SELECTION AND RETURN OF EXPERIENCE OF INTEGRATED MOTO-COMPRESSORS ON TWO OIL & GAS SITES

Paper No. PCIC Europe EUR22_11

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Abstract – With the development of high-speed motors and active magnetic bearings, integrated moto-compressors (seal less, oil free, centrifugal compressor driven by variable speed drive system) using process gas to cool the motor have been developed as an alternative solution to conventional compression trains using either turbines or low speed motor associated with gearbox.
The first part of the paper presents and describes the integrated moto-compressors and variable speed drive technologies used on two Oil & Gas sites in Europe and South America. The second part of the paper explains and gives the reasons of the selection of integrated moto-compressors for these two Oil & Gas sites. Finally, the last part of the paper provides the site operator and manufacturer return of experience of these integrated moto-compressors.

Index Terms — High-speed motor, integrated moto-compressor, magnetic bearings, VSD.

I. INTRODUCTION

With the development of high-speed motors and active magnetic bearings, integrated moto-compressors (seal less, oil free, centrifugal compressor driven by variable speed drive system) using process gas to cool the motor have been developed as an alternative solution to conventional compression trains using either turbines or low speed motor associated with gearbox. The first part of the paper presents and describes the integrated moto-compressors and variable speed drive technologies used on two Oil & Gas sites in Europe and South America. The second part of the paper explains and gives the reasons of the selection of integrated moto-compressors for these two Oil & Gas sites. Finally, the last part of the paper provides the site operator and manufacturer return of experience of these integrated moto-compressors.

II. INTEGRATED MOTO-COMPRESSORS AND VARIABLE SPEED DRIVE TECHNOLOGIES

A. Integrated moto-compressors

In a conventional electric motor driven compressor package, the compressor is directly driven by a 4-pole air cooled induction motor fed by the VSD, through a gearbox, and the complete shaft line is supported by oil lubricated bearings. Thanks to the development of the high-speed asynchronous atmospheric motors and the AMBs technologies, high speed and oil free motor driven compressor became available in the 90s. The high-speed motor technology allowed getting rid of the speed increaser oil lubricated gearbox to drive the compressor. The latter being supported by active magnetic bearings allowed getting completely rid of lube oil systems. Directly connecting the motor and the compressor in a hermetic pressure casing, in which both high-sped motor and AMBs are cooled by the process gas, allowed getting rid of the dry gas seals and the associated conditioning system. The gas processed in upstream conditions is containing a large percentage of methane which is a better dielectric insulator than air, with thermal conductivity 4 times higher than air, which improves the cooling and compactness of the motor [1].

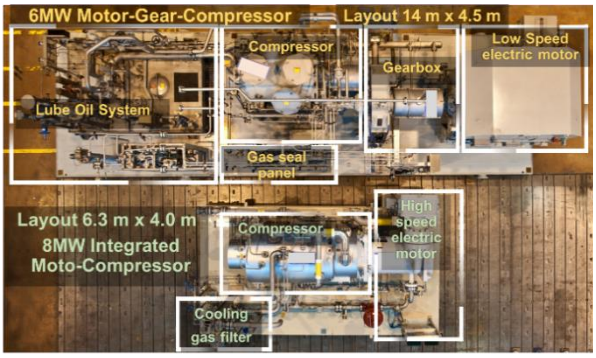

Fig.1. Gearbox Conventional Architecture vs Integrated Multi-Stage Architecture Layout

Compared to conventional electric compression, the integrated motor technology has the following main advantages (Fig.1):

- Strong reduction of weight and footprint,
- 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 direct emission (no gas leakage to the flare, no oil vapor) and low noise,
- Reduced maintenance (no DGS),
- Reduction of commissioning time and start-up operations,
- Reduction of integrated CAPEX and low OPEX.

When pressure ratio is lower than 1.6:1 the moto-compressor architecture can be simplified with a unique impeller generating the requested head to increase the pressure. Consequently, this impeller can be directly mounted on the motor shaft, saving the requirement of a separated compressor shaft and associated set of magnetic bearing. This simple architecture keeps the rigid shaft rotodynamic (Fig.2).

To keep the highest efficiency and avoid having the cooling flow recirculating on the complete compressor head, the electrical motor and AMB cooling is generated by a small fan (a small centrifugal stage) mounted on the opposite side of the main compression impeller (Fig.3). This small fan picks the fresh gas upstream the compressor flange, generate just enough head to ensure a safe and reliable cooling flow on the complete operating range, while the hot gas is re injected between the inlet flange of the compressor and the cooling flow supply. Specific distance between the various connection avoids unwanted recirculation.

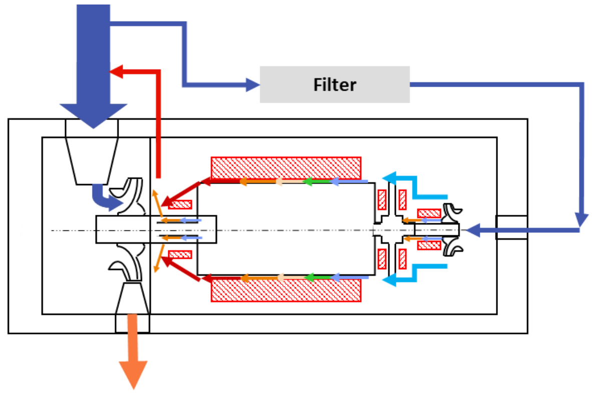

Fig.2. Integrated Single-Stage Architecture

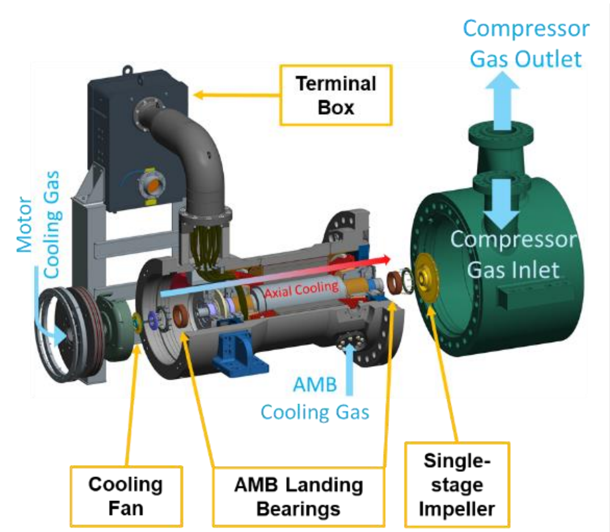

Fig.3. Integrated Single-Stage CAD View

The integrated architecture using a multi-stage compressor is adapted to the large compression ratio (Fig.4). This architecture uses a flexible coupling between motor and compressor, like couplings used for conventional compressor packages [2].

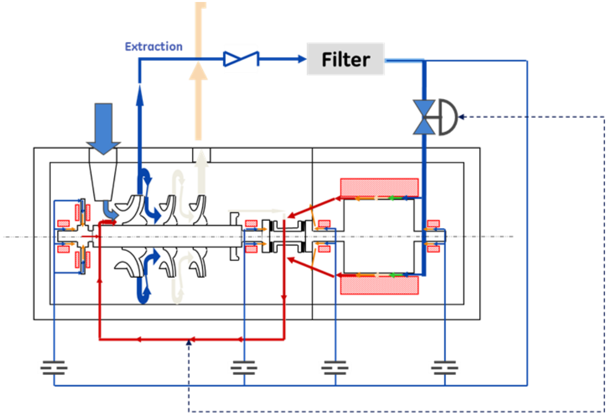

Fig.4. Integrated Multi-Stage Architecture

The squirrel cage rotor of the motor is adapted for high-speed conditions and comprises a steel lamination assembly compressed by tie rods between two end rings and two shaft ends (Fig. 5). The cage bars can expand axially through the end ring. The copper bars are inserted in the slots between the two end rings to form the squirrel cage. The laminated technology allows high efficiency, and high rotor peripheral speed up to 270 m/s.

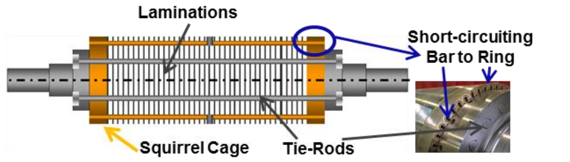

Fig.5 Laminated Induction Rotor Technology

For its dynamic behavior, the rotor of the motor operates in subcritical free-free mode when using magnetic bearings, meaning that the first bending mode is above operating speed with sufficient separation margin.

In 2007, and after a long qualification process, integrated compression system was validated for “Clean and Dry” natural gas applications with low contaminants such as H_2S (< 15 ppm) and with some limitation in terms of pressure, speed, and power [3]. Except for high H_2S & CO_2 (Acid) and Ammoniac contents, cracked gas, and high discharge pressure above 300 bar, 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),
- LNG: Mix-refrigerant, Boil of Gas,
- Downstream: Ethylene, Propane, Butene, H_2 …

The integrated motor (Fig.6) is designed for the following conditions [1]:

- Up to 15 bar partial pressure CO_2,
- Up to 15 mbar partial pressure of Wet H_2S,
- Up to 150 mbar partial pressure of Dry H_2S,
- Up to 200 bar SOP,
- Up to 100% relative humidity at suction,
- RGD < 30 bars/min.

The gas outlet temperature of the motor is limited and controlled to avoid any risk of gas fouling which can clog the end-windings and the ventilation ducts of the stator.

Fig.6. Single-Stage Motor-Compressor during string test

B. Variable speed drive

The Variable Speed Drive is a Voltage Source Inverter (VSI) commonly used to drive integrated electric compression train (Fig.7) since it allows to control high speed induction motor at a requested power factor, maximizing the torque generation by an optimum vector control. This technology is applied to many low speed and high-speed applications in a wider range of power.

The rectifier is a Diode Front End selected in 24-pulse configuration to minimize current harmonic emission in the upstream electrical grid [1]. It combines two parallel 12-pulse rectifiers arrangement with one primary Star circuit (RY) & one primary Delta circuit (RΔ) with 4 secondaries circuits (R1), (R2), (R3), (R4) producing a 15-degree phase lag (Fig.8).

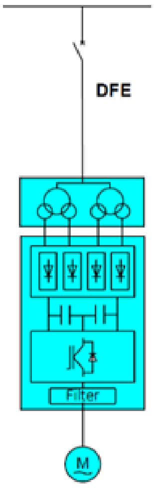

Fig.7.
24-Pulse-DFE
NPP-Inverter

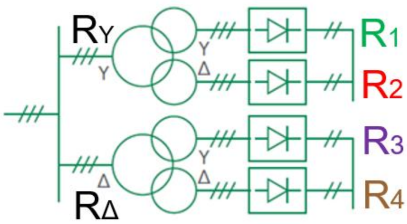

Fig.8. 24-pulse Rectifier

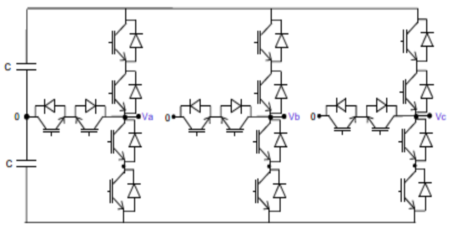

Fig.9. NPP VSI Inverter Topology

The inverter is a NPP PWM VSI inverter where the clamping diode valves of an NPC inverter (Fig.10) are replaced here by an IEGT valve giving additional controllability (Fig.11). With such a topology, each valve commutates with only half the DC bus voltage, reducing the devices commutation losses by three (see Table I) [4]. 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 (Fig.9).

TABLE I
NPC vs NPP Comparison

Converter Type	NPC	NPP
Level #	+	+
IGBT #	++	+
Diodes #	+	+
Output Voltage THD	+	+
Max commutation voltage	+	++
Rotor Max Voltage	+	++
Rotor Max Current	+	++
Max commutation frequency	+	++
Max current	+	+
(N+1) redundancy	-	+

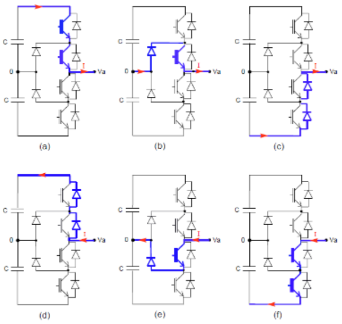

Fig.10. NPC Commutations

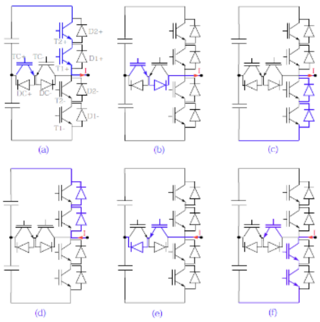

Fig.11. NPP Commutations

Due to the high-speed motor, the VSI inverter operates at fundamental frequencies above 90 Hz therefore there is a power derating of the inverter due to the significant switching losses of power semiconductors. A VSI output sine filter would have been normally used 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 (Fig.12).

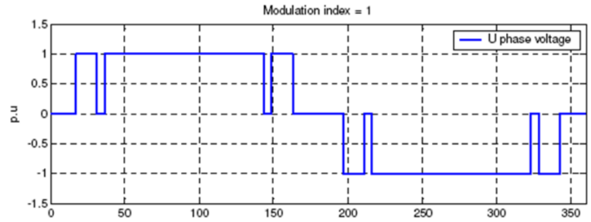

Fig.12 Example of pulse synchronous control

Therefore, due to this thermal margin, sine filter is not used and is replaced by a 3 times lighter LLC filter which is nevertheless necessary to avoid risk of reflected wave and voltage overshoot at motor terminal (Fig.13).

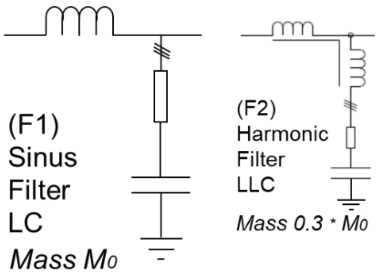

Fig.13. Inverter Sinus and LLC Filters

III. REASONS OF THE SELECTION OF INTEGRATED MOTO-COMPRESSORS

The two business cases, respectively named BC#1 and BC#2, are presented below (see Table II):

TABLE II
Business Cases Characteristics

Parameters	BC #1	BC #2
Location	France	Bolivia
Process	Downstream	Export compression
Process Gas	Ethylene	Natural gas
Compressor Architecture	Multi-Stage	Single-Stage
Unit #	1	2
Commissioning	2015	2016
Gas Flow	0.77 MSm^3/day	7.5 MSm^3/day
Pressure	13 to 97 bars	73 to 106 bars
Motor Voltage	2.4 kV	2.8kV
Motor Power	3.2MW	4.7MW
Rated Speed	11,617 rpm	11,553 rpm
Inverter	3-Level	3-Level
Rectifier	DFE	DFE

A. BC#1 - European site

From the Northeast to the South of France, several ethylene production plants delivered their product to the chemical customers through a common pipeline. Ethylene stream was either from North to South or from South to North depending on the production available or the storage capacity level. Decision was taken to stop the ethylene production plant located at the Northeast and to increase the flow rate from the South to the North. To reach the new duty, one existing compression station composed with two redundant reciprocating compressors had to be upgraded. The main design criteria were the ethylene flow demand and temperature fluctuations, the start-up conditions including a large differential pressure range and the possibility to not depressurize the compressor while is stopped for a long period. Three scenarios were considered:

- Revamp and upgrade of the two existing reciprocating compressors.
- New conventional motor driven centrifugal compressor
- New integrated moto-compressor

Integrated double stage moto-compression has been selected for the following main reasons (Fig.14 & 15):

Fig.14. Ethylene Integrated Compression

- A product dedicated to the pipeline applications and continuously improved with the return of experience
- A fully hermetic moto-compressor package enabling zero emission released to the atmosphere.
- A high level of availability due to the 6 years in between servicing. The maintenance activity was also supposed to be simplified because of the few mechanical components (no gearbox, no piston/cylinder) and the use of magnetic bearings.
- A reduced footprint of the overall process unit.
- A possible remote control of the compressor.

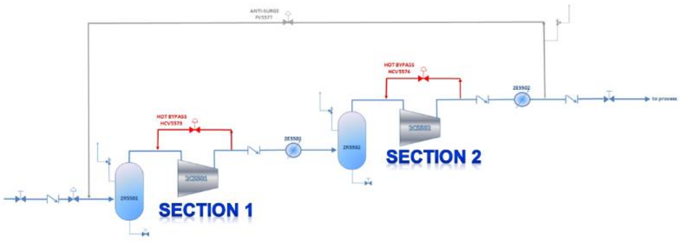

Fig.15. Process Flow Diagram

B. BC#2 - South America site

This solution is in a very remote location, at more than 1000-meter altitude. Natural gas streams coming from various well pads are gathered in a central processing facility where the gas is treated, including dehydration, to reach Customer specification. The integrated moto-compression located in this central facility is used to boost gas in a long export pipeline after treatment (Fig.16).

Fig.16. Export Integrated Compression

The operating mode of the integrated moto-compression is continuous with seasonal variations in export flow demand. Hence, maximum availability is required for this duty. Integrated moto-compression has been selected for the following main reasons:

- Being a relatively low-pressure ratio service, compression could be achieved with a single stage/impeller configuration, for which a conventional arrangement with low-speed motor plus gearbox plus compressor would have been significantly more complex than the overhung impeller integrated moto-compressor which has been selected (only two bearings versus eight bearings for a conventional solution). The latter arrangement eliminated the auxiliaries usually needed for a conventional package (e.g., no nitrogen needed for dry gas seals, thus simplifying the installation) and significantly reduced the amount of remaining instrumentation for a simplified maintenance in operation.

- The central processing facility accessibility was reduced, and the integrated moto-compression drastically simplified the packages transportation.

IV. REX OF INTEGRATED MOTO-COMPRESSORS

A. REX Operators

1. BC#1 - European site

This project has been an opportunity to develop the first ethylene integrated moto-compression. According to the pressure and temperature, ethylene becomes either a gas or a supercritical fluid which makes the process control and regulation complex. The development and commissioning of this new process control were probably the main difficulties faced by the project team. Here below are the main lessons learned:

- Starting conditions at Settle Out Pressure (SOP) and process transient conditions shall be properly studied to avoid issues during commissioning and at later stage during normal operations.
- Good communication between the compressor, motor and VSD manufacturer is key to properly tune the VSD software and save time during commissioning.
- Cabling shall be thoroughly checked after construction to secure the commissioning planning.
- Kinetic support used to mitigate voltage dips shall be properly tuned to avoid spurious trip by having the compressor going into surge area.
- Compressor load flow controller shall use a PID regulation instead of an on/off control to avoid gas flow fluctuation.
- Lightning EMC disturbance mitigation shall not be overlooked to avoid power control board failure.

When issues and tuning were made, without any delay, the compression unit had started in 2015 and the first servicing held in 2021 without any major issue discovered.

2. BC#2 - South America site

The integrated moto-compressors were commissioned between the end of 2016 and the beginning of 2017. At the compressors level, commissioning has been essentially slowed down by connections issues at the high voltage junction boxes and by control system issues. From a construction standpoint, it was observed that high frequency motor and VSD require a special attention with regards to cable installation (Fig.17), screen earthing and earth mesh grid. The latter shall not be underestimated as it can produce EMC issues leading to spurious trip of the VSD.

Operational experience also demonstrated that VSD internal cabling must be properly verified at converter factory and that any modification, upgrade or cabling modification on site be properly monitored to ensure proper reliability/availability of the VSD. Ethernet connection switches are not equivalent, they shall be extensively tested before site implementation to ensure compatibility and proper integration within the site ethernet network.

Fig.17. Shield burnt by high current circulation

At the end of summer 2021, each integrated moto-compressor cumulated more than 17,000 and 19,000 hours. While the compressor part (motor plus compressor) exhibited very good mechanical and thermodynamic performances, several upsets were encountered with the VSD, leading to a reduced availability of the overall compression system. This was due to a lack of feedback from the new control architecture that had been implemented for this project. The hardware was sensitive to EMC disturbances (Fig.18) which generated premature and spurious trips originated by the VSD control system.

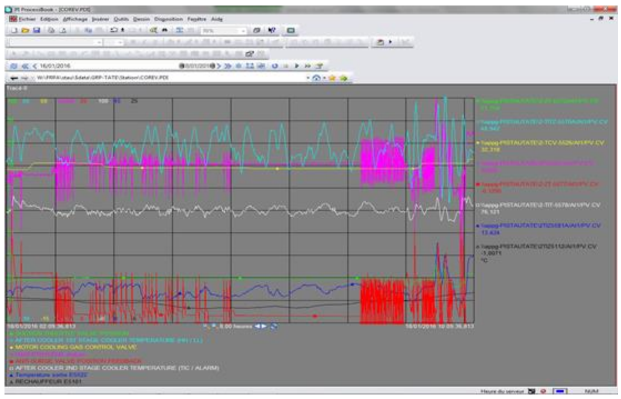

Fig.18. Export fluctuations

However, despite the previously mentioned issues which have been resolved by the VSD supplier, the integrated moto-compression is viewed as a flexible system by the operators of the facility. This REX enabled the VSD supplier to integrate a whole series of tests into its Real-Time Control Simulator platform, making the robustness of the system more reliable.

B. Manufacturers REX and Challenges

1. Moto-compressor Platforming

Since this moto-compressor introduction in 2007, the compressor and motor manufacturers have implemented some upgrade on the initial design of the unit.

The coupling chamber access was originally a square bolted trapper (Fig.19), it is now a standard RF flange with associated counter flange. Because the change is only the drilling geometry, the round shape does not change the compressor casing design, neither the accessibility of the coupling while using the standard flange design facilitated a lot the maintenance (Fig.20).


Fig.19. Coupling access square shaped


Fig.20. Coupling access standard RTJ flange

The motor casing was initially a welded casing with bolted cover. The AMB connector on the motor were different and using different mounting method from the compressor ones (Fig.21). The new motor casing is now using a design like the compressor one, i.e., using bolted flange and full machined design with a motor cover closed with shear ring. Electric motor casing is identical for both single-stage and multi-stage compressor arrangements (Fig.22). Regarding the AMB connector, it is now using the same design as the compressor casing. It simplifies the moto-compressor assembly during manufacturing and the maintenance operation.

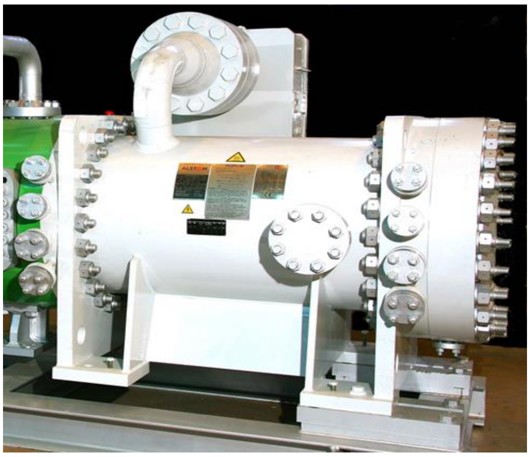
Fig.21. Original welded motor casing


Fig.22. Full machined motor casing

2. BC#2

On the BC#2 project, the compressor manufacturer introduces a simplified version of the multi-stage arrangement to match the low-pressure ratio requirement below 1.6:1.

The first challenge was to manage the axial thrust on the unit. It is important to predict and compensate properly the axial thrust as magnetic thrust bearing has a lower capacity compared to oil thrust bearing. In the single stage arrangement, the axial thrust is a combination of thrust generated by the variation of gas momentum (so-called dynamic axial forces) and the differential pressure across the impeller and across the balance piston (so-called static axial forces) [5]. Usually, static axial force of the impeller is mainly compensated by axial force of balance drum and the remaining by the thrust bearing, keeping some capabilities for dynamics axial forces (Fig.23). The compressor manufacturer developed and patented [6] a dynamics axial thrust compensation device to avoid reaching the limit of magnetic bearing thrust capacity without limiting the operating range of the unit (i.e., limiting dynamics axial thrust). This device allows compensating the variation of gas momentum across the impeller, especially when operating in large flow (close to choke flow) thus expanding the operability of the unit.

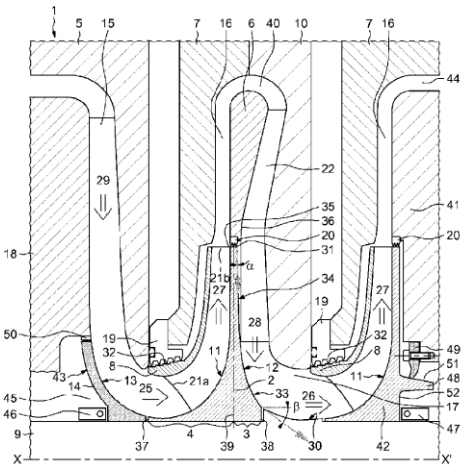
Fig.23. Dynamics Thrust compensation device

The second challenge was to validate the new cooling flow schematic with a fan. On multistage arrangement, the cooling gas is extracted from the 1st impeller discharge, generating a recirculation of gas on a fraction of the total head generated by the compressor. Using such a configuration on a single impeller compressor generates a recirculation on the total head generated by the compressor and thus affects more the performance. To maximize efficiency, it has been decided to install a cooling fan on the non-driving end of the motor to ensure the cooling of the complete unit (Fig.24). The general principle of the cooling circuit of a single stage overhung integrated machine is shown in figure below

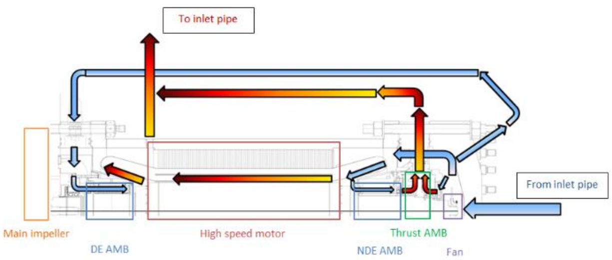

Fig.24. Single stage overhung integrated compressor cooling scheme

The system is fully autonomous and passive. No active regulating device is used. The flow delivered by the fan is split in four main branches, corresponding to the elements to be cooled:

- Thrust bearing outboard,
- NDE radial AMB + inboard thrust bearing,
- Motor stator and rotor,
- DE radial AMB.

Main challenge was to ensure a safe and reliable cooling of each electrical component on the complete operating range without any active regulation. As much as possible, mastering the cooling system requires having knowledge of the pressure, temperature and flows that goes through the different branches of the circuit A cooling model based on the multistage one has been developed to have a simulation tool to prove the safe behavior on the complete operating range and to validate the passive cooling method [7]. Pressure drops across the various component to be cooled by the process gas are well known thank to the multistage experience, and a dedicated 1D pressure drop & cooling model validate the principle of passive cooling.

Main challenge was the proper calibration of the cooling flow to ensure the reliability of the modeling. The 1D pressure drop model (Fig. 25) validated the principle of passive cooling.

BC#2 was the first single stage arrangement manufactured. To validate modeling, extensive instrumentation and measure has been recorded during the test of the unit and the orifice that usually distribute the flow in the various branch of cooling have been replaced by manual lockable valves to fine tune the flow distribution (Fig.26).

Fig.25. Schematic cooling network

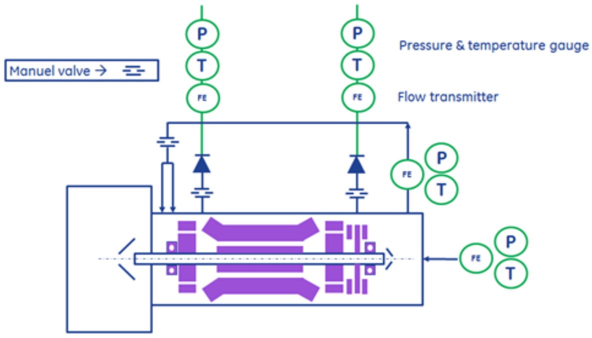

Fig.26. Additional instrumentation for cooling validation

The test sequence includes a simulate test (PTC 10 type II) to characterize the behavior of the reliability of the model. Regarding the fan, performances are determined thanks to the special instrumentation installed around it. While the fan pressure ratio was properly predicted, the efficiency was over predicted. The experimental efficiency must be considered carefully as the temperature increase through the fan is very low (~5 °C). The value of efficiency is of low importance as the power absorbed by the fan is very small with respect to the full system power. The experimental pressure drop characteristics of the different elements are re-injected in the simulation tool.

The application of the calibrated simulation tool allows determining the real cooling circuit characteristic. it appears than the achieved pressure drop is about half the initial estimated one. Therefore, the fan would work in the stone wall region. On the first unit, thanks to a manual valve upstream the fan, an artificial pressure drop has been created to have a better matching between the selected fan and the circuit characteristic. Once calibrated, the cooling repartition model match well the experimental result (Fig.27).

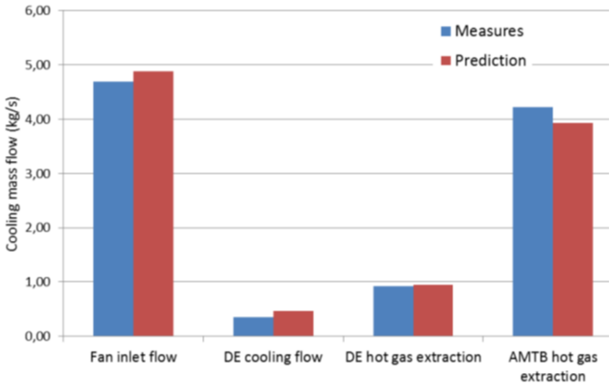

Fig.27. Flow repartition comparison during type II test

Seven different stable points executed during the type I tests have been analyzed to validate the model in a much wider range. The predicted and measured values are compared in the figures (Fig.28).

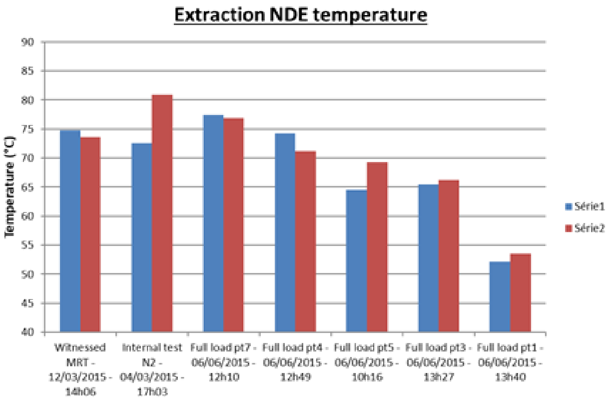

Fig.28. Comparison of predicted and measured cooling parameters during type I test

In general, a very good agreement is observed, meaning that both the flow repartition and the system losses are well modelled. The global mass flows are within 5% and the discharge temperatures are within 5°C, except for the point with Nitrogen N_2.

At the light of these results, the system was considered qualified, and the prediction tool now used on any case to design an optimum fan for each application.

V. CONCLUSIONS

The integrated moto-compressors line is a mature and proven solution with many references, bringing several advantages compared to conventional solution: no shaft end seal leakage, no restriction in long term pressurization for dry gas, improved availability thanks to dry gas seal absence. The overall casing of the motor-compressor has been improved and structured to facilitate assembly and maintenance operations for the two types of single-stage and multi-stage compressors and the range of associated asynchronous motors.

On the VSD side, there is still the need having a standard product approach which is not the case today where the VSD is customized for each project. Return of experience has shown that a special focus shall be put on the VSD and compressor control software's to configure it and debug it prior to the commissioning. Field Service Engineer (FSE) training shall be improved to secure the commissioning and improve the resolution of issues at site before production start-up.

VI. ACKNOWLEDGEMENTS

Special thanks to Thomas Alban (Engineering Director of Baker Hughes Thermodyn) and Sylvain Guillemin (R&D Principal Engineer of Baker Hughes Thermodyn) for their support for this paper.

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VIII. NOMENCLATURE

AMB	Active Magnetic Bearing
CAPEX	CAPital Expenditure
DC	Direct Current
DE	Driven End
DFE	Diode Front End
DGS	Dry Gas Seal.
EMC	ElectroMagnetic Compatibility
FSE	Field Service Engineer
IEGT	Injection Enhanced Gate Transistor
HGBP	Hot Gas ByPass
NDE	Non-Driven End
NPC	Neutral Point Clamped
NPP	Neutral Point Piloted.
OPEX	OPerational EXpenditure
PWM	Pulse Width Modulation
REX	Return Of Experience
SOP	Settle Out Pressure
VPI	Vacuum Pressure Impregnation
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

IX. VITA

Lionel DURANTAY is graduated from the ENSEM of Nancy, France (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 40+ technical papers. He presently holds 15+ patents. He is currently Chief Technology Leader in GE Power Conversion.
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