# ELECTRIC SYSTEMS FOR HIGH POWER COMPRESSOR TRAINS IN OIL AND GAS APPLICATIONS— SYSTEM DESIGN, VALIDATION APPROACH, AND PERFORMANCE

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## ABSTRACT

This paper presents the development process for a new variable frequency drive (VFD) system for large size compressor trains for natural gas and liquefied natural gas (LNG) applications. The paper covers the multiple steps of the product development process, from identification of applications requirements, definition of design

constraints and targets, generation of the product concept, selection of the switching component, topology and system configuration, and the validation strategy. The paper will discuss the test rig setup and the results of the test campaign for the 35 MW VFD prototype. It will also provide a comparative overview of the different technical solutions available on the market and explain how the technology presented better accommodates the challenges of specific process applications. Finally, the potential evolution of the developed technology to higher power levels will be illustrated.

## INTRODUCTION

As the oil and gas industry moves toward wider adoption of electrical drivers in high power applications, the demand for and interest in new power electronics solutions that offer improved reliability and performance are also growing. This trend opens new discussions about the optimal configuration for motors and power electronics to maximize system reliability and ensure optimum integration between the rotating machinery and power electronics.

In the oil and gas industry, power electronic equipment is typically applied in compressor applications where a train may include one or more compressor casings, electric motors, and, sometimes, gears and/or gas turbines. In general, the major concerns regarding the adoption of a variable speed drive system (VSDS) as a driver for large power trains are related to:

- Reliability of systems and components.

- Potential excitation of torsional and lateral compressor train vibrations by motor torque distortion.

- Scarcity of VSDS references above 15 MVA.

For power electronic solutions to meet the increasing demands and the stringent needs of oil and gas industry applications, they must be based on a special-purpose design that starts from the mechanical constraints of the entire shaft center line and typical train torque requirements. The electrical system technology and specifications need to be defined at the following level of technology:

- Drive topology selection

- Control strategy selection

- Definition of key performance parameters

Among the existing power electronic solutions, load commutated inverter (LCI) technology, which has been in use in the industry since the 80s, is still considered the most mature and preferred solution at power levels above 10 MVA. Its strengths include reliability and an installed base numbering in the hundreds. Voltage source inverter (VSI) systems based on transistor or gate-controlled thyristor switches on the other hand, even though broadly applied up to 20 MVA in the steel industry for at least a decade, have been restricted to 10 to 15 MVA in oil and gas applications. However, the increased availability from different suppliers of innovative solutions that promise better performance are currently opening the oil and gas industry to VSI systems at even higher power levels.

In VSI equipment based on integrated gate controlled thyristor (IGCT) or insulated gate bipolar transistor (IGBT) switching components, the jump from the typical 10 MVA to higher power levels is in general accomplished by combining basic blocks as follows:

- Switching components in series

- Single-phase converters in series (multicells)

- Paralleling three-phase drives (feeding multiwinding motor or single winding motor through inductors)

- Combination of the above methods

Each of the above-mentioned solutions presents pros and cons and requires a specific control strategy to achieve high quality outputs and to minimize the injection of harmonics into the supply line and motor windings.

This paper presents a multithreaded drive system configuration based on IGCT switches, where the total power rating is reached by paralleling from two to four three-phase medium voltage power converters. The multithreaded drive system feeds a single winding three-phase synchronous motor through inductors (one per thread).

In the configuration presented in this paper, the basic module is a three-level neutral point clamped (3L NPC) power converter with a rated power of 10 MVA. Each drive's phase is made up of four IGCTs with two diodes clamped with the midpoint of the direct current (DC) link (Figure 1).
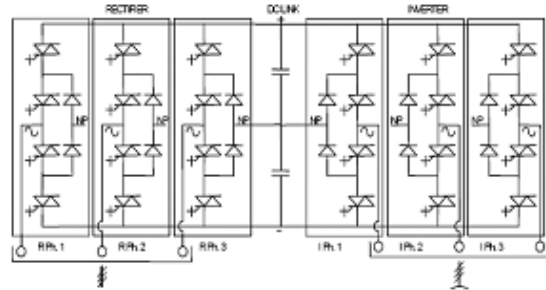


*Figure 1. Three-Level NPC IGCT Drive.*

By closing two of the four switches, the load may be alternatively connected to the top, mid and down point of the DC link, resulting in a three-level output on the line-to-neutral voltage ($-Vdc/2$, 0, $+Vdc/2$), and five levels on the line-to-line voltage, with reduced harmonic content (Figure 2).
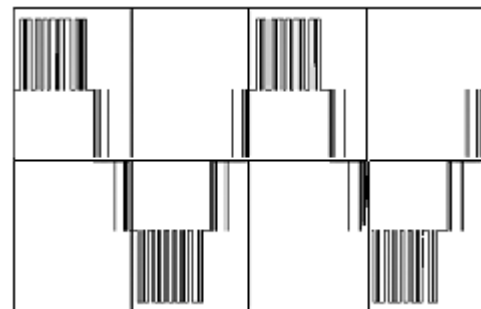


*Figure 2. Three-Level NPC Line-to-Line Voltage Waveform.*

The multithreaded configuration (Figure 3) has a major advantage in building up large power equipment utilizing single modules of lower power already proven and referenced. In addition, the configuration allows redundancy at the module level and fault tolerant operations with the VFD system operating at a reduced power level should there be a failure in one or more modules.
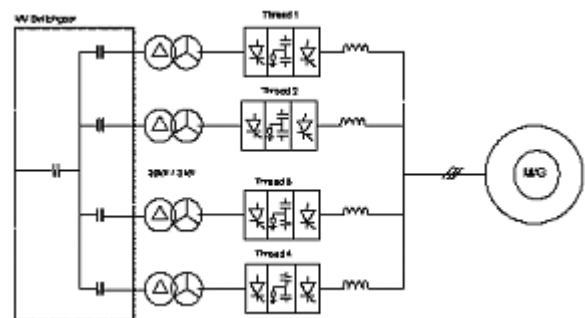


*Figure 3. Multithread VFD Sketch.*

**ELECTRIC SYSTEMS FOR HIGH POWER
COMPRESSOR TRAINS IN OIL AND GAS APPLICATIONS—
SYSTEM DESIGN, VALIDATION APPROACH, AND PERFORMANCE**

63

The challenge of the multithreaded configuration is to obtain a quality of voltage and current waveforms higher than that achieved by simply superimposing the signals from the single threads. The solution presented by the authors is based on a control strategy that, by interleaving (phase shifting) the gating carriers in each thread, achieves high quality output and cancels the harmonics in the motor current and voltage. The major benefit is a low motor torque ripple at the motor coupling and an air gap torque frequency spectrum that may be tuned in order to minimize those torque components that potentially create issues for the rotordynamics of the combined shaft line (motor, gear, compressor casings, and, if applicable, gas turbine).

## LARGE VFDS IN THE OIL AND GAS INDUSTRY

Large VFD systems in the oil and gas industry are typically adopted in gas reinjection, pipeline recompression, and refrigeration processes in LNG production plants. The typical configuration of electrically driven compressor systems is one (for pipelines) or more (for reinjection) compressor casings running at a speed between 3000 rpm to 6000 to 8000 rpm, coupled to a synchronous 2- or 4-pole electric motor either directly or through a speed reducing gear (Figure 4).
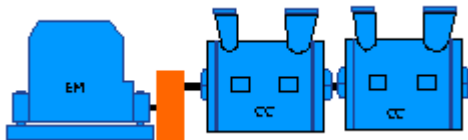


*Figure 4. Typical Configuration for Centrifugal Compressor Train Driven by Electric Motor.*

In the case of LNG, it is possible to identify two train configurations:

• Gas turbine driven LNG trains in which case the gas turbine (GT) is the main driver while the electric motor may act as a starter, a helper (to augment the GT power output when high ambient temperature reduces the turbine output below the power requested by the compressor train), and a generator to provide excess GT power to the electrical grid. In this configuration, the shaft line includes the GT, compressor casings (one or more, either axial or centrifugal), gears (where needed) and electric motor (Figure 5).
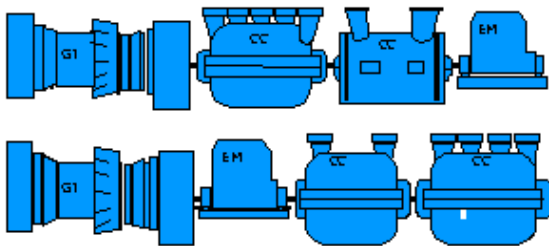


*Figure 5. Typical Configurations of LNG Compression Trains.*

• Electric motor driven LNG trains where the electric motor acts as the starter and driver. In this case the shaft line includes only compressor casings, a gear if needed, and the electric motor.

The design constraints of such systems are mainly associated with:

• Reliability of power electronics systems that affects the availability of the entire system and therefore the production rate of the process. The reliability of the VFD systems depends on the number of switching components as well as their reliability and the redundancy options offered by the topology.

• Integration of the electrical equipment with the power generation system (either a local grid or a dedicated power generation plant). The interaction of the VFD system with the power system depends on the level of harmonic content in the voltage input, the power factor on the grid side, and the power system impedance level.

• Torsional and lateral vibration levels of the full train shaft center line, in particular, torque pulsation at startup and steady-state (fatigue analysis), and torsio-lateral phenomena, caused by excitation of torsional modes, driving excessive train lateral vibrations. The last case is especially important when a gear box is part of the compression train, for in these cases, low frequency motor torque (e.g., 5 to 15 Hz) components may cause extremely high lateral vibrations that could compromise the operability of the train. A typical example is shown in Figures 6 and 7 where the excitation of a train's first torsional mode at 9 Hz with relatively low pulsation mechanical torques caused radial vibrations in excess of 150 microns at the same frequency.
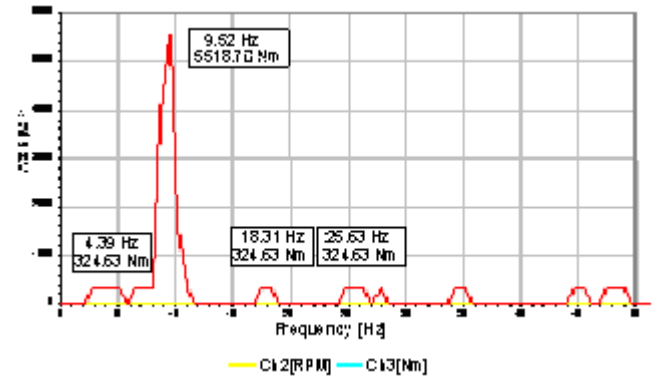


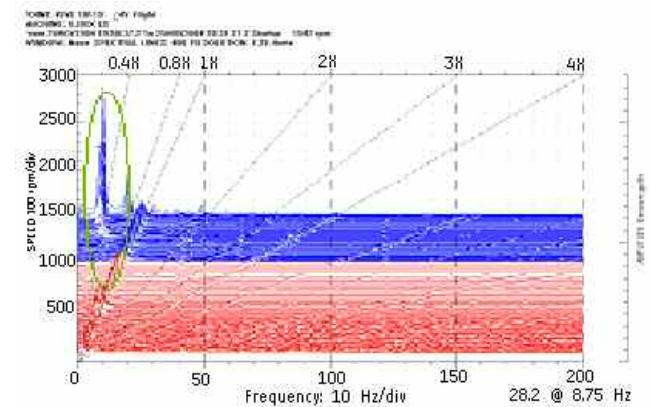*Figure 6. Torsional Vibration Frequency Causing Trip of a Compressor Train.*



*Figure 7. Lateral Vibration Frequency Causing Trip of a Compressor Train.*

The selection of VFD systems is generally determined by these three major factors: while the LCI is considered first in class for reliability, its drawbacks are weak integration into the power system (either local grid or dedicated power generation) and high torque ripple and torque pulsations that may excite torsional modes in compressor trains. The VSI technologies, on the contrary, are gaining ground, offering better performance on both the grid and the motor sides and differentiated solutions to increase reliability based on switching components and topology configurations.

## DESIGN OPTIONS AND CHOICES

As outlined above, the main requirements in the targeted oil and gas applications are very high power (30MW and higher), very low torque harmonics, and high reliability.

Thyristors are available at very high power ratings. Furthermore, series connection is relatively simple and a proven approach. By using additional thyristor devices, redundancy can be easily implemented. Therefore, they are commonly used in very high power applications. However, they can switch only once per fundamental cycle since they cannot be actively turned off. Hence the achievable power quality is comparatively poor. This typically implies the installation of bulky and expensive grid-side filters, which require careful design and tuning. Filters for the variable frequency machine side are typically not practical. Hence thyristors are not attractive for a high torque quality drive application such as considered here.

Consequently, only self-commutated topologies are considered in the following, which need fully controllable semiconductor devices. The available voltage and current ratings of these devices have increased significantly in the past. Nevertheless, the targeted power level cannot be achieved with state-of-the-art semiconductors in a standard topology, e.g., two- or three-level converters using one semiconductor per switch position. For example, the power of a typical high power, medium voltage drive based on a three-level neutral point clamped (NPC) converter using 4.5 kV and 4 kA integrated gate commutated thyristors is rated to approximately 10MW. Hence, it is mandatory to use several semiconductor devices in series or parallel connection. This can be done on a device level using direct series or parallel connection, where these devices are switched synchronously.

Alternatively, multilevel topologies can be chosen to increase the achievable voltage level compared to two-level inverters. Here several devices are effectively connected in series; additional degrees of freedom allow for switching these devices independently. This increases both the available number of discrete voltage levels and the effective switching frequencies. As a result, the voltage harmonics can be reduced, thus directly improving current and torque quality. As a third option, complete converter modules can be paralleled (or series connected using isolation transformers). This option can also be used to enhance the achievable output performance as will be highlighted in the subsequent sections. As described, using more semiconductors can address the power requirement and improve the power quality using suitable topologies. However, the higher part count of the system is a drawback, which increases the likelihood of failures thus reducing the reliability of the system. As a countermeasure, some means of redundancy is generally required in these kinds of systems to fulfill the stringent system availability requirements common in the oil and gas industry.

In summary, it can be seen that standard converter solutions do not satisfactorily address all three requirements, i.e., power level, power quality, and availability.

### Selection of Switching Component

At high power levels, typically either IGBTs or IGCTs are used nowadays in self-commutated converters (Bernet, 2000). IGBTs dominate in drives with lower to medium power levels, since at lower voltages they facilitate very fast switching frequencies. At higher voltage levels their losses increase, their switching frequency decreases significantly, and their decreased current capability limits the maximum power that can be handled by a single device to almost constant or even decreasing values. This makes IGCTs more attractive for higher voltage and power levels. They offer higher power capability per device, which reduces the component count and leads to higher reliability. Consequently, in this drive system a 4.5 kV 4 kA IGCT was chosen as the switching device. As will be detailed later, this high power rating allows the drive requirements, namely power and power quality, to be achieved at a comparably low part count as a basis for high reliability.

### Selection of Drive Topology

As already mentioned, multilevel topologies can increase both the power level and the output performance of a converter combining multiple semiconductor switches. Well-known options are the diode clamped, flying capacitor (FC), and the cascaded cell (CC) topologies, which use different concepts to balance the voltage among the switches (Rodríguez, et al., 2002).

Diode-clamped multilevel converters use additional clamping diodes to clamp the blocking voltage on each device to appropriate levels (Choi, et al., 1991). One DC-link with intermediate taps is shared among all three phase-legs of a full converter bridge. As a drawback, the DC-link tap potentials cannot be controlled for more than three levels when active power flow is needed, as is the case, for example, in drives. In addition, the required blocking voltage of the clamping diodes increases as the number of levels increases, and the mechanical layout to ensure low stray inductances becomes a challenge. Hence, DC converters with more than three levels are rarely used. In contrast, three-level DC converters are commonly used and can be considered a standard and proven topology. Since the diode clamps are connected to the mid or neutral point of the DC-link capacitor here, they are normally referred to as neutral point clamped (NPC) converters.

Flying capacitor multilevel converters use additional capacitors to clamp the voltage on each device (Meynard and Foch, 1992). Therefore, this topology is also known as capacitor clamped. No additional semiconductors are needed here. The potential of the clamp capacitors with respect to the DC-link changes depending on the switching state of the semiconductor, i.e., it is "flying." Hence, these capacitors cannot be shared among the phases. In addition, the size of these elements increases significantly with the number of levels, which also restricts the practical level number of this topology typically to four.

In the cascaded cell topology, several independent H-bridge converter cells are connected in series in each phase (Peng, et al., 1995). Through such an extremely modular design, high level numbers can be achieved easily. The drawback is that each converter cell needs an isolated DC-link, which also has to sustain low frequency (i.e., two times fundamental) power fluctuations since it is connected to a single phase only. If active power flow is needed, e.g., in drives, a complicated feeding transformer is needed to supply all DC-links separately.

The high power and high output performance needed for the targeted drive application would imply high level numbers when directly adopting one of the aforementioned multilevel topologies. However, all topologies show disadvantages in this case. Hence, an interleaved shunt converter topology is chosen. Here, four independent three-level NPC converters are connected via individual inductors to the machine. This allows the switching of the converters independently from each other enabling higher output performance than single or hard paralleled converters. Furthermore, this topology builds on standard high-power converter units that can work independently of each other. This allows an elegant way to design a redundant drive system. The detailed working principle of the system is explained in the following section.

## DRIVE SYSTEM DESCRIPTION

### Product Specification

The specification for the new drive system targets compression train applications in the power range from 10 to 35 MW. The frequency system output is up to 110 Hz, allowing operation with two-pole as well as four-pole motors running at 3000 rpm (100 HZ rated frequency).

To validate the new system, it was decided to build a system prototype rated for 35 MW mechanical power at 3000 rpm for operation with a four-pole synchronous machine (100 Hz fundamental frequency), 3.3 kV rated voltage, and 6123 A rated current. In order

ELECTRIC SYSTEMS FOR HIGH POWER
COMPRESSOR TRAINS IN OIL AND GAS APPLICATIONS—
SYSTEM DESIGN, VALIDATION APPROACH, AND PERFORMANCE

65

to meet the power requirement, the prototype drive system was built by paralleling four three-level NPCs, each rated at 10 MVA following the topology and control described in the next sessions.

*Topology*

The chosen topology (Figure 8) is a system built on two to four (depending on the power requirements) independent threads connected in parallel on the grid and the machine side. Each thread consists of a transformer, a three-level NPC IGCT converter comprising an active front end (AFE) and an inverter (INV) bridge and crosscurrent inductors. Additional switchgear is used for protection and allows individual isolation or connection of each thread to the system.
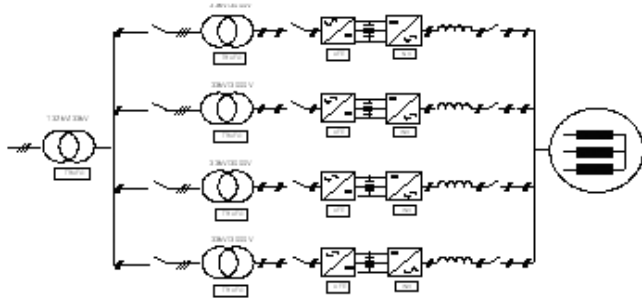


*Figure 8. Drive Topology Comprising Transformers, Converter Bridges, Cross-Current Inductors, and Motor.*

The cross current inductors serve dual purposes. First, they are needed to limit the switching frequency currents between the threads caused by the interleaved switching of the converters. (Lower frequency components of the current are effectively eliminated by the control as described later.) Second, the inductors provide effective decoupling of the threads in case of failures such as a short-circuit in a converter caused, e.g., by a semiconductor breakdown. Through this measure, failure propagation from one thread to another is avoided. The faulted thread can be isolated without endangering the remaining threads and the remaining threads can still operate the machine achieving full redundancy.

The stray inductance of the feeding transformer provides similar functionality on the grid side.

*Control*

The structure of the control hardware is designed such that it meets the above specified requirements—namely redundancy and high availability. This is achieved by equipping each thread with its own dedicated control hardware, which is identical for all four threads. The control units may act independent from each other— e.g., a failure in one thread does not affect operability of the control units of the other threads. Coordination and data exchange among the four independent threads is enabled by a reflective memory. Specifically, the control units have only local memory, of which a given fraction is allocated as reflective memory. When new data are written into this fraction of the control unit's memory, these changes are propagated to the memory of the other units via fiber optics. Provided that data are changed consecutively, the reflective memory acts as a single virtual memory unit that is physically located in and accessible by each of the four thread control units. This concept allows for seamless data exchange between the thread controllers while ensuring high reliability.

The control software is identical for all four threads. It consists of two main parts—a machine and a thread current controller. The machine controller is based on a state-of-the-art field oriented control scheme working in a stator-flux oriented orthogonal coordinate system (Xu, et al., 1988). The torque reference is translated into a torque producing current reference, while flux errors are mapped into an orthogonal flux producing current

reference. In steady-state the machine is completely fluxed via the field current supplied by the brushless exciter.

The two current references of the machine controller are divided by the number of threads and passed to the local thread (current) controllers. The latter regulate the thread currents independent from each other using measurements of the thread currents for feedback. The output of the thread current controller is a space vector. Each thread features a pulse width modulator (PWM) that drives the IGCTs of the thread inverter by synthesizing an appropriate switching pattern (Figure 9). The switching pattern can be asynchronous, implying that the PWM runs with a fixed switching frequency, or synchronous, where the PWM frequencies are synchronized to a multiple of the fundamental frequency.
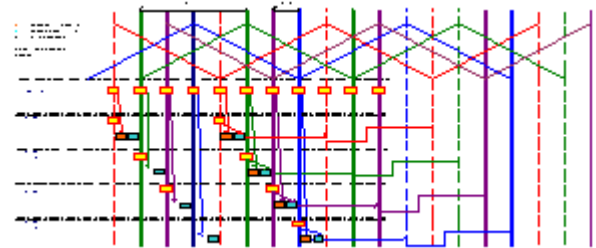


*Figure 9. Control Timing Showing Machine and Thread Control.*

Since each thread controller acts locally, fluctuations in the DC-link voltage and/or variations in the inductors are accounted for locally. This ensures that the four thread currents are equalized and sum up to the required machine current. Undesired circulating currents between the threads are thus avoided.

To enhance the performance of the drive, the four threads are interleaved, i.e., the four thread controllers use the same sampling interval, but sample and act at time-instants shifted in time with respect to each other, as shown on Figure 10 (e.g., a quarter of a sampling interval for four threads). Interleaved thread control implies that the machine controller works locally on one thread control unit at a time, and the machine controller execution is passed consecutively from thread controller unit to thread controller unit. This gives rise to a virtual master controller that is physically handed over from one thread control unit to the next one. Hence the machine controller runs at four times the sampling interval of the thread current controllers. Moreover, interleaving simplifies the concept of the reflective memory by ensuring that no two threads write data into the memory at the same time.
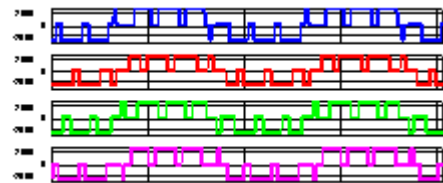


*Figure 10. Converter Voltage Pulse Pattern of the Same Phase at Four Threads Illustrating the Interleaving Principle.*

With respect to noninterleaved control, where all four threads run at the same time-instant, the benefit of interleaving regarding the drive performance is twofold. First, the control can react faster since the machine controller runs at four times the rate of the thread current controllers and thread controller execution is spread within the sampling interval. Second, and most importantly, the machine current waveform of the four interleaved three-level NPC inverters effectively resembles the current waveform of a nine-level inverter.

In the current system each of the four threads are equipped with an active front end (AFE) that allows full regeneration. Each AFE independently controls its DC-link voltages.

Finally, the control concept relies on four independent thread control units that exchange data by one single virtual memory (realized with reflective memory cards). In a field-oriented controller setting, the machine (virtual master) controller sets the thread current references, while the thread (slave) controllers regulate its thread currents. Interleaving greatly enhances the waveform of the machine current. The use of four independent threads with four independent control units yields a great level of redundancy. Neither a physical master controller nor a central memory unit is required due to the sequential execution of the machine controller on the local thread controllers and the reflective memory card.

VALIDATION APPROACH

The very ambitious time schedule of less than one year from the conceptual design to a mature product validated in extensive field tests imposed significant challenges on the product development and validation procedures. More specifically, to ensure that the schedule was met, a sophisticated and stringent validation process was mandatory. During this process, the product was validated at every single development step, thus allowing the detection and correction of deficiencies in a stage as early as possible. The key steps in the validation process can be summarized as follows:

• *Simulations*—The control code and the electrical drive were implemented in detail in a state-of-the-art simulation environment. Specifically, a system was employed allowing the power electronic systems to be accurately modeled up to the switching transients of the semiconductor switches. The fundamental system concept of four parallel and interleaved threads was validated in terms of the size and effectiveness of the cross current inductors, the current and voltage waveforms, the current and torque total harmonic distortion (THD), and the control software. Simulations were carried out both at a number of relevant operating points and for various startup scenarios.

• *Tests on scaled-down drive*—In a second step, tests were conducted on a scaled-down experimental setup of the electrical drive with a rated power of 100 kW. These tests focused both on the control hardware—in particular on the input/output (I/O) cards, the interthread communication, the reflective memory, etc., as well as on the software, namely the machine and thread controllers, and the human machine interface. The scaled-down drive accurately resembled the full-scale drive, except for the phase legs, which used low-power IGBTs (rather than IGCTs).

• *Leg tests*—In parallel to the test campaign on the scaled-down drive, the electrical and thermal behavior of the IGCT phase legs of the full-scale converter was validated.

• *Pump-back tests*—While the electrical machine was still being manufactured and tested, so-called pump-back tests (Figure 11) were carried out, where one pair of threads ran in the motoring mode, while the other pair ran in the generating mode. In this configuration, power is pumped from the grid side to the machine side and back. Due to the arrangement of four parallel threads it is straightforward to set up, configure, and run pump-back tests. These tests allowed the validation of the threads both in motoring and generating mode without an electrical machine connected and without consuming any significant amount of electrical energy.

• *Motor-generator load tests*—The final test campaign was carried out with the four threads driving in parallel the synchronous motor, which was in turn coupled with a load generator feeding a resistor bank of 30 MW (Figure 12). The test was focused on validating the overall drive power capability and the machine controller including the flux regulator and the brushless exciter, and to thus validate the complete electrical drive system. The motor-generator test was carried out in a test facility in Italy (Figure 13).
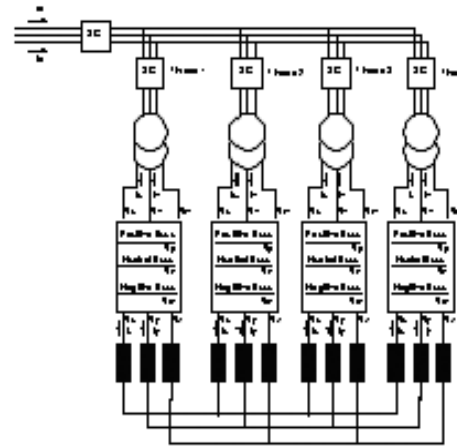


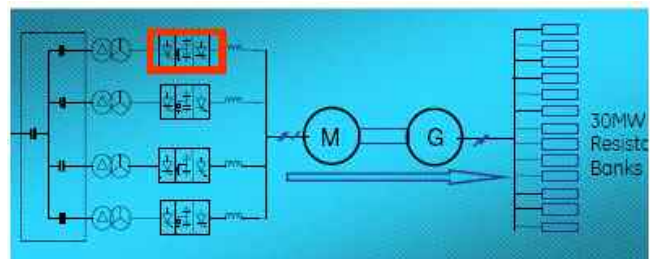*Figure 11. Pump-Back Test Configuration.*



*Figure 12. 35 MW Prototype Test Configuration in Motor Mode.*



*Figure 13. Full Drive System with Load Machine at Oil and Gas Test Facility.*

Since the completion of the nine-month validation campaign, the drive has been used successfully as part of a test setup for mechanical equipment such as compressors and gas turbines.

VALIDATION RESULTS

Typical experimental results obtained during the motor-generator load tests at 3000 rpm and 30 MW are shown below. The lower plot of Figure 14 shows the very smooth machine current that is the sum of the four interleaved thread currents shown in the upper plot. The benefit of interleaving can be easily observed as the machine current exhibits significantly lower current (and hence torque) distortions than the contributing thread currents.
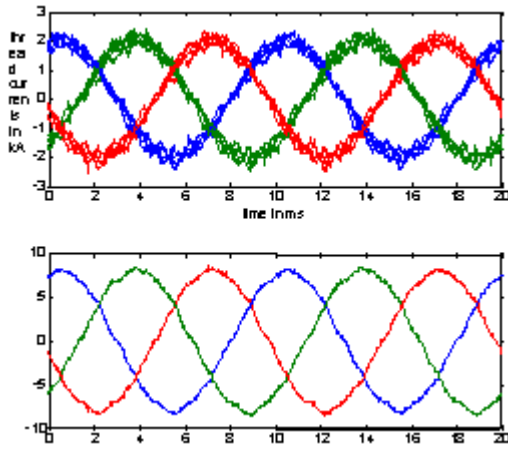
**ELECTRIC SYSTEMS FOR HIGH POWER
COMPRESSOR TRAINS IN OIL AND GAS APPLICATIONS—
SYSTEM DESIGN, VALIDATION APPROACH, AND PERFORMANCE**

67

*Figure 14. Measured Thread (Upper Plot) and Machine Currents (Lower Plot) at 3000 RPM and 30 MW .*

It is of particular interest to observe the motor torque distortion results achieved. The total motor torque ripple at the motor rated point in steady-state is defined by Equation (1):

$$Torque\ ripple = \left(T\max - T\min\right) / Taverage \qquad \textbf{(1)}$$

Comparing the torque ripple measured at the motor coupling generated by the new system (Figure 15) and by an LCI of the same class (Figure 16, with different scale), the IGCT interleaved system shows a torque ripple three times lower at the same operating conditions (30 MW and 3300 rpm).
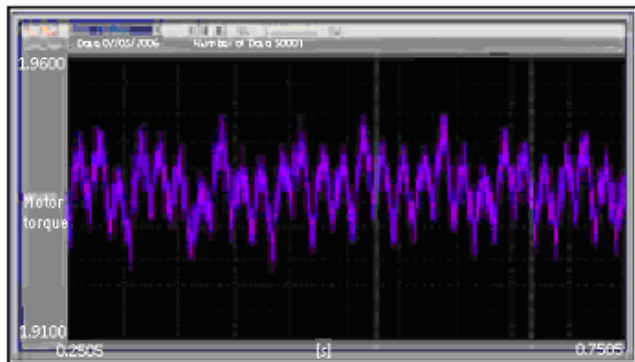


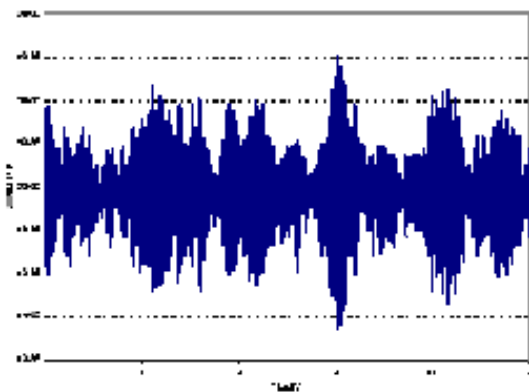*Figure 15. Multithread IGCT Drive System Torque Ripple Not Exceeding 4 Percent.*



*Figure 16. LCI Drive Torque Ripple Approaching 15 Percent.*

The other concern in oil and gas compressor train applications is the amplitude of the torque harmonic corresponding to the first torsional mode of the compressor train. The excitation of the first torsional mode may occur at steady-state at any operating point and during the train startup. Once again, comparing the performance at startup for the new IGCT multithreaded system (Figure 17) and an LCI of the same class (Figure18), a reduction of the first torsional mode stimulus amplitude with the IGCT drive of more than three times can be observed.
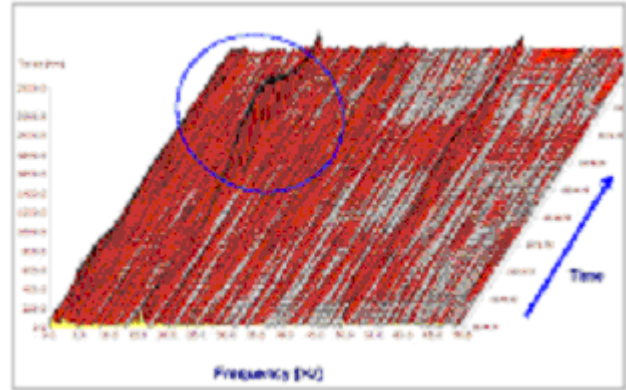


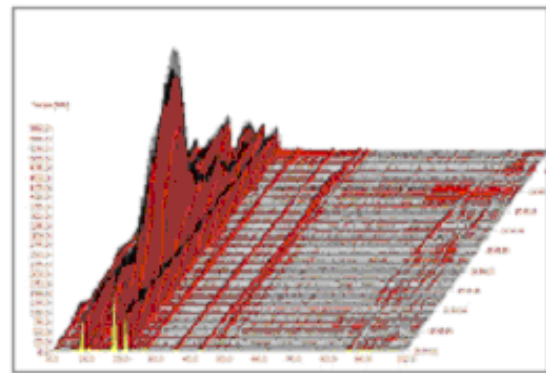*Figure 17. Torque Spectrum at Startup for the Multithread IGCT Drive.*



*Figure 18. Torque Spectrum at Startup for an Equivalent LCI Drive.*

## PRODUCT EVOLUTION

The topology and control platform developed represent an architecture that may be extended in power and frequency by:

- Increasing the thread output voltage.
- Changing the switching device.
- Increasing the thread power density.

In particular, a voltage increase from 3.3 kV to 6.6 kV could bring the total system power up to 70 to 80 MVA while keeping the same topology and using the same validated control platform.

Alternative control software and firmware could be used with the same topology to target the integration of controls where an electric drive and gas turbine are used to drive the same compressor shaft center line (e.g., GT helper for LNG trains).

This product, when operating with two-pole synchronous motors, allows motor shaft speeds up to 6600 rpm, offering solutions for gearless electric driven gas pipeline applications.

The same topology with a low voltage (LV) IGBT replacing the IGCT could also represent a viable option for highly reliable drives for pumps and small compressors in the 5 to 15 MVA power range.

## CONCLUSIONS

The overall test results illustrated in the previous sections show that the multithread interleaved drive system meets and in some cases exceeds the design targets and expected performance. The configuration allows high power at reduced system complexity with low parts count and proven hardware.

The same configuration can be extended to higher power by increasing the single thread power density or the NPC output voltage.

The interleaving control strategy delivers higher quality output and optimized performance improving the behavior and operability of compressor trains. Finally the new drive system and its development program represent an example of integrated design of a compressor train, where the integration of the electrical and mechanical systems starts at the conceptual design of the main driver.

## NOMENCLATURE

AFE    = Active front end
CC     = Cascaded cell
DC     = Direct current
EM     = Electric motor
FC     = Flying capacitor
GT     = Gas turbine
Hz     = Hertz
I/O    = Input/output
IGBT   = Insulated gate bipolar transistor
IGCT   = Integrated gate controlled thyristor
INV    = Inverter
LCI    = Load commutated inverter
LNG    = Liquefied natural gas
LV     = Low voltage
MV     = Medium voltage
MVA    = Megavoltampere
MW     = Megawatt
NG     = Natural gas
NPC    = Neutral point clamped
PWM    = Pulse width modulation
RPM    = Revolutions per minute
THD    = Thermohydrodynamic
VFD    = Variable frequency drive
VSDS   = Variable speed drive system
VSI    = Voltage source inverter

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