balanced with the physical size. It is incorrect to say that the physical size of the system depends on the converter topology. Furthermore, frame sizes have other limits, which means “sweet spots” are different for different manufacturers. If an LCI system includes a filter system, the size depends on whether it is placed outdoors or indoors. Iron-core reactors are used indoors, which makes the arrangement compact, whereas air-core reactors are commonly used outdoors. High power VSI arrangements often cannot be realized with just one transformer, which increases the equipment size in comparison with an LCI with filter system, where usually only one transformer is used. For very high power VSI-ASD systems that must be used in parallel, which gives a clear disadvantage compared to the LCI.

F. Reliability and availability

Performance item	20 MW		50 MW	
	LCI	**VSI**	**LCI**	**VSI**
Reliability	**++**	**+**	**++**	**-**

As explained in [19], Mean Time Between Failure (MTBF) and other reliability figures should be used with care. They are relevant when comparing different layouts in the same drive; however, they cannot be used to rank the reliability between different suppliers because of the different approaches that were taken to obtain the numbers. They can be used to compare two different systems if the same company/person that has used a uniform approach in both cases makes the comparison. Although it is impossible to deliver a supplier independent comparison of reliability figures between VSI and LCI based system topology, it can be said that the ASD is the most complex system component. Therefore, the following considerations focus on the ASD. A drive supplier compares the failure rate of the topologies based on [20]. The advantage is that the concept is simple and predictive. The drawback is that the assigned failure rate for each component is based on estimates, which lead to many degrees of variance. All components without redundancy are considered in a logical series configuration and a component failure is expected to lead to a system failure. MMC is considered including cell redundancy, which is needed for compensating the disadvantage of requiring a large amount of power components.

TABLE III
RELATIONSHIP OF RELIABILITY BETWEEN VSI & LCI FOR 20 MW AND 50 MW

Shaft power	20 MW		50 MW	
ASD topology	VSI	LCI	VSI	LCI
Reliability	1.0	1.1	1.0	1.4

Table III shows the comparisons of two independent systems (20 & 50 MW) where the VSI reliability is used as a reference for both (one per unit). The reason the LCI has the advantage for 20 MW is its simple topology. The LCI maintains its advantage at higher power because of its scalability requiring fewer additional components.

Based on field experience, only about 25% of trips are related to the drive itself. Out of this 25%, 90% are related to the implementation and design of the converter and the remaining 10% are related to the MTBF of the components. Thus, only about 2.5% of all trips are related to component issues. The most important factor is good system engineering, including network integration, mechanical-electrical interaction, and system protection. In addition, continuous improvements and high maturity of equipment lead to high availability.

As stated in [19], an ASD with a requirement to operate for years without a shutdown, be it scheduled or un-scheduled needs a redundancy on the macro level, *i.e.* a complete ASD or redundant converter. There are many possible ways to realize full drive redundancy. However, further explanations are based on following boundary conditions:

a. The process allows zero torque for < 150 ms in case of an ASD failure.
b. This requires ASD and if applicable excitation system (exciter converter) redundancy.
c. Both ASDs are totally independent, including control and cooling, and are rated to run 100% motor power.

Due to the differences in the protection concepts of VSI and LCI as described in section G, the LCI can have the main circuit breaker on the secondary side of the input transformer. This means ASD input transformer redundancy is optional and does not influence the switchover performance for LCI. Nonetheless, a system as presented in Fig. 12 is assumed.

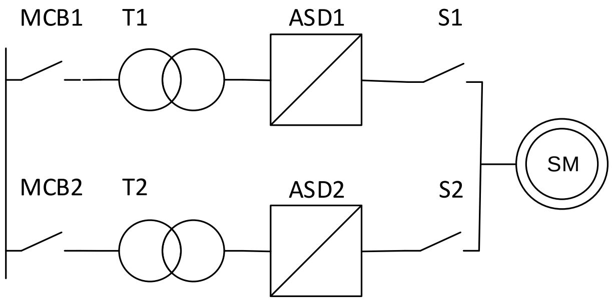

Fig. 12 Overview of a redundant ASD system (incl. redundant input transformers)

A network filter is not considered as critical ASD systems are designed to provide full torque without it. One filter system is sufficient.

The LCI topology is superior because decoupling of system 1 and 2 is achieved by thyristors in blocking state, decoupling is independent on the main circuit breaker (MCB) and output switches (S1/2). In addition, charging of the DC-link is not required and the MCB can be switched on anytime. With S1/2 closed and the inherent line and motor voltage measurements, the LCI is always aware of the status of the motor (and network). With the zero-current feedback of the faulty system, the control can be released immediately.

G. Safety

Performance item	LCI	VSI
Safety	++	+

Many safety functions (*e.g.* functional safety, or arc fault protection, which are covered for power electronics converters in [21]) are available and topology independent. However, the complexity that is required to achieve a high level of safety functions in general can be different. A VSI solution includes a passive diode rectifier on the line side and capacitors to decouple from the motor side. An LCI solution is based on a thyristor bridge and a reactor for decoupling as shown in Fig. 13.

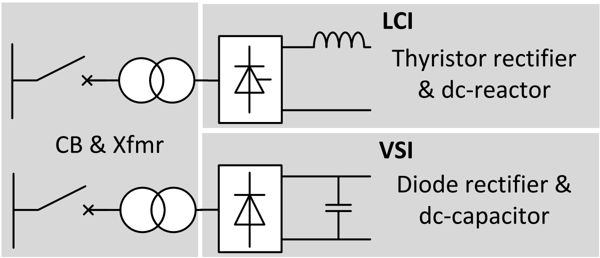

Fig. 13 Input section of a VSI and LCI adjustable speed drive (principle)

The protection concept of the VSI solution is very closely linked to and depends on the circuit breaker due to the inability to block/switch off current. The LCI system is dimensioned in a way to be able to force the current to zero in a short-circuit case because of the high, non-repetitive surge current capability of modern thyristors. In addition, the circuit breaker can be switched on without the risk of a high-voltage connection to a discharged dc-link, which leads to damage for VSI.

VSI topologies based on IGBT modules inherit the risk of plasma leakage in case of failures. Press-pack semiconductors are more robust and preferred for high-power applications.

III. CONCLUSIONS

As shown in earlier publications [22] and [23] and despite of the availability of more variants of VSI solutions, neither VSI nor LCI can be shown to be superior to the other for high power applications in general. The well-proven and simple LCI topology leads to highest reliability, whereas VSI based drives can lead to more flexibility in terms of system integration. With a model predictive control algorithm for the LCI, the gap regarding dynamic performance is closing.

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