Testing large ASDSs

Testing adjustable speed drive systems which are bringing new levels of efficiency to oil and gas customers

DANIELE BUZZINI, MAURIZIO ZAGO – Driving a compressor by means of an adjustable speed drive system (ASDS), which is the ensemble of transformer, converter and motor, assures higher flexibility, higher efficiency, lower maintenance costs and a lower impact on the environment. For these reasons the extensive use of ASDS driven compressors and pumps is increasing in oil and gas applications, specifically for transportation, gas liquefaction and injection. This article goes behind the scenes to look at the testing of large ASDSs and how customers are given the evidence that the system meets the performance of the design stage before its delivery to site [1].

In 2009, ABB's Process Automation division for oil and gas won two contracts which include two ASDSs rated at 18.2 MW which will drive centrifugal compressors for gas lift facilities and two ASDSs rated 13.5 MW that will drive centrifugal compressors for gas injection facilities in the UAE. The ASDSs selected for this project are all based on load commutated inverter (LCI) technology, each one composed by a four winding transformer, a 12-pulse LCI, a synchronous motor and a power factor compensation and harmonic filter ➔ 1. The four windings transformer has one primary and three secondary windings. Two secondary windings feed the 12-pulse converter rectifier, which is line commutated, while the third feeds the power factor compensation and harmonic filter. The windings dedicated to the converter are 30 degree phase shifted thus creating the 12-pulse reaction line side which contributes to eliminate the non characteristic harmonic currents such as the 5th, 7th, 17th, 19th.

The LCI converter is one of the most reliable drives available on the market. The LCI is based on thyristor technology and it consists of two six-pulse input thyristor rectifiers, a DC-Link reactor, two six-pulse thyristor inverters, the control system and a synchronous motor excitation unit and cooling unit. The LCI acts as a current source for the motor, the controlled rectifiers are line commutated while the inverters are load commutated. The thyristors are selected in N+1 configuration so that, even in case of single failure, the converter is still capable of providing full power, therefore maintaining the system's availability. The DC reactor serves to smooth the DC current as well as to reduce fault currents in the DC link.

The four-pole, solid rotor, synchronous machine has two 30° phase shifted windings, suitable for 12-pulse inverter connection. The current fed in each of the three phase windings remains a six-pulse current, but the resulting magnetic field in the air gap presents only 12-pulse characteristic harmonics. This reduces the shaft torque ripple as well as the rotor temperature rise caused by the losses of induced current harmonics in the rotor.

The motor excitation is brushless with a tri-phase stator winding (exciter machine), fed by a static excitation unit mounted within the LCI excitation cabinet. The exciter winding itself, generating the rotating field, is fed via the exciter machine and the rotating diode bridge.

The power factor compensation and harmonic filter (PFCHF) has the primary function of compensating the LCI reactive power consumption. The choice of the filter composition (ie, the number of branches, tuning etc.) has been done in such a way to reduce as far as possible the injection of current harmonics by ASDS into the grid.

The back to back test

For this specific project, the end user requested a performance test of the whole ASDS according to the Shell Design and Engineering Practice. The LCI converter is an inherent four-quadrant converter, meaning it can be operated in motor and braking mode, which is well suited to the back to back test configuration. In the back to back test arrangement, two ASDS were lined up: one working as motor (driver) and one acting as generator (braker) ➔ 2. The active power adsorbed by the motor is generated by the braker and recycled in the motor again. On the other hand the reactive power is adsorbed by both the converter (driver and breaker). As a consequence, most of the power remains in the process and only the losses of the two VSDSs, and the excess reactive power which is not compensated by the two filter systems, consume energy fed from the test bay supply network. The absorbed power was 8 MVA of which 1.7 MW was active power and 7.8 Mvar was reactive power.

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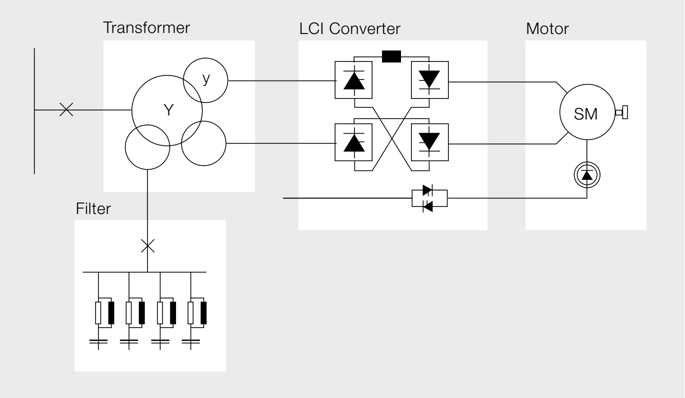
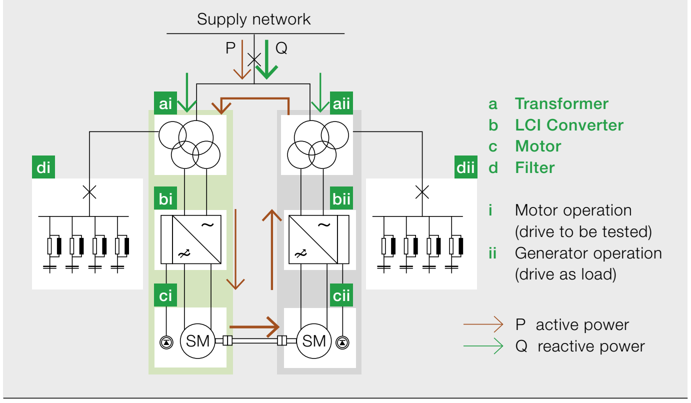
The back to back test arrangement makes it possible to run the ASDSs at their rated power, a condition not otherwise possible during either the compressor string test nor during site test. In fact, with these two test configurations, the load applied to the motor shaft corresponds to the compressor rating, in this

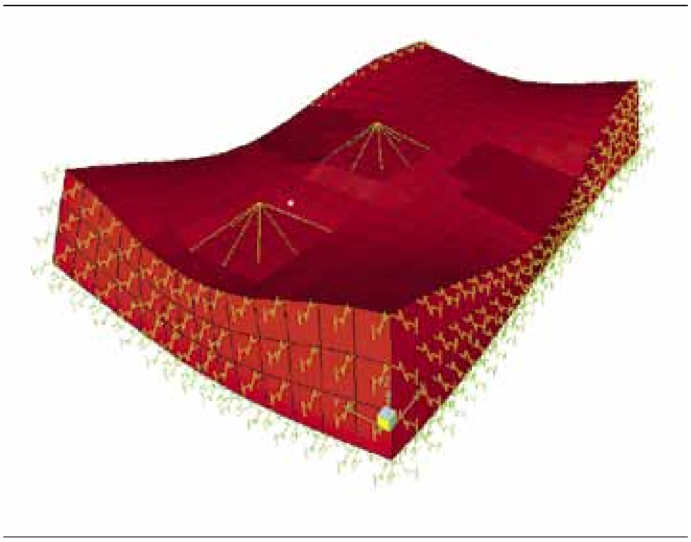
1 ASDS overview



2 Back to back test setup



3 FE flexible model of the foundation



4 Construction of the foundation

case 10.6 MW and 15 MW for the gas injection and gas lift respectively, while the rated power of the synchronous machines are 13.5 MW and 18.2 MW. Such a test requires available power, adequate facilities and experienced know how. The cooperation between ABB's Process Automation experts and the team from CESI was the key to success.

Test-field power figures

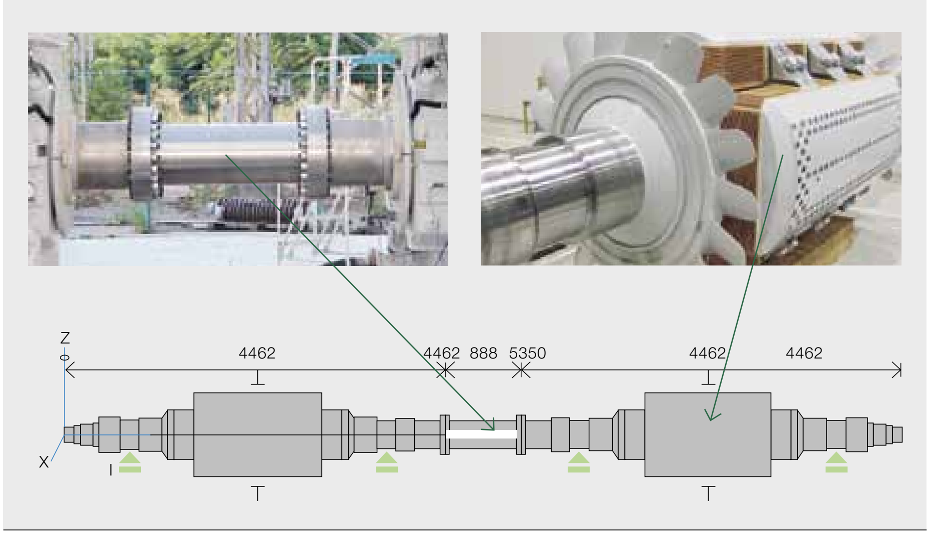
The test bay is fed by a devoted 70 MVA, 220/24 kV transformer, directly connected to the Italian high voltage power transmission grid. This ensures a reliable and stable power supply as well as a high short circuit power at the point of coupling (PCC) 600 MVA. The high short circuit power at PCC means a lower voltage drop at equal load conditions and a higher harmonic current injection to the utility system. This made it possible to make the design of the harmonic filter easier and more cost effective. A 20/25 MVA autotransformer is used to step up the voltage to the ASDS transformer primary winding voltage: 33 kV. The autotransformer, with its inherent low short circuit impedance, is the perfect choice to keep a high short circuit level at supply side. The short circuit power at 33 kV is in fact 350 MVA, in a ratio larger than 20 compared to the adsorbed power, hence no dynamic issues were faced.

The importance of a stiff foundation

Special care has been taken to design the foundation for the rotating machines. The foundation must ensure a rigid mounting for the rotating machine (IEC 60034-14). A foundation of 20 × 13 × 3 m was designed and built from scratch in the test bay. A finite element (FEM) model of the foundation resting on the Winkler spring bed was set up to compute flexible eigenvalues and eigenvectors → 3. Since flexible modes can be excided by unbalanced forces, a dynamic analysis was carried out with the FEM model to evaluate the foundation vibration at the motor fixing point. The maximum vertical vibration of the motor fixing point was calculated around

The LCI converter is an inherent four-quadrant converter and is well suited to the back to back test configuration.

5 Back to back shafting construction



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10^{-3} mm/s, below the lowest threshold values listed in the IEC 60034-14 for class B vibration limits (25 percent of 1.5 mm/s for motor with shafts height greater than 280 mm) ➔ 4.

Rotor dynamic analysis and pulsating torque in the air gap

The coupling between the two synchronous machines was designed to withstand short circuit torques and to avoid possible resonances due to the pulsating torque in the air gap of the rotating machines generated by the converter operation ➔ 5.

The power converter driven machines are subject to pulsating torque in the air gap ➔ 6. The pulsating torque components are due to the current harmonics which are impressed on the motor by the converters. These pulsating torque components can be classified as follows (f_M = motor frequency; f_N = line frequency):

- integer pulsating torques with the frequencies n f_M, (n = 6, 12, 18, 24)
- non-integer pulsating torques with the frequencies k f_N (k= 6, 12)
- non-integer pulsating torques depending on both the network frequency and the motor frequency according to: $f = |n f_M \pm k f_N|$ (n = 6,16; k = 6, 12).

Although the amplitudes of the pulsating torque are small compared to the driving torque, they can excite resonances when their frequencies coincide with a natural frequency (modes) of the shafting. The coupling was designed in order to guarantee a separation margin between the intersections (resonances) of the inclined lines and the modes.

Harmonic filter and reactive power compensation

To compensate reactive power and harmonics a filter system was designed and commissioned for this test ➔ 7. The filter used during the test was built up in three branches and tuned to the, 5th, 11th and 23rd harmonic order, to reduce the current harmonics injected by the LCI converter into the network. The capacitors of the harmonic filter are also used to compensate the reactive power adsorbed by the converter.

The characteristic current harmonics are absorbed by the filter branches for the 11th and 23rd. The non-characteristic harmonics N=5 are absorbed by the 5th harmonic filter ➔ 8. The reactive power of all three filter branches (per drive) adds up to 11.5 MVAr for the gas lift system and 6.5 MVAr for the gas injection system (only 5th and 11th filter branches were switched on). The measured voltage THD was 0.85 percent, far below the recommended IEC prescriptions (<5 percent IEC 61000-2-4, class 1).

Test schedule and results

The ASDS has been subjected to the entire test sequence listed in the Shell Design and Engineering Practice for AC electrical VSDs. Heat run, load, no load, functional and fault condition tests have been carried out ➔ 9. A network analyzer installed in the test bay shows the voltage and current at the primary and secondary side of the transformer when the filter is switched on ➔ 10.

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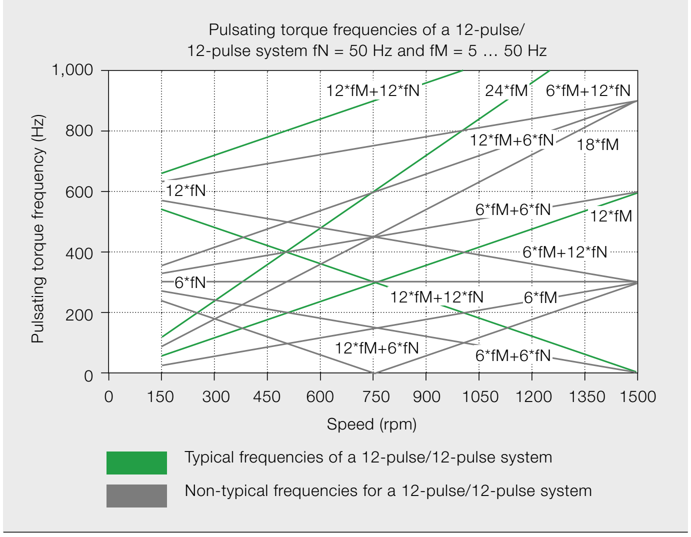
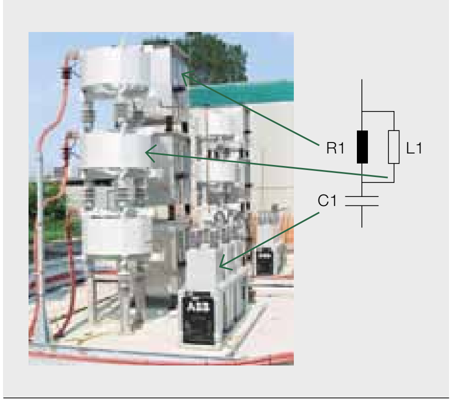
The efficiency of the adjustable speed drive system is determined by summation of the losses of the drive system equipment that are measured or calculated (segregated losses method) [2]. The test has shown that the efficiency of the

6 Pulsating torques

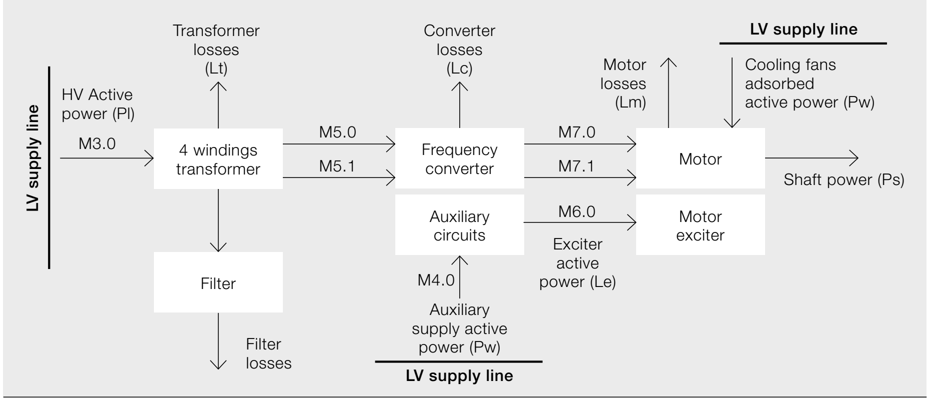


7 Reactive power and harmonics filter

8 5th harmonic filter branch



9 Active power flow during tests



ASDS is 95.76 percent. This value complies with the anticipated figure.

A proper measurement strategy has to be adopted for measuring the electrical variables in the case of a distorted load like a frequency converter.

Active power is defined as:

$$P = \frac{1}{k \cdot T} \cdot \int_{\tau}^{\tau + k \cdot T} p \cdot dt$$

(p is the instantaneous power: $p = v \cdot i$)

Applying Fourier analysis to voltage and current, the active power results as the sum of two terms: P_1 and P_H, the fundamental active power and the harmonic active power respectively.

$$P = P_1 + P_H$$

Fundamental active power (W)

$$P_1 = V_1 \cdot I_1 \cdot \cos\delta_1$$

Harmonic active power (non fundamental active power, W)

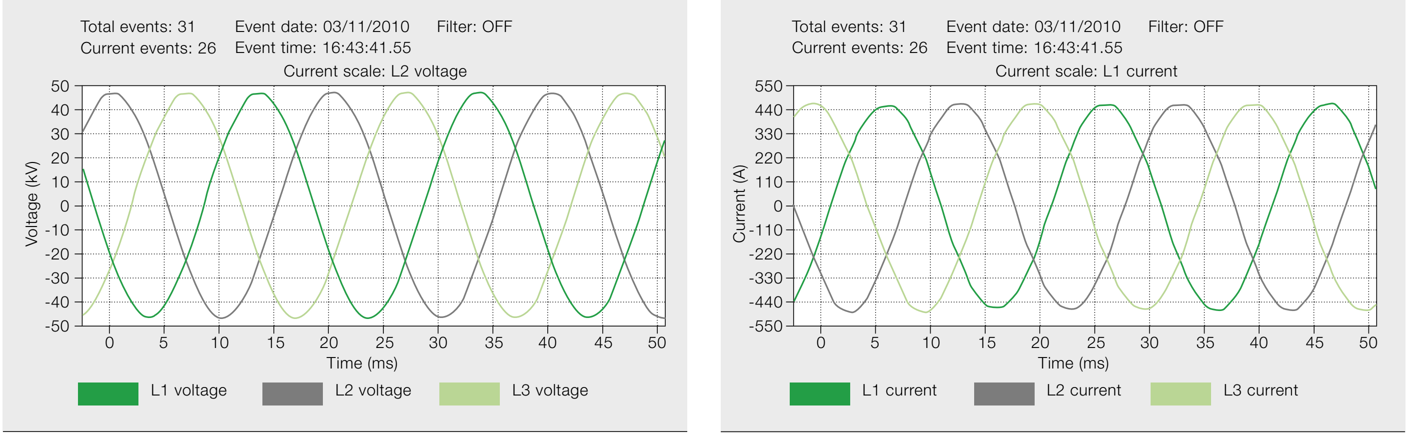
$$P_H = V_0 \cdot I_0 + \sum_{h \neq 1} V_h \cdot I_h \cdot \cos\delta_h$$

For the electrical machine the harmonic active power is not a useful power, that is, it does not contribute to the positive sequence torque. Consequently, it is meaningful to separate the fundamental active power P_1 from the harmonic active power P_H.

The measurement of P_H itself is not an effective way to evaluate harmonic power flow, because some harmonic orders may generate power while others dissipate power in the observed load, leading to mutual cancellation in the P_H term. Only a complete listing of the harmonic voltage and current phasors (magnitude and phase) can lead to a clear understanding of the contributions made by each harmonic to the electric energy flow [3].

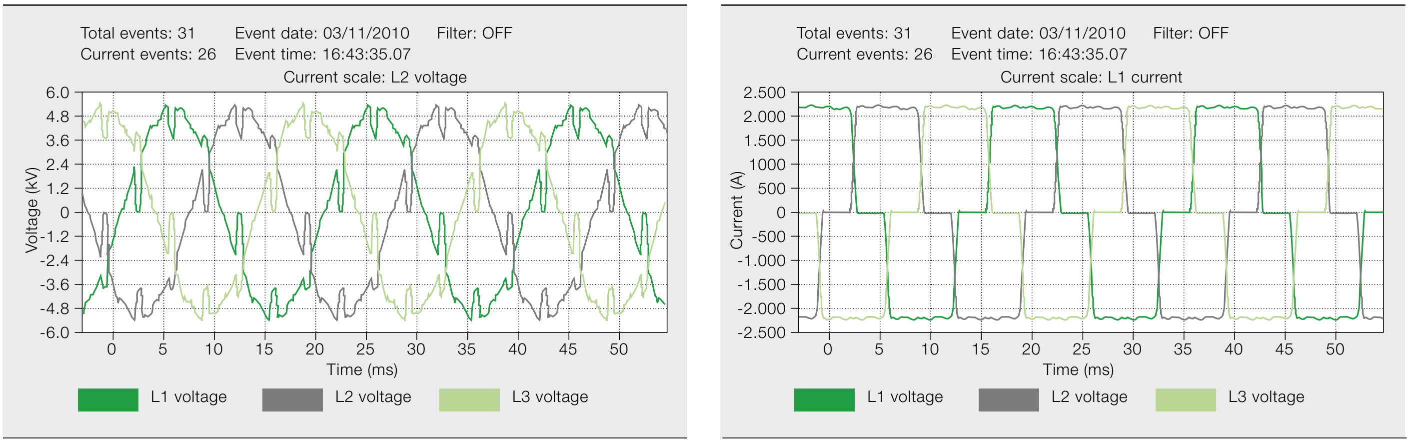
The test experience gained in this field is used to give customers the confidence that their drive system meets their efficiency requirements.

10 Voltage and current at primary and secondary side of four windings transformer



10a Voltage at primary side

10b Current at primary side



10c Voltage at secondary side

10d Current at secondary side

Valuable outcomes

Two 13.5 MW and two 18.2 MW ASDSs have been successfully tested by ABB's Process Automation division for oil and gas in its test facilities at CESI Milan, Italy. The test set up is ready to accommodate machines of up to 40 MW and more.

The test experience gained in this field is used to give customers the confidence that their drive system meets their efficiency requirements and that the system will deliver the nominal power it is designed to. Furthermore the full load performance test can prove that the equipment is compliant for the project specification according to the standards of the oil and gas industry.

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Further reading

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