INTEGRATED MOTO-COMPRESSOR VERSUS CONVENTIONAL SOLUTION

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Abstract – Up to 30 MW, thanks to the development of high speed induction & permanent magnets motors and active magnetic bearings, integrated moto-compressors represent today an alternative solution to conventional compression trains using turbines, for both onshore and offshore applications. The process gas is used to cool both the motor and the magnetic bearings making the unit fully hermetic. The first part of the paper describes the integrated solution from an architecture stand point, driven single-stage or multi-stages compressors. This seal less and oil free technology offers numerous advantages such as simplicity, compactness, robustness with zero hydrocarbon emission with very limited maintenance. The second part deals with gas classification and qualification in terms of contaminants (Water, H2S, CO2 ...) and process conditions as the process gas is directly in contact with the motor components (stator, rotor, cabling and magnetic bearings). The third part focuses on the advantages of using an Active Front End Voltage Source Inverter without sinus filter in association with the high-speed motor. Today, the technology is available for most of upstream oil and gas applications.

Index Terms – Electromechanical systems, Compressors, Induction motors, Voltage-source converters, Active magnetic bearings, Gas, System optimization.

I. TRADITIONAL COMPRESSION TRAIN ARCHITECTURES & CONSTRAINTS WHERE WE CAME FROM!

Centrifugal compressors are essential to the Oil & Gas industry. From Upstream to Downstream they respond to totally different operational needs with a large variety of gases. Downstream refinery and chemical segment mainly use them for large ethylene, propylene and cracked gas compressors running on a continuous regime. Midstream business is oriented on storage and transportation of commercial gas with intermittent operations. Whereas Upstream is a combination of numerous services: high pressure gas injection to enhance oil recovery, low pressure gas recovery to avoid routine flaring, gas export, refrigerant compressors for LNG applications, CO2 reinjection etc. with an equivalent combination of operating regime: continuous, intermittent or even recycling.

A centrifugal compressor is an equipment dedicated to a specific application, which makes its design in terms of pressure, flow rate, absorbed power, type of gas and compressibility, aerodynamics internals, totally unique. On one hand, a recovery flare gas compressor can be limited to a very small quantity of gas compressed from atmospheric pressure to only few bars requiring an absorbed power down to 10 kW, and on the other hand injection compression trains reach 800 bar discharge pressure, LNG compression trains handle millions of cubic meters per day requiring tens of MWs. Other applications such as propane, CO2 or ethylene compressor are completely different in terms of aerodynamic design. The water saturation, H2S, CO2 or other chloride contaminants will impact the very challenging material selection to avoid corrosion or sulfide stress cracking phenomena. A compression train design is of course linked to the centrifugal compressor but must also consider, the type of driver, the environment, the installation and the operating requirements. For downstream a compressor is usually driven via a steam turbine or electrical motor but for upstream and midstream gas turbines are often used as driver. Based on the driver selection, the shaft line might require including a lubricated gearbox to meet speed and power requirement, especially in the case of a gas turbine which is also sensitive to ambient conditions. The environment has also, an unneglectable impact on these units. It is important to note that, especially for upstream, compression units are installed everywhere around the planet and very often in harsh environment. From onshore installations located either close to the arctic or Antarctic in cold and windy sectors, to hot areas such as the Middle East, or even in wet and stringent atmospheres the packaging of the compressor is significantly different. For offshore, not only are the units installed in marine environment, but the support may vary from a fixed rig to a floating production facility impacting the overall design.

The operating requirements and the potential production evolution validates that the electrical drive make the unit more flexible from an operating stand point compare to a turbine drive for an upstream and offshore application (Fig. 1 and 2). Such electrical motor compressor package is widely used in the upstream and offshore segment. The footprint (length x width) and weight of a typical 10 MW train are respectively about 12 x 5 meters and 100 tons.

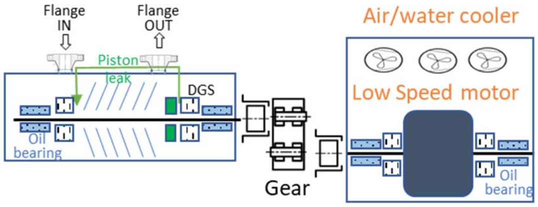


Fig.1 Standard Oil Lubricated Gearbox Moto-compressor Architecture (A-1)

Fig.2 Standard Gearbox Moto-compressor Package

Their almost standardized configuration still presents several main concerns as summarized here-after:

- Large and heavy conventional speed synchronous or induction Electrical Motor (EM) powered by a VSD, both EM and VSD being water cooled,
- Requirement for a speed increase lubricated gear box (typical from 1500 or 1800 rpm to 15000 rpm for 4-pole motors),
- Requirement for low and high-speed couplings,
- The compressor is equipped with dry gas Seals DGS, which clearly represent the weakness point of the package from a reliability stand point,
- Requirement for a lubricating oil system to lubricate the whole shaft line bearings and to remove the heat generated by the gear box, with all auxiliaries (pumps, filters, coolers, valves, etc.),
- Atmospheric oil drainage for offshore floating installation,
- Requirement for a complex and expensive seal gas conditioning system to properly feed the DGS and including: scrubber, filter, pressure control valves, pressure safety valves, heater, booster, nitrogen and instrument air supplies and many transmitters,
- Many auxiliary and connections for air, nitrogen, cooling water and air supplies,
- Continuous gas leakage to the flare from primary dry gas seal and oil vapor from bearings,
- Noisy package requiring sometime acoustic treatment on gear box and/or compressor, or worse complete enclosure to match local regulation requirements,
- Long commission time due to the complexity of the package,
- Large integrated CAPEX and high OPEX.

II. HISTORY OF INTEGRATED COMPRESSORS WHERE WE ARE TODAY…

A. The Technology Breakthroughs

At the end of the 80's, thanks to the development of two technologies breakthroughs, the High Speed (HS) asynchronous motors and the Active Magnetic Bearings (AMB), high speed and oil free motor driven compressor packages have been introduced on the market based on two solutions: Standalone and Integrated.

Based on available technologies [1], the squirrel cage rotor is adapted for high speed conditions up to 18000 rpm and the permanent magnet rotor technology above 15000 rpm. The induction rotor comprises a steel lamination assembly compressed by tie rods between two end rings and two shaft ends, named shaft-less technology (Fig. 7). The cage bars can expand axially through the end ring avoiding any risk of deterioration by thermal fatigue mechanism at the interface of the copper bars and the steel shaft, respectively having coefficients of thermal expansion of 17.10^{-6} K^{-1} and 12.10^{-6} K^{-1}. The copper bars are inserted in the slots between the two end rings to form the squirrel cage (Fig. 3). The laminated technology allows high efficiency in reducing the high frequencies losses induced by the VSD, and high rotor peripheral speed up to 270 m/s, providing high robustness in terms of aging and stability over the time [2]. The system of insulation of the stator is customized for high speed VSD: Class H (180°C) Insulation, Class F (155°C) Temperature Rise, Vacuum Pressure Impregnated (VPI).

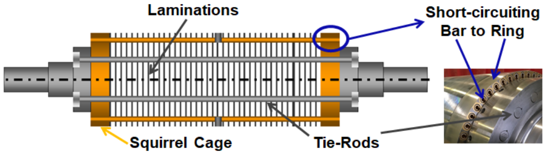


Fig.3 HS Laminated Induction Rotor Technology

B. Standalone Solution

In a Standalone system, the compressor is directly driven by the HS air cooled induction motor fed by the VSD, removing the gearbox. The AMB assures an oil free shaft line without disturbances of bending natural frequencies. A project of full electric platform in Norway uses this technology [3]. The HS motors and the AMB are directly cooled using air at the atmospheric pressure. The compressors which are directly driven by the HS motor are still equipped with DGS and their associated conditioning system. If the shaft lines are "oil free", the DGS and associated systems make the architectures quite complex and not optimized.

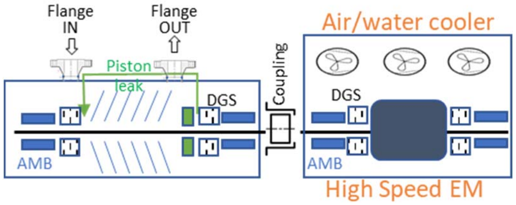


Fig.4 Standalone HS moto-compressor architecture (A-2)

Fig.5 Standalone Motor Compressor during Shop Testing

C. Integrated Solution for Mid-Stream Market

To simplify the Standalone configuration the idea of Integrated concept came to directly cool the HS induction motor and the AMB using the process gas handled by the compressor. The process gas used to cool the motor and the bearings allows to remove the shaft end seals and the associated conditioning system, making the moto compressor package fully hermetic. The first objective was to use this technology for pipeline stations requiring high gas flows and low-pressure ratio (Fig.8):

- Gas is mainly dry and clean methane which is a better dielectric insulator than air and with thermal conductivity 4 times higher than air to improve the cooling and compactness of the motor without changing the stator resin of impregnation.
- A solution with single-stage impellers at the end of the electric rotor makes it possible to generate enough pressure ratio for the pipeline (Fig.6 & 7).

When operating conditions require adjustment below 80% of the nominal speed, the integrated high compression is a CAPEX & OPEX justified alternative to conventional compressions [4]. The first order was delivered in 1989 for a pipeline station in US

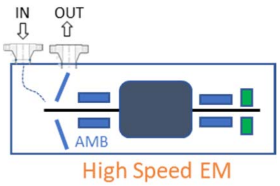


Fig.6 Integrated Single-Stage Architecture (A-3)

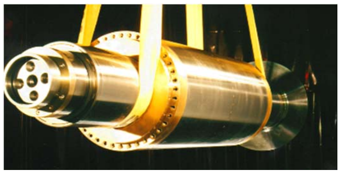


Fig.7 Laminated High-Speed Squirrel Cage Rotor

Fig. 8 Pipeline Station in US using 4 Integrated Compression Units of 3.4MW @ 10 000 rpm [5]

In the 2000s, the next step was to increase the compression ratio with an integrated architecture using a multi-stage compressor for pipe & storage markets (Fig. 9 & 12).

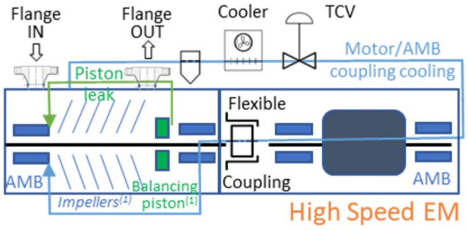


Fig.9 Integrated Multi-Stage Architecture (A-4)

The architecture using a flexible coupling, or a quill shaft, is very robust and adapted for these applications because it avoids the vibratory interactions between the motor and the compressor, simplifying the Single Input Single Output (SISO) control command of the AMB [2][6]. Since this time more than 80 systems are in operation all over the world with cumulated hours over 4.000.000 hours. Some machines are subject to gas refouling. They must be cleaned during maintenance operations scheduled with the operator (Fig.10 and Fig.11).

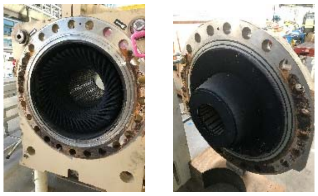


Fig. 10 Example of motor pollution by gas refouling after 5 years of operation

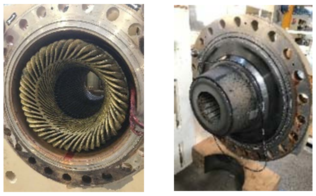


Fig. 11 Example of motor cleaning during periodic maintenance operation

In 2007, and after a long qualification process the qualification of Integrated compression system was validated for “Clean and Dry” natural gas applications with low contaminants such as H2S (< 15 ppm) and with some limitation in term of pressure, speed and power. Two (4.5MW - 2.8kV - 12000rpm) systems were ordered, tested [7] and installed in Bolivia, suitable to export 7.5 MSm^3/day of natural gas on the domestic network from 73 to 106 bars. The units with a single overhang impeller are based on a rigid shaft installed on two AMBs and requiring a single magnetic bearing cabinet (Fig.13). The commissioning and start-up of both units was performed in 2016.

Fig.12 Pipeline Station 8.6MW - 6kV - 11000 rpm

Fig.13 Single-Stage Motor-Compressor during string test

D. Integrated Solution for Up-Stream Market

In 2005, the qualification and prototyping of integrated machines for subsea compression applications were launched. Thanks to the tremendous advantages offer by such simple architecture, the same concept can be used for upstream topside applications whatever the gas application and the location (onshore vs offshore, indoor vs outside). The main concern of the architecture is the capability of the HS motor and the AMB to be cooled and to operate within the process gas which contains contaminants such as H2S, CO2 with water saturated conditions, and some condensation may happen during coast down and pressurized stops. Although process gas is showing zero or very low amount of dissolved oxygen, the combination of oxidizing components such as CO_2 or H_2S

and water makes the gas susceptible to promote corrosion of metallic and non-metallic parts. In Upstream field, generally 3 types of gas are classified:

- **Sweet gas** containing CO_2 with relevant amount that makes the pH low enough to promote general corrosion on Low Allow Steels (LAS),
- **Sour gas** that brings H_2S under a certain amount, which increases the susceptibility of certain alloys to Sulfide Stress Cracking,
- **Acid gas** with high level of H_2S and CO_2 which is very aggressive in term of general and localized corrosion on metals. Almost no reference of hermetic moto-compressor is known in the literature.

In addition of these oxidizing components some contaminants such as chlorides, free hydrogen, mercury, ammoniac … can bring additional environmental risks to metals. Upstream services at lower pressure than the TEG unit (generally between 60 and 100 bar) are very often associated to one of to the 3 latest listed gas conditions. The motor including all its component needs to sustain the operating pressure which is the suction pressure of the compressor in normal operation or the settle out pressure in stand by condition. This may impact the design of the motor casing including its sealing and the Low Voltage and Medium Voltage connections and penetrators. All nonmetallic component need to withstand the rapid decompression rate the unit can face during emergency shut down. Since 2005, manufacturers have produced large effort to make the Integrated moto-compressors compliant to sweet and sour gas. Following Technical Readiness Level (TRL), three types of tests, under polluted pressurized natural gas conditions, have been performed to validate the product development:

- **Tests-1**: Component aging under pressure tests & Rapid Gas Decompression to pre-select potential or existing materials classified on 4 categories: Iron-alloys (steel, stainless-steel, laminations…), Non-iron alloys (copper, nickel…), Composites (Resin, Organic, Insulation…) and Penetrators & Probes,
- **Tests-2**: Aging and Rapid Gas Decompression (RGD) tests on components at scale 1 or reduced following a Design Of Experiment methodology (DOE),
- **Tests-3**: Final product testing on system demonstrator.

For example, the **Tests-1** allowed the selection of resins of impregnation resistant to the risks of hydrolysis under pressure whose conditions of saturation in water vapor are characteristic of the storage and upstream processes (Fig.14, 15 & 16) [8]. Some resins tested were completely hydrolyzed after 1000 hours of aging in an autoclave. The **Tests-2** motor was designed to explore multiple parameters. This included a stator with frame and end-shields designed and built with twelve different combinations of turns, ground-wall, finishing tape and feedthrough connectors. Each of the twelve insulation systems was dedicated to a unique, electrically-separable coil set (Fig.17). The main purpose of the stator frame and end-shields was to provide a full-scale autoclave for testing the different electrical insulation systems for the stator windings [9] and lead connections. Several samples were also introduced inside the enclosure of the machine that were exposed to the same corrosive environment as the winding and are being used on future machines based on their performance during this environmental ageing test (Rotor with different coatings).

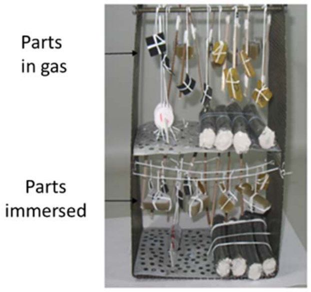


Fig 14 Samples for ageing **Tests-1** under pressure

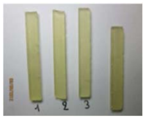


Fig.15 Resin before **Tests-1**

Fig.16 Resin after 1000h ageing **Tests-1**

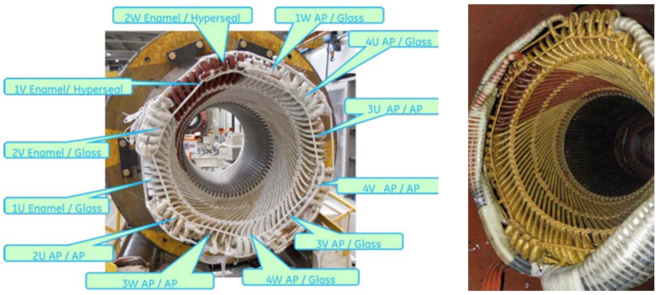


Fig. 17 Stator during manufacturing (left view) and after **Tests-2** cumulated 2500 ageing hours (right view)

The motor was subjected to a series of tests at different pressures, temperatures, gas compositions, and time lengths. These tests were intended to expose the motor internals to harsh environment and determine if the system performance degraded overtime (Fig. 18) [10].

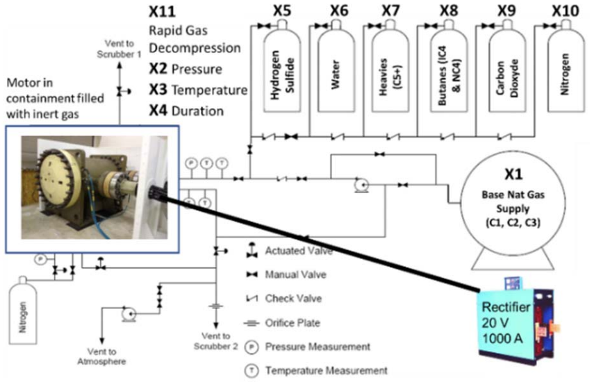


Fig.18 **Tests-2** Design Of Experiment

Before, during, and after testing, a series of electrical performance tests were conducted. These were done to explore the effects of gas on the insulation and the copper conductors. Test techniques employed included winding resistance, insulation resistance, capacitance and dissipation factor, and partial discharge analysis.

The **Tests-3** were performed on 11MW-6kV-11000rpm Subsea demonstrator in Norway (Fig.19). A weakness of power cables against Mono Ethylene Glycol (MEG) used as antifreeze was discovered during the tests (Fig.20). This allowed to validate a solution of cables resistant under RGD conditions (Fig.21).

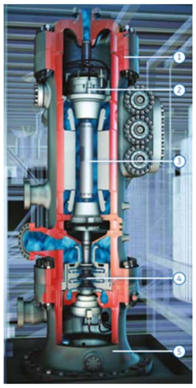


Fig.19 Subsea Integrated Moto-Compressor

Fig.20 Cable Insulation Failure during **Tests-3**

Fig.21 Cables improvements for Subsea Demonstrator

The up-stream integrated motor is designed for the following conditions.

- Up to 15 bar partial pressure CO2
- Up to 15 mbar partial pressure of Wet H2S
- Up to 150 mbar partial pressure of Dry H2S
- Up to 200 bar SOP
- Up to 100% relative humidity at suction
- RGD < 30 bars/min
- Experimental particules erosion « wear map »
- Up to 1µg/Nm^3 of gaseaous Mercury

In 2016, the qualification of this technology for “Water Saturated” natural gas applications was pronounced, meaning 100% of relative humidity, with only some traces of H2S, and in 2018 the qualification for “Water Saturated” natural gas applications covering up 15 bar partial pressure of CO2 and 15 mbar partial pressure of H2S both at settle out pressure. The qualification is also limited by some pressure constraints to cope with AMBs capabilities and connector limitations. Nevertheless, 80% of the upstream applications might be today based on this innovative technology including the following main advantages (Fig.22):

- Strong reduction of weight and footprint (and compactness)
- No more gear box, no more lube oil system, no more dry gas seal systems,
- No cooling water, no lubricating oil, no instrument air, no nitrogen,
- Only few remaining instruments,
- No emission (no gas leakage to the flare, no oil vapor) and low noise,
- Maintenance free (no DGS),
- Reduction of commissioning time and start-up operations,
- Reduction of integrated CAPEX and low OPEX

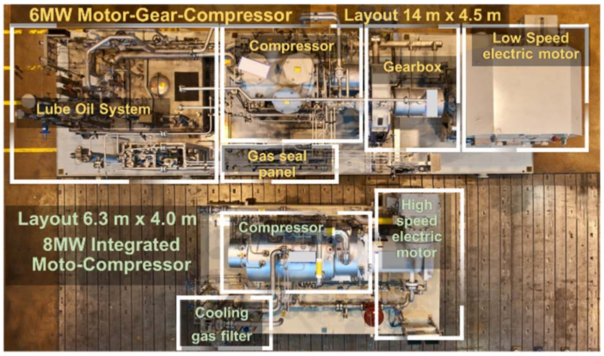


Fig.22 Gearbox Standalone Architecture (A-1) vs Integrated Multi-Stage Architecture Layout (A-4)

III. ELECTRICAL SYSTEM

Variable speed electrical systems are powered by a 50 or 60Hz grids that are either islanded (powered by aero derivative gas turbine generators) or public via onshore wiring of a few kilometers or off-shore up to 200km [3]. The management of harmonics and the active and reactive power of the grid for powers in the range of 50 to 100 MW is a key point of the choice and sizing of the electrical system. Furthermore, for off-shore applications, as the motor-compressor, the weight and size of the embedded electrical system must be minimized.

A. Voltage Source Inverter

Voltage Source Inverter (VSI) drive is commonly used to drive integrated electric compression train since it allows to control high speed induction motor at a requested power factor, maximizing the torque generation by an optimum vector control [2]. VSI technology has been applied to many low speed and high-speed applications in a wider range of power. VSI drives inverters can deliver now several MW within a small volume and with a small number of power components, what give them a high reliability. Due to the high-speed motor, the VSI inverters operate at fundamental frequencies above 60 Hz therefore there is a power derating of the inverter due to the significant switching losses of power semiconductors. A VSI output sine filter is usually required to feed the high-speed motor but by controlling the semiconductors of the inverter with a pulse synchronous control there is a significant reduction of the harmonics of currents fed into the motor, limiting the stator Joule losses and the torque pulsations. In a refinement of the diode-clamped converter, the so-called NPP PWM VSI converter, the clamping diode valves are replaced by IEGT valve giving additional controllability. With such a topology, each valve commutates with only half the DC bus voltage, which reduces drastically the losses of the device commutation. The output voltage is increased proportionally to the number of power switches per valve, each device being operated with the same current and sharing the same voltage. A 3kV 3-Level NPP inverter has 2 IEGTs in serial arrangement per half phase (#ph = 2) and 2 IEGTs in back to back arrangement at neutral point location (#np = 1+1) (Fig.23).

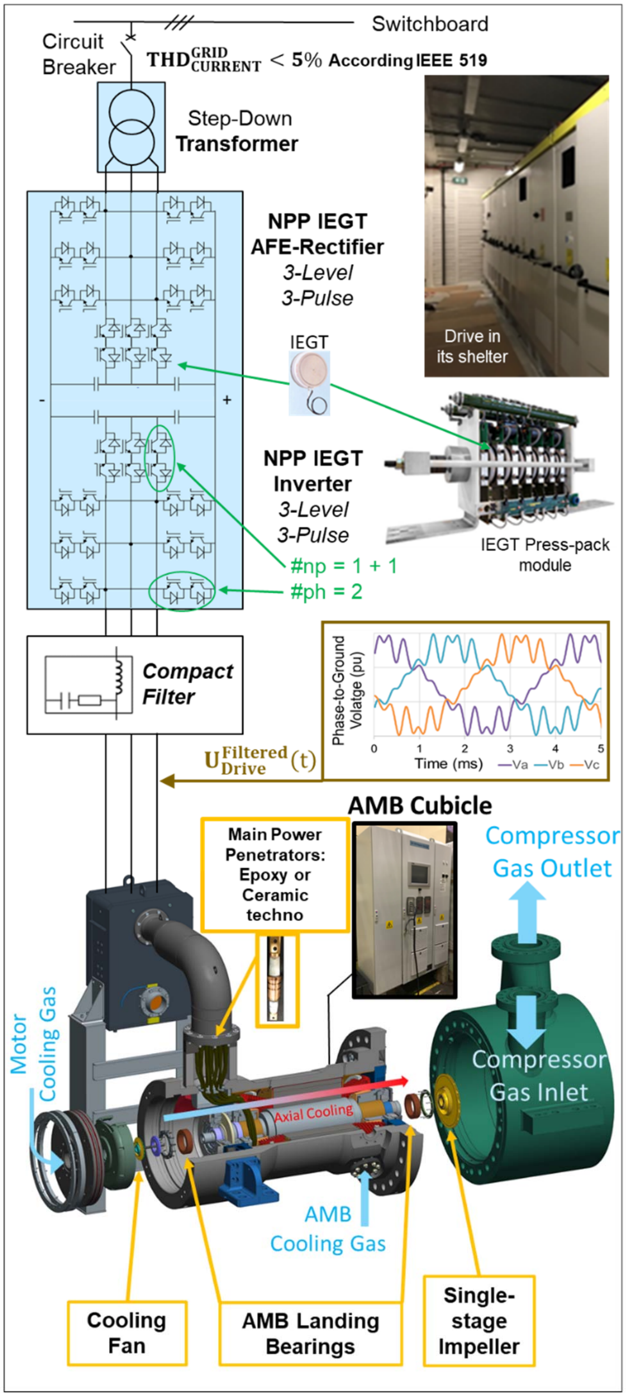


Fig. 23 NPP 3-level VSI-AFE Integrated Single-Stage System

The failure mode of the press-pack self-commutated power devices connected in series is its short-circuiting. If a cell in a valve fails to switch on, then the whole voltage of the valve is applied to a single component which cannot withstand it and short-circuit itself. For many years, this feature has been used in thyristor valves to increase the availability of large VSD. By increasing the number of power devices in each valve, above what would be strictly necessary regarding their voltage withstand capability, it becomes possible to continue operating an VSD even in case of failing power devices. Above 3kV, this possibility is quite valuable for trains where any unintentional stop can cause severe production losses (Fig.24). The switching angles of the pulse synchronous control PWM are found by solving the following system of equations if, for instance, it chosen to remove harmonics 5 and 7 (Fig.25).

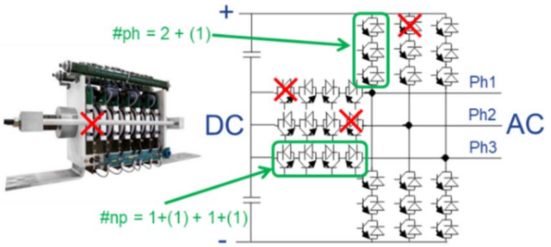


Fig.24 (N+1) Redundancy in a VSI operating with (N) Cells

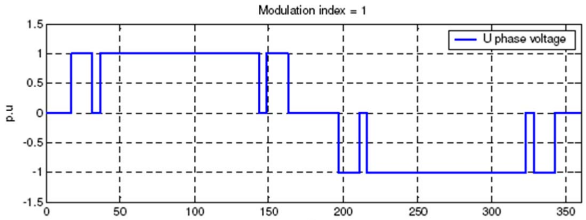


Fig.25 Example of pulse synchronous control

$$\begin{cases} \cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) = \dfrac{\pi * M}{4} & (1) \\ \cos(5*\alpha_1) - \cos(5*\alpha_2) + \cos(5*\alpha_3) = 0 & (2) \\ \cos(7*\alpha_1) - \cos(7*\alpha_2) + \cos(7*\alpha_3) = 0 & (3) \end{cases}$$

where: M is the modulation depth

α_1, α_2, …, α_n are the switching angles

When the motor thermal margin is sufficient, the LC sine filter can be avoided and replaced by a LLC filter or a dV/dt filter which is in any case necessary to avoid any risk of reflected wave and voltage overshoot at motor (Fig. 26, 27, 28). The dV/dt filter reduces the semiconductors transient switching voltages below 1.5kV/µs to protect the inter-turn insulation of the stator coils as requested by the IEC or API standards (Fig.29). The dV/dt filter is very compact and lightweight compared to a sinus filter (Weight ratio of 10) which for this latest often requires either a crow bar or a discharge resistor to damp a possible self-excitation resonance when the VSI is stopped or tripped when spinning.

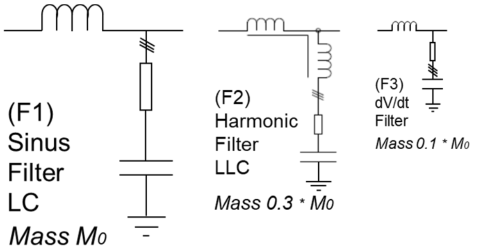


Fig.26 Inverter Filters Comparison

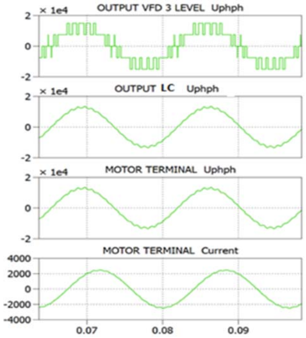


Fig. 27 Motor Voltages and Currents with Sinus Filter

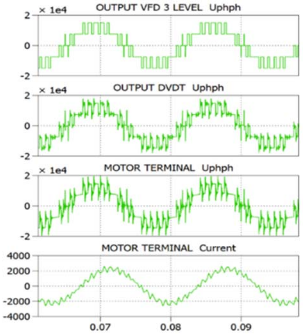


Fig. 28 Motor Voltages and Currents with dV/dt Filter

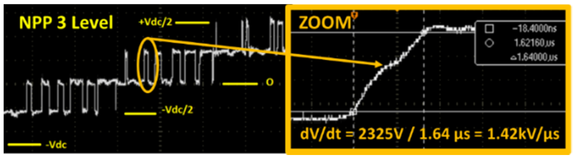


Fig.29 Phase to Phase voltage of a 3-Level NPP VSI with dV/dt output filter with zoom on dV/dt slope

B. Rectifier and Grid Management

Usually VSI drives are used with a Diode Front End (DFE) rectifier, but offshore where there is weight and footprint limitations, it is proposed to use an Active Front End (AFE) rectifier since it simplifies the design, the cost, the footprint and the weight of the VSD transformer which is simpler with only one secondary winding instead of a multi winding configuration used with DFE rectifiers (Fig.30). When the switchboard is at Medium Voltage (≤13.8kV), it is even possible to remove the transformer, in this case the rectifier is directly connected to the busbar through an input reactor dedicated to limit the short circuit current and filtering the line current. The weight and footprint are furthermore reduced. For subsea cable power from shore applications, with an AFE the Power Factor of the VSI can be regulated to 1 (Fig.31). At the offshore point of connection between the platform and the subsea cable, there is no offshore reactive power exchange during operation of the integrated compression train. This minimizes offshore voltage variations during load ramp up and load shedding, therefore offshore grid is more stable and more robust to load variation disturbances. The following table I summarizes the DFE & AFE converters range using NPP technology including weight and layout.

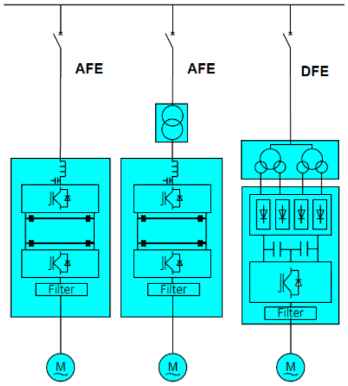


Fig. 30 VSI AFE vs VSI DFE

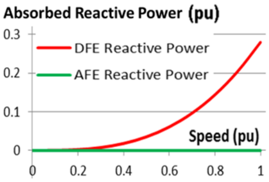


Fig. 31 VSI Reactive Power Consumption vs Motor Speed

TABLE I
Extract of the 3-Level NPP-VSI Drive Range

Ph-Ph V	3 kV	6 kV	6 kV	7.5 kV
Power	6.5 MW	8.8 MW	13.7 MW	20 MW
# ph ; # np	2 ; 1+1	4 ; 3+3	4 ; 3+3	6 ; 3+3
VSI-DFE (m^3)	5.6x1.0x2.5	6.6x1.4x2.5	6.8x1.4x2.5	9.8x1.4x2.5
VSI-DFE	5.8 Tons	7.4 Tons	7.8 Tons	11 Tons
VSI-AFE (m^3)	9.4x1.0x 2.5	12.4x1.4x 2.5	12.8x1.4x 2.5	15.8x1.4x 2.5
VSI-AFE	9.5 Tons	14 Tons	15.5 Tons	15 Tons
Sinus-Filter(m^3)	2.8x1.0x2.5	4.2x1.4x2.5	5.0x1.4x2.5	6.2x1.4x2.5
Sinus-Filter M_0	2.7 Tons	5.9 Tons	6.4 Tons	7 Tons

IV. WHAT SHOULD BE THE FUTURE & WHERE WE WOULD LIKE TO GO!

A. End-user Standpoint

Most of the recent offshore Projects have been based on all electrical concepts. This is also a clear market tendency regarding the added value from operational and flexibility stand points. The moto compressors and more precisely the "fully integrated" packages are perfectly in line with the "all electrical" concept. It even represents a realistic solution in response to un-manned plants in the coming years. Even if the current technology of the machine is already available for almost all upstream applications the objective is to optimize and simplify the integration of the unit in a complete compression module including the following main equipment:

- Inlet and outlet process Shut Down Valves,
- Process equipment such as inlet scrubber, discharge cooler, if any, and the anti-surge loop and valve,
- Dedicated control/electrical room for VSD, sine filter if any, package UCP/PLC and AMB cabinet.

Such a module would be pre-commissioned to ease the integration on yard and to simplify the commissioning and the start-up activities at site. In addition, some simplifications might be envisaged to make the technology even more attractive for future projects:

- Simplification of the motor cooling system without any regulating valve, without any stator temperature measurement and lowering the number of residual transmitters on the package,
- No intermediate connecting boxes for HV (HS motor) and LV (AMBs) supplies,
- Liquid tolerant design to remove the inlet scrubber in conjunction with high head impellers to simplify the architecture and the arrangement,
- Rigid shaft for the HS motor rotor with only one or two impeller(s) installed overhung and with a single AMB(s) cabinet,
- New VSD topology to avoid the sine filter for compactness and robustness.

B. Manufacturer Standpoint

Except for high H_2S & CO_2 (Acid) and Ammoniac contents, cracked gas, and high-pressure reinjection above 400 bars, the integrated compression can be used for all other types of gas whose process conditions change over time:

- **Mid & Upstream:** Natural Gas and Associated gas (Sweet and Sour)
- **Downstream:** Ethylene (Fig.32), CO2, LNG Mix-refrigerant (Fig. 33), Propane, Butene, H_2 …

Fig.32 Ethylene Integrated Compression
2.8MW - 2.4kV - 11000 rpm
13 to 97 bars - 0.77 MSm³/day

Fig.33 Mix-Refrigerant LNG Integrated Compression
8MW – 5.6kV – 9400rpm

The map of pressure ratio as a function of the volume flow shows how the qualified compression stage architecture covers the different segments. In addition, alternative architectures with single stage, tandem trains or multi-driver (Fig.34 and Fig.35) illustrate how the compression capability can be improved thanks to a system optimization (Fig.36).

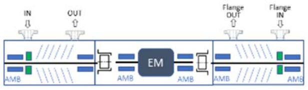


Fig.34 Dual Compressor Architecture (A-5)

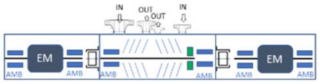
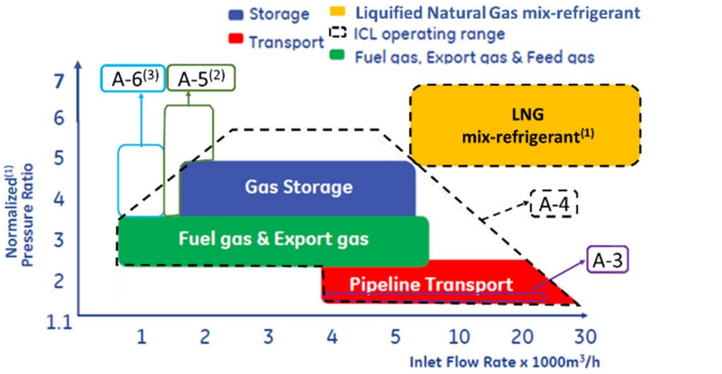


Fig. 35 Dual Motors Architecture (A-6)

For a given project, the methodology of design of compression could be described as follow. The end-user defines a need for compression in terms of mass flow for a given process (pipeline, storage...). The goal of the manufacturers is to propose an optimization in term of CAPEX and OPEX of the solution by segmentation using integrated or standalone (if gas not adapted) variable speed architectures.



(1): Pressure ratio map is normalized for a Natural Gas with a Mol. Weight ranging from 20 to 24 gr/mol
(2): gas storage applications with extended pressure ratio for low inlet pressure
(3): gas storage applications with extended pressure ratio for high inlet pressure

Fig.36 Integrated Compression Map vs Business Applications

The total compression power is defined for the following formula:

$$P_{comp} = Q_m(\text{Customer}).\Delta H(\text{Process}).\eta_{comp}(\text{Segmentation}) \qquad (4)$$

The optimum power delivers by a single-stage compressor is:

$$P_j^{(SS)}(t,\omega_j) = k_j\ .\ \rho_{gas,j}(t)\ .\left\{\frac{p_{o,j}(t)}{p_{i,j}(t)}.\varphi_{c,j}\ .\eta_j(\varphi_{c,j})\right\}_{(\omega_j)}.\omega_j(t) \qquad (5)$$

where $\rho_{gas,j}(t)$ is the gas density, proportional to $\frac{M_{mol,j}(t).p_{I,j}(t)}{T_{I,j}(t)}$ (6)

In the case of N stages of compression, the two extreme approaches are to compare, in one hand, the N-stage compressor whose optimized power in variable speed condition is given by:

$$P_{j=1,N}^{(MS)}(t,\omega^{(opt)}) = \sum_{j=1}^{N}\left\{k_j\ .\ \rho_{gas,j}(t)\ .\left\{\frac{p_{o,j}(t)}{p_{i,j}(t)}.\varphi_{c,j}\ .\eta_j(\varphi_{c,j})\right\}_{(\omega_{opt})}\right\}.\omega^{(opt)} \qquad (7)$$

and, on the other hand, N-single-stage compressors having each speed of impeller optimized:

$$P_{j=1,N}^{(SS)}\left(t,\omega_j^{(opt)}\right) = \sum_{j=1}^{N}\left\{k_j\ .\ \rho_{gas,j}(t)\ .\left\{\frac{p_{o,j}(t)}{p_{i,j}(t)}.\varphi_{c,j}\ .\eta_j(\varphi_{c,j})\right\}_{(\omega_j^{(opt)})}.\omega_j^{(opt)}(t)\right\} \qquad (8)$$

where the following equations are satisfied:

$1.2 < \frac{p_o(t)}{p_i(t)} * \frac{(M_{Mol}^{(gas)})}{(M_{mol}^{(CH_4)}=16_{g/mol})} < 1.4$ for best pressure ratio (9)

$0.005 < \varphi_c < 0.1$ maximizing $\eta(\varphi_c)$ where $\varphi_c = 0.05$ (10)

$T_o(t) < T_{max}^{design}$ avoiding materials failure (11)

$\omega < 1.3 * \frac{\text{Gas Sound Speed}}{R_{outer}}$ avoiding choke (12)

The cost of one N-stage moto-compressor is cheaper than a set of N-single-stage moto-compressors. The optimal solution in term of CAPEX and OPEX is between those two configurations of stages segmentation, without forgetting the start and stop conditions to avoid the severe conditions of Rapid Gas Decompression (RGD):

$P_{j=1,N}^{(MS)}(t,\omega^{(opt)}) \leq$ Optimal Solution $\leq P_{j=1,N}^{(SS)}(t,\omega_1^{(opt)},\dots,\omega_N^{(opt)})$ (13)

where for each electric system, the power consumption is:

$$P_{elec}(t) = \Gamma_{motor}(\text{Cooling})\ .\ \eta_{motor}(\text{Gas friction}).\eta_{VSI\ SYST}\ .\omega_{opt}(t) \qquad (14)$$

To conclude, the integrated compression consists in aiming at the specific speed, for a high efficiency and a gas transformation close to isothermal conditions. The next step of development is to improve the motor cooling to remove the sinus filter and to increase the compressor efficiency...

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VII. NOMENCLATURE

ΔH	Polytrophic Head (m).	Q_V	Volume Flow Rate (m^3/s).
R_{outer}	Impeller Outer Diameter (m).	Q_m	Mass Flow Rate (kg/s).
ω	Tip Speed Pulsation (Rad/s).	Γ_{motor}	Motor Torque (N.m).
φ_c	Gas Flow Coefficient.	P	Power (W).
p_i	Inlet Pressure (N/m^2).	T_i	Inlet Temperature (K).
p_o	Outlet Pressure (N/m^2)	T_o	Outlet Temperature (K).
M_{mol}	Molar Mass (g/mole).	#np	# of IEGTs on neutral point.
η_i	Impeller Efficiency.	#ph	# of IEGTs per half phase.
L	Inductance (H).	C	Capacitance (F).

AFE	Active Front End.
AMB	Active Magnetic Bearing.
CAPEX	CAPital Expenditure.
DFE	Diode Front End.
DGS	Dry Gas Seals.
DOE	Design Of Experiment.
IEGT	Injection Enhanced Gate Transistor.
LNG	Liquefied Natural Gas.
NPP	Neutral Point Piloted.
OPEX	OPerational EXpenditure.
PWM	Pulse Width Modulation.
RGD	Rapid Gas Decompression.
VPI	Vacuum Pressure Impregnation.
VSD	Variable Speed Drive.
VSI	Voltage Source Inverter.

VIII. VITA

Lionel DURANTAY graduated from the ENSEM (Ecole Nationale Supérieure d'Electricité et de Mécanique) with an engineering degree in 1989 then passed PhD in 1993. As R&D Leader, he has developed innovative variable speed motors & generators solutions for Oil & Gas, Renewable and Marine businesses. He has authored or coauthored 35+ technical papers. He presently holds 12+ patents. He is currently Chief Technology Leader in GE's rotating machines group.

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