

# Variable Frequency Drives – a Comparison of VSI versus LCI Systems

## Introduction

TMEIC is a leader in the innovative design and manufacture of large ac variable frequency drive systems. TMEIC has been very active in developing the most advanced high capacity Voltage Source Inverter (VSI) drives, large enough to compete with Load Commutated Inverter (LCI) drives. This study compares the strengths and weaknesses of TMEIC's VSI drives with competitive LCI drives.

## LCI & VSI Comparison Summary

The LCI drive has a long history and its advantages and limitations are well understood. It is simple and reliable, but requires careful attention to ac power system issues related to harmonic currents and reactive power. It also demands specially designed motors with low reactance, and must work with harmonic heating and air gap torque harmonics.

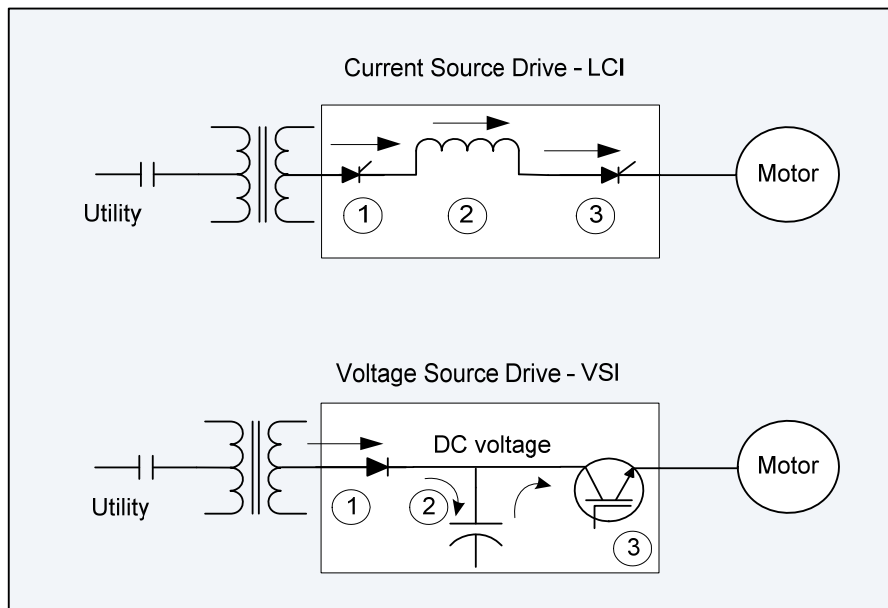


Figure 1. Simplified Block Diagram of LCI and VSI Drives

Medium voltage VSI drives have progressed significantly in the past 15 years, and are now the standard practice in such demanding applications as main drives in metal processing, which require high overload with very high performance up to about 20 MW. The development of high power, controllable semiconductor devices and pulse width modulated (PWM) control has made VSI drives both possible and suitable for broader applications such as high power drives for large compressors and blowers. The resulting VSI designs now provide many advantages over their LCI predecessors, including low power system harmonics, low reactive power demand, and low torque pulsations in the motor air gap and shaft.

## 1. Summary Comparison of VSI versus LCI Technology & Systems

The following table summarizes the differences between VSI drives and LCI drives. These will be discussed in later sections.

	VSI System	LCI System
Line Current Total Harmonic Distortion	2 % THD Harmonic filter is not required	Up to 12 % THD Harmonic filter is required
Air gap torque ripple	0.5 – 1 % Standard mechanical system design is possible	Up to 7 % Special mechanical system design required for torque pulsations
Input Power Factor	Greater than 0.95 PF correction equipment is not necessary	0.5 – 0.92 Power factor equipment (capacitor) is necessary
Power system stability	Stable	Delicate
AC power disturbance	Ride through or Automatic restart	Can ride through
Reliability, MTBF	28 years Proven technology	Greater than 10 year MTBF Proven technology
Repair time, MTTR	About 0.5 hours	About 2 hours
Equipment size	Standard VSI drive lineup	Much more space required for LCI lineup, Harmonic Filter, PF correction, and Reactor
Motor	Independent from converter	Special design. Strongly affected by converter and harmonic heating
Motor types	Induction or Synchronous motor	Synchronous motor only
Motor power and Drive	100 MW, 4 banks TMdrive-XL85	120 MW
Drive output voltage	XL type VSI up to 7.2 kV; MVG type VSI up to 11 kV	Up to 11 kV

## 2. Supplier Capability

Recent semiconductor and VSI developments have produced high power VSI drives, with a single channel power level up to 30 MVA, as shown in Figure 2. Multiple parallel channels can be employed as described in the table.



Figure 2.

Typical large VSI  
TMEIC TMdrive-XL85

### TMEIC VSI Capability

	TMdrive-70	TMdrive-XL55	TMdrive-XL75	TMdrive-XL85
VSI output power range for single channel	8/10 MVA	8 MVA	20 MVA	30 MVA
Voltage of maximum motor size	3.3 kV	6.6 kV	6.0 kV	7.2 kV
Power Semiconductor type	IEGT	IGBT	IEGT	GCT
Maximum number of parallel VSI channels	4	2	4	4
Maximum system power	40 MVA	16 MVA	80 MVA	120 MVA
Length of single channel lineup	126 inch	221 inch	370 inch	319 inch

LCIs have been used for many years for their high power and variable speed. A typical large LCI is shown in Figure 3.



Figure 3.  
Typical large LCI

### Capability of Competitive LCIs

	Brand A LCI	Brand B LCI
LCI output range for synchronous motors	Standard 72 MW	Standard 74 MW
Motor voltage of maximum size synchronous motor	10.2 kV	11 kV
Power Semiconductor switching device type	SCR	SCR
Maximum MW rating of single LCI channel	36	37 (120 max)
Maximum system power	Special, 101 MW	Special, 120 MW
Length of single channel lineup, not including power factor correction and harmonic filter	NA	433 inch

LCIs are usually larger than the comparative power VSI. This is illustrated in Figure 4.

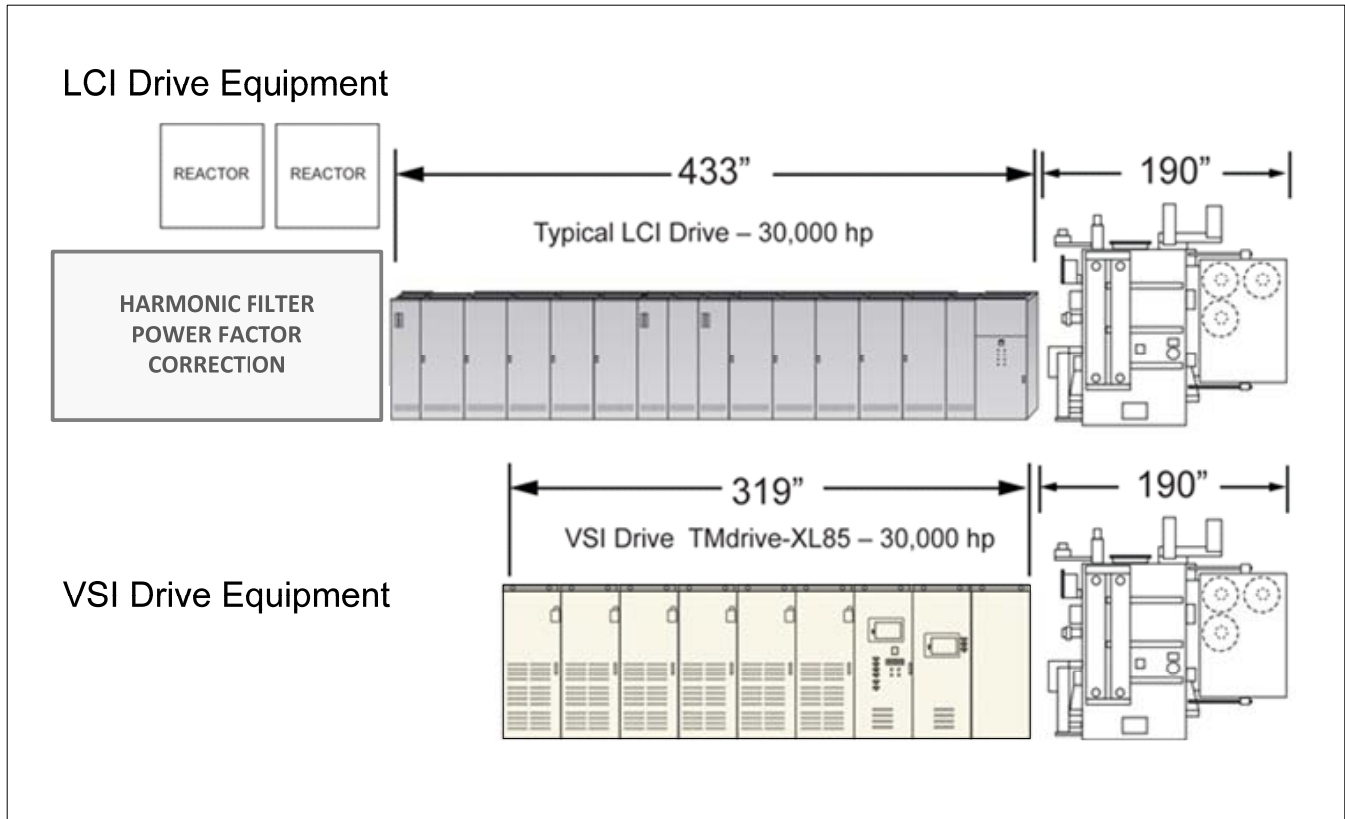


Figure 4. Size Comparison of VSI System with LCI System

### 3. Design Considerations

#### VSI Drive Design

- The only limitations in the designs are the power converter ratings. These ratings are based on the capacities of the power semiconductor devices (IEGT and GCT) and the cooling systems. The nominal ratings are based on 40° C maximum ambient temperature and altitudes less than 1000m. Applications outside these conditions require de-rating.
- There are no limitations on input voltage because the input transformer is separate from the drive. The maximum motor voltage is inherent in the converter design depending on the voltage margin in the devices and power circuit topology. TMEIC has used the highest motor voltage possible consistent with adequate device voltage margin.
- The TMdrive-XL55, XL75, and XL85 drives have 36-pulse diode rectifier source converters. The likelihood of beat frequencies and inter-harmonics is very low. For compressor applications, the loading required to maintain continuous current in the source converter occurs well below the minimum continuous speed.
- The 36-pulse source connection requires six sets of 3-phase cables. To minimize cost, the distance between the input transformer and the drive is made as small as possible. However, there is no electrical limit to the distance except for voltage drop in very long cables.
- The only limitation in cable length between the drive and motor is the voltage drop in the cables.

- f. An output filter has not been used in the past for any VSI drives.
- g. The motors for VSI drives are custom built with appropriate motor insulation systems. This usually means a higher voltage insulation system than for a standard utility-fed motor.

**LCI Drive Design**

- a. The input transformer is separate from the LCI drive, so there are no limits on the input transformer primary voltage. The motor voltage can be as high as 11 kV (with the motor connected directly to the drive) based on the rating of the SCRs and the components in the power circuit.
- b. The LCI drive always operates at continuous current by design. Inter-harmonics in the power system are minimized by having sufficient inductance in the dc link inductor that decouples the source and load converters.
- c. The cable limits for the LCI system are established by the capacitance of the cables. There is a capacitance limit that should not be exceeded to prevent di/dt failures in the SCRs; this limit is usually about 300 m.
- d. Cable length limits to the motor are subject to the same considerations for capacitance and voltage drop as for the cabling between the transformer and source converter.
- e. Output filters are not applicable to LCI drives.

**4. Supplier Capability and Experience with VFD-driven Motors**

The LCI can only operate with a synchronous motor, but the VSI can operate with a synchronous or an induction motor. Since the induction motor has a lower cost, in many medium power applications this is an advantage to the VSI system. TMEIC has extensive experience building both large induction and synchronous variable speed motors, as summarized in the table below.

<b>Motor Type</b>	<b>TMEIC Motor Capability</b>
Synchronous motor	Power range up to approximately 100 MW Speed range up to 6,500 rpm (2-pole motor)
Induction motor	Power range up to 25 MW Speed range up to 12,000 rpm (2-pole motor)
Motor voltage	Up to 13.8 kV
Large motor design	Custom design
Number of 3-phase winding sets	1

## 5. Power System Harmonics and need for Filters

LCIs still develop considerable input current harmonics, although using multiple converters improves the situation. VSI development has reduced the effect of the converter on the power supply to levels well below the IEEE519 standard. This is illustrated in Figure 5.

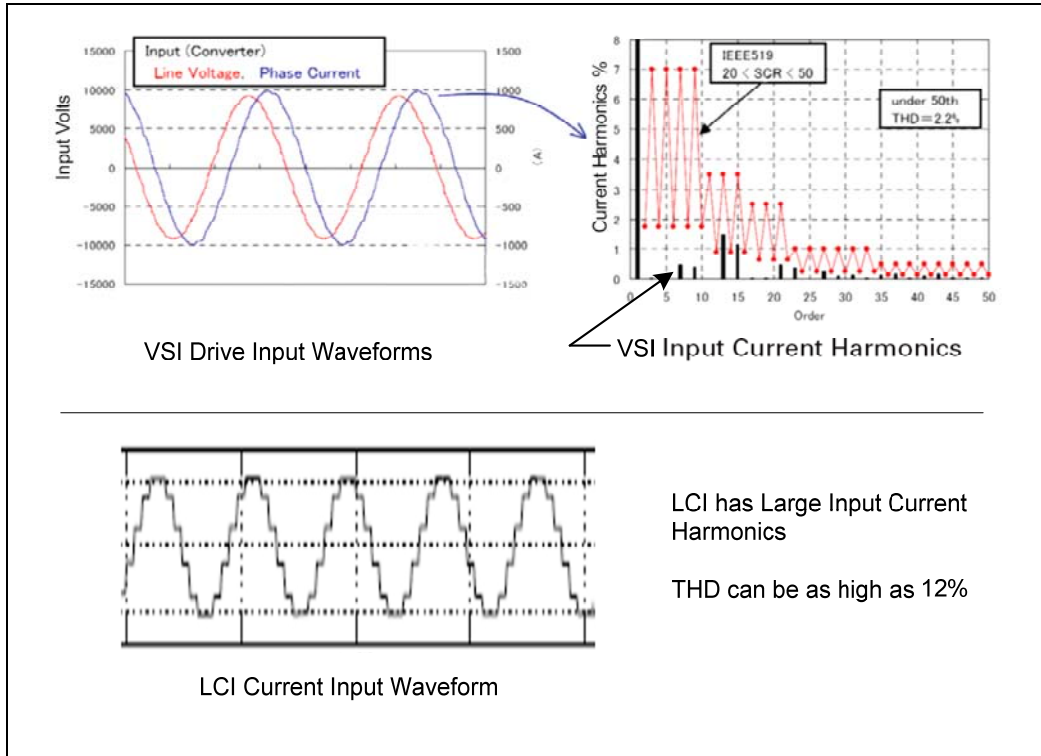


Figure 5. Total Harmonic Distortion for large VSI and LCI

VSI Harmonic Distortion	LCI Harmonic Distortion
TMEIC's large XL drives have 36-pulse diode source converters, resulting in very low input current harmonics. As shown in Figure 5, the total harmonic distortion (THD) is 2.2 %, well below the IEEE519 standard.	LCI total harmonic current distortion (THD) can be as high as 10-12 % for 12-pulse systems, requiring harmonic filters on the input. LCI drives have either 6-pulse or 12-pulse source converters. If multiple converters are used in a system, the transformers for the system can be designed with secondary phase shifts that result in low harmonics on the ac system. For example, a dual channel system with two 12-pulse source converters can be connected for 24-pulse harmonic currents that need no harmonic filters.

## 6. Power Factor versus Load

LCI drives have low input power factor, especially at lower speeds, and often additional power factor correction equipment is required. VSI drives on the other hand operate at close to unity power factor.

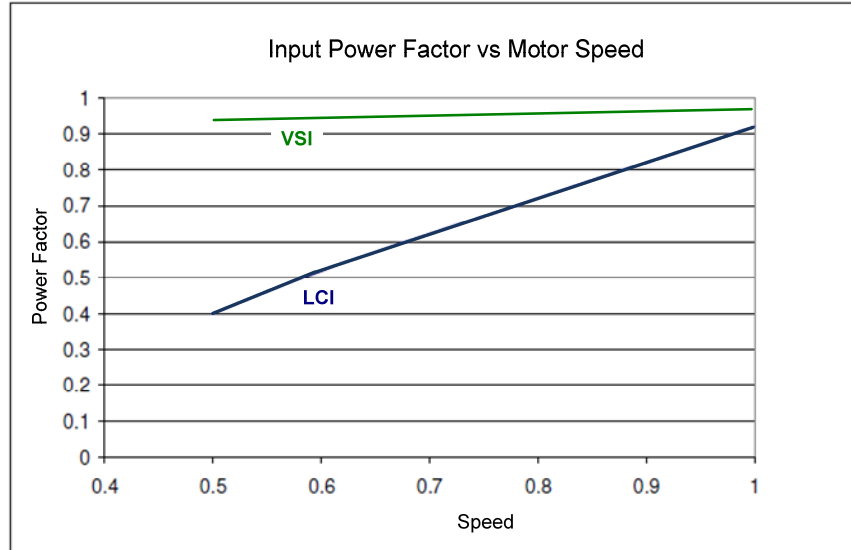


Figure 6. Power Factor Variation with Speed

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### VSI Power Factor

The power factor of a VSI with diode rectifiers is essentially constant at 0.95 or better over the normal operating range. The diode converters only draw kW from the ac supply and no phase delay is possible.

Regenerative source converters (active front ends) operate at unity power factor, or can operate to provide VARs to the power system (leading power factor). This characteristic can be used on isolated drives supplied by weak power systems that may require voltage support. The reactive power can be made without external capacitors and is controllable within the rating of the source converter. The TMdrive-70 and TMdrive-80 have regenerative source converters.

### LCI Power factor

The input power factor of LCI drives varies with the motor voltage, which is usually proportional to motor speed when the motor is operating below rated voltage. For a variable torque load, the input power factor varies from 0.4 at 50% speed to 0.92 at rated motor voltage and speed.

Power Factor variation with speed is shown in Figure 6. This reactive power demand usually requires addition of capacitors to support voltage at the supply bus.



## 7. Machine side Harmonics and their Effect on Motor Design

VSI's have three or five switching levels producing output harmonics much lower than those from an LCI. Motors used with an LCI require special design to accommodate these harmonic currents and resulting heat.

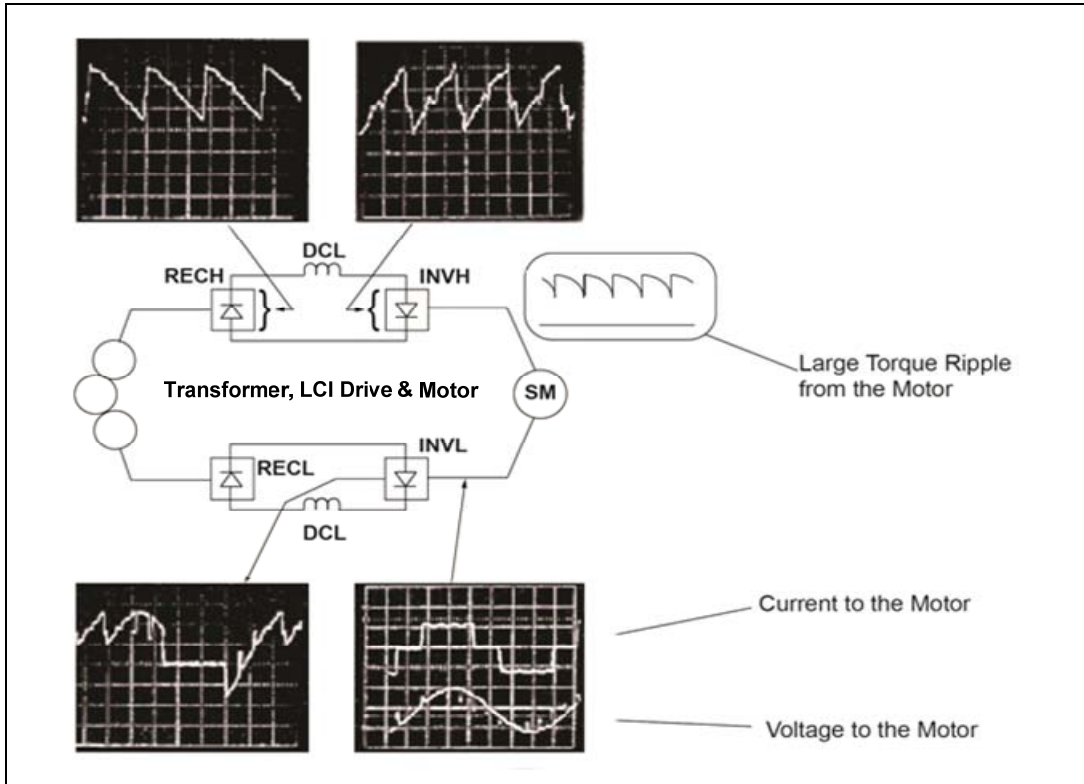


Figure 7. LCI Voltage and Current Waveforms

### VSI Output Harmonics

Data on the VSI output harmonic currents are used in designing the motor and accounting for the motor temperature. Generally, the current harmonics from a PWM drive are low because the voltage harmonics are reduced by effective waveform shaping and the higher number of switching levels in the drive, five with TMEIC XL drives

### LCI Output Harmonics

The motor is designed for the harmonic currents it will experience in operation. Depending on the number of windings, the harmonic currents may be 6-pulse (25 % THD) or 12-pulse (10 % THD). Even with a 12-pulse connection, the current harmonics are likely to be much higher than a PWM-fed motor. Proper motor design must accommodate the harmonic currents.

## 8. Torque Ripple Produced in the Motor

The main risk with output torque pulsations is they may be close to a mechanical resonant frequency and excite powerful torsional vibrations, which can lead to shaft or coupling cracks and failure. Poor output waveforms from the LCI can produce such torque pulsations or ripples. There are not many strategies for improving the motor air gap torque pulsations, usually modifications to the mechanical drive train are the best way to avoid resonances, for example a damped coupling can be inserted.

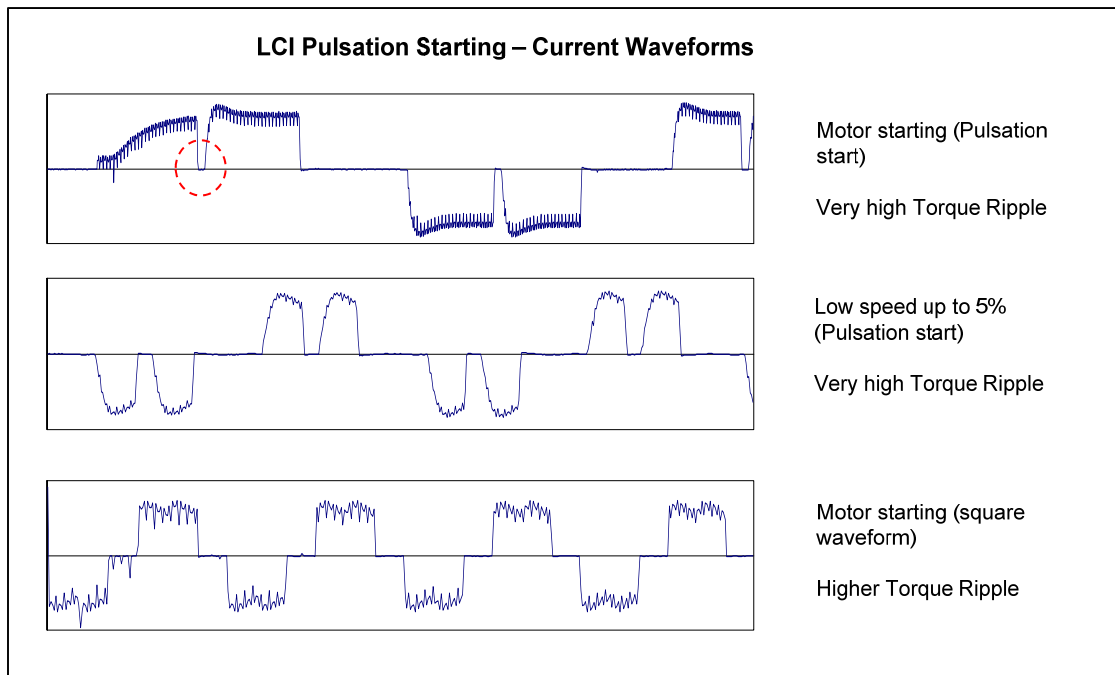


Figure 8. LCI Motor Starting Current Waveforms causing Torque Pulsations

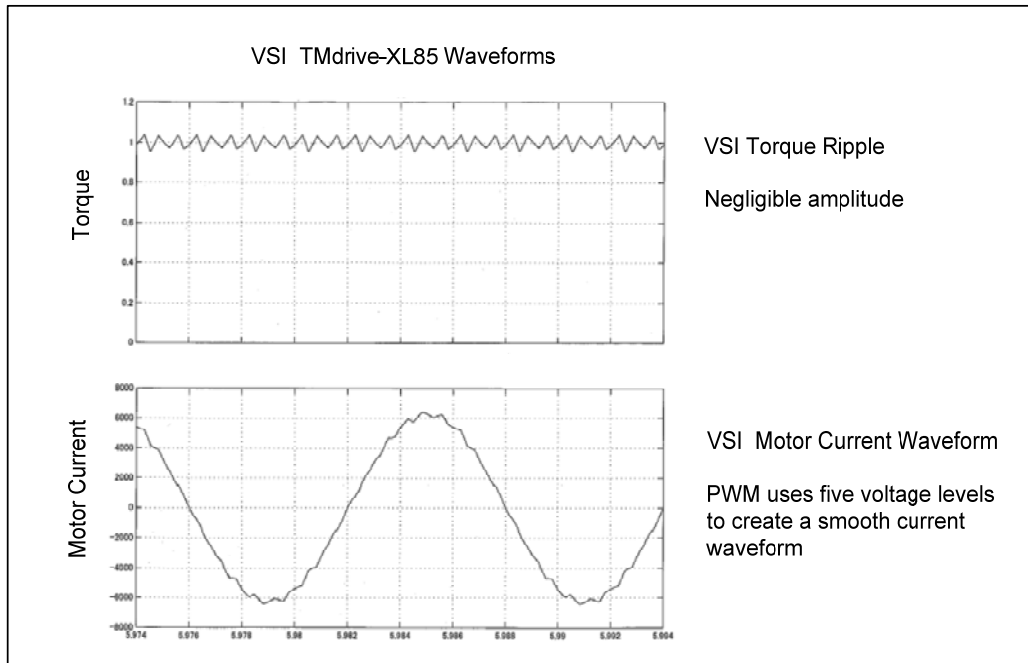


Figure 9. VSI Motor Current Waveforms causing Negligible Torque Pulsations

### VSI Torque Ripple

The Pulse Width Modulation (PWM) drive control strategy has been developed to minimize or eliminate low frequency motor air gap torque pulsations when driving a compressor. The target value for motor air gap torque harmonics at frequencies less than 100 Hz (6,000 rpm) is less than 2% of rated motor torque.

### LCI Torque Ripple

An LCI normally has large motor air gap torque pulsations that are proportional to the average motor torque. The amplitude depends on the number of converters connected to the motor. A 12-pulse motor (two converters) would have about 25% peak-to-peak torque ripple. If the ripple frequency is close to the torsional shaft vibration frequency, resonance can occur.

The possibility of modulation torques is also present in an LCI drive. The source converter ripple frequency and the load converter ripple can interact across the dc link reactor to cause low frequency modulation of the motor currents. This can result in low frequency torque pulsations at high motor speeds.

## 9. Reliability

Both the VSI and LCI have high reliability. Based on 12 years of field experience with over 1000 medium voltage TMdrive-70 VSI drives in the steel industry, the MTBF is 37 years. The MTBF of LCIs is also believed to be high.

<b>VSI Reliability</b>	<b>LCI Reliability</b>
Based on field experience with similar medium voltage VSI drives, the MTBF of a single XL drive has been estimate to be 28 years. These drives are designed and built to high quality standards and have redundant water cooling water pumps with automatic switchover.	The MTBF of a typical LCI drive is more than 10 years, based on a large amount of field operating experience over the past 40 years.

## 10. Drive Repair

Through careful design and modular construction, the repair times of both the VSI and LCI have been reduced to just a few hours.

<b>VSI Repair</b>	<b>LCI Repair</b>
The repair time (MTTR) of the VSI drive is about 0.5 hours for power units and control, assuming trained technicians and spare modules are readily available. Complete power modules are replaced; faulty modules are repaired at a TMEIC service center.	The estimated MTTR of an LCI drive is 2 hours from identification of the problem to replacement of the failed part in the power section or control system.

## 11. System Efficiencies

The motor efficiencies shown in the following table are based on 2-pole synchronous motors. The drive efficiencies are published data from TMEIC and two LCI vendors. The overall system efficiency is the product of all the system components – Drive, Motor, Transformer, Power Factor Correction, and Filter. The results show the overall VSI system efficiencies are about 1% higher than LCI systems, mainly due to the required power factor correction and harmonic filter.

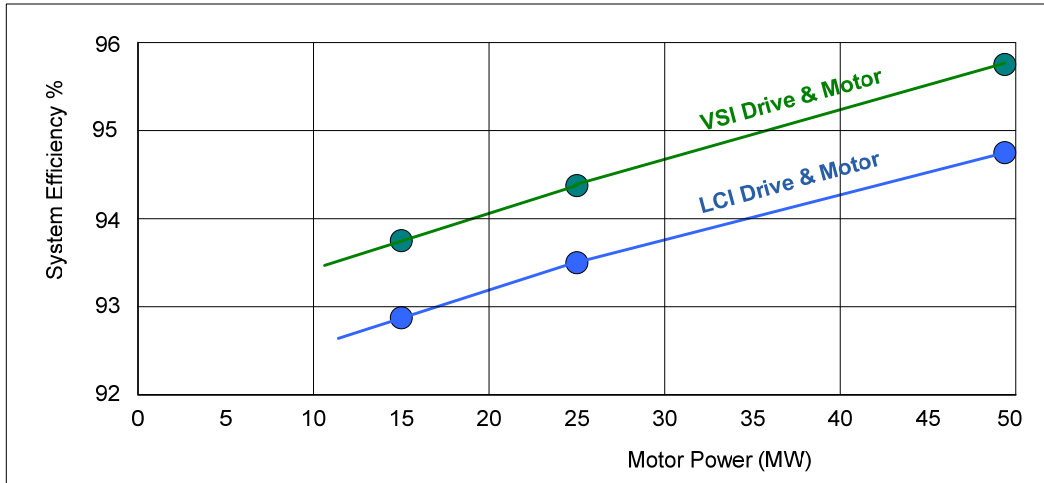


Figure 10. Comparison of Overall System Efficiency for different size systems

### Component and System Efficiencies

Power Level	Drive Type	Drive Effic.%	Motor Effic.%	Transformer Effic. %	Harmonic Filter/Power Factor correction Effic. %	Entire System Effic.%
15 MW	VSI	98.6	96.6	98.5	Not required	93.8
	LCI	99.0	96.2	98.5	99.0	92.9
25 MW	VSI	98.6	97.2	98.5	Not required	94.4
	LCI	99.0	96.8	98.5	99.0	93.5
50 MW	VSI	98.6	98.0	99.0	Not required	95.7
	LCI	99.0	97.6	99.0	99.0	94.7

## Summary

The latest high-power VSI designs now provide many advantages over their LCI predecessors. These advantages include low power system harmonics, low reactive power demand, and low torque pulsations in the motor air gap and shaft. In addition, the ability to drive induction motors instead of more expensive synchronous motors provides for equipment cost savings.

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February, 2013