How Magnetic Bearings Contribute to TotalEnergies Ambition Lessons Learnt and Expectations from Magnetic Bearings

Alain GELIN[a], Antoine LUCAS[a]

a TotalEnergies, Avenue Larribau, 64018 Pau Cedex, France, alain.gelin@totalenergies.com

Abstract

The purpose of this paper is to present how Active Magnetic Bearings contribute to TotalEnergies Net Zero Ambition in 2050. TotalEnergies is operating hundreds of Turbomachines worldwide to enhance Oil Recovery and to handle associated Gas from Liquefaction to Transportation businesses. By allowing physical segregation of processing streams from atmosphere, Active Magnetic Bearings help to avoid incidental hydrocarbon and thus CO_2 releases. The recent development of High-Speed Induction Electrical Motors in conjunction with the utilization of Active Magnetic Bearings offer many opportunities to reinvent the future in term of compression systems and to address carbon footprint reduction efforts. This paper will describe the technology of Integrated compressor solutions and will present some Green and Brown Field experiences. The paper will also focus on lessons learnt from a major Operator of Turbomachinery's and his expectations in term of Magnetic Bearings to meet future climate challenges.

Keywords: *Magnetic Bearings, Integrated Compressors, High Speed Electrical Motors, Lessons Learnt*

1. Introduction

TotalEnergies is a global multi-energy Company that produces, refines, and markets energies: oil and biofuels, natural and green gases, and electricity from renewables. Active in more than 130 countries, TotalEnergies put sustainable development in all its dimensions at the heart of its Projects and Operations. As a major player in the energy, Company's ambition is to reinvent the way energy is produced and consumed to get net zero by 2050, together with society, and to offer solutions to address the climate challenge.

TotalEnergies is active across the energy value chain from Production, Transportation and Processing into intermediate or finished products; to Storage and Distribution to meet the needs of individual and business customers. The Company is also developing carbon reduction projects for its own sites and for its customers by the deployment of solutions to enhance energy efficiency and to capture and store carbon (CCS and natural carbon sinks). To face climate challenges, TotalEnergy is moving forward, together, towards new energies and its energy mix will move from more than 90% Oil&Gas in 2020 to 25 % in 2050, see Fig.1 & 2.

Figure 1 - TTE Energy Mix

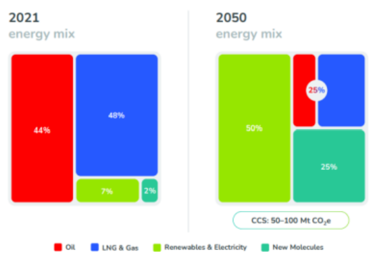

Figure 2 - Energy Mix from 2021 to 2050

2. From the origins… to the future with Integrated Compressor

As an example, the operation of a large FPSO (Floating Production Storage and Offloading) producing around 150 to 200 thousand barrels of oil per day with about 7 to 10 MMscfd of associated gas to be recompress for exportation or to enhance oil recovery, see Fig. 3 and 4, would require an installed power of about 100 MW. The corresponding CO_2 emission due to fuel gas consumption and combustion is estimated to roughly 600 kT CO_2 per year using open cycle gas turbines.

Another example of CO_2 emission is related to Liquified Natural Gas (LNG) applications. A liquefaction plant of 1 MTPA (Million Tonnes Per Annum) of liquefied natural gas using refrigerant compressors requires about 43 MW mechanical power, and when open cycle gas turbines are used to drive the refrigerant compressors, the corresponding CO_2 emissions are roughly 265 kT CO_2eq/y.

Figure 3 - FPSO in Operation in Angola

Figure 4 - FPSO in Operation in Nigeria

Both examples demonstrate the necessity to rethink oil and gas facilities design to reduce CO_2 and Greenhouse Gas (GHG) emissions, that Active Magnetic Bearings (AMBs) will contribute to meet.

Here below are some examples of actions already taken to reduce global emissions for either Greenfield or Brownfield Projects:

- Power generation based on Combined Cycle Gas Turbines (CCGTs) instead of Open Cycle to drastically reduced CO_2 emissions by roughly 30% thanks to lower fuel gas consumption
- Retrofit of Turbo Compressors by Electrical Compressors, and fed from renewable power or distant grid
- All electrical solutions including power generation based on Wind and/or Solar farms
- All new Projects are based on Zero routine flaring strategy that TotalEnergies is committed to achieve by 2030 on all its facilities, with Flare Gas recovery systems that are now mandatory
- Retrofit of installations with dedicated flare gas recovery systems. Many available technologies are proven such as static ejectors, dry screw compressors, liquid ring compressors, reciprocating or centrifugal compressors
- Rebundling of centrifugal compressors to avoid or to limit operation in recycle mode with excessive power consumption
- Dry Gas Seals (DGS) reliability and availability improvements. The DGSs with their associated conditioning and monitoring systems are very complex. Many failures have been reported that could have escalated to catastrophic events. As an example, the complete failure in 2009 of a DGS for a very high-pressure compressor, see Fig. 5 resulted of a large amount of released gas to the lube oil system. The process gas and lubricant oil mixture released by all ports and vents lines and reached the hot part of the exhaust of the 30 MW Gas Turbine leading to ignition. The fire propagated all around the package putting the integrity of the platform at risk.

Figure 5 - Dry Gas Seal Catastrophic Failure

Figure 6 - Fire ignition due to DGS failure

In 1987, TotalEnergies commissioned and put in operation a centrifugal compressor fitted with Active Magnetic Bearings (AMBs) and DGSs. This world first application, see Fig. 7 was installed in Lacq field in the southwest of France to handle sour gas containing about 20% of H2S toxic gas. To avoid any contamination of the AMBs, the DGSs of the compressor were fed with “clean and dry” fuel/seal gas. This compressor was decommissioned in 2005 after more 130 000 operating hours without any issue. Three (3) other centrifugal compressors with AMBs were installed on this field in the 90’s for gas re-boosting. Many Turbo Expanders also equipped with AMBs are operated by TotalEnergies for natural gas treatment and dew pointing. These experiences on AMBs made the Company very confident about the technology.

In 1994, TotalEnergies commissioned and started a High-Speed Electrical Motor (HSEM) compressor package in Donges refinery in France (3600 kW @ 6300 rpm), see Fig 8. The technology of the induction motor is based on a fully laminated rotor stacked with tie rods allowing the reach very high peripheral speed around 270 m/s. The motor, still in operation today, is working at atmospheric pressure and is cooled using atmospheric air, a dedicated air/water heat exchanger is required. The rotor of this first High-Speed electrical solution was nevertheless fitted with hydrodynamic oil lubricated bearings.

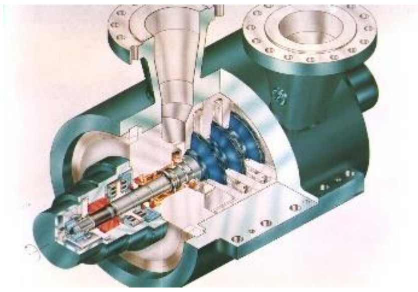

Figure 7 - KB-403 Lacq Compressor fitted with AMBs

Figure 8 – Donges High Speed Motor fitted with AMBs

More recently, and associating both AMB and HSEM technologies, TotalEnergies decided to move forward introducing the "so-called" Stand-Alone and Oil-Free solutions for high-speed motor compressor packages. The compressor is directly driven by the high-Speed motor without the requirement for a speed increaser gear box and the complete shaft line is supported by AMBs, see Fig.9. Without gear box and lubricated bearings, the complete lube oil system can be removed, and the package becomes less complex as some auxiliaries are removed. The HSEM and the AMBs are cooled using air at the atmospheric pressure. To be noted that the size of the atmospheric air cooler on top of the motor is larger than the motor core itself and it requires auxiliary motors for internal air circulation.

Unfortunately, the compressor is still equipped with DGSs and associated conditioning system to isolate the electro-magnetic components from the process gas. The DGS conditioning seal gas panel contains many auxiliary process equipment such as filters, scrubbers, booster, heater and more than 30 transmitters are used for the control, see Fig. 10.

In addition to that, an acoustic insulation hood or blankets are applied onto the motor to limit noise emission due the high speed and the thin frame walls of the atmospheric HSEM, see Fig. 11.

Figure 9 - HS Stand Alone Package

Figure 10 - DGS Monitoring Panel

Figure 11 - Package with noise insulation

3. Fully Hermetic and Integrated Package

The Dry Gas Seals with their associated seal gas conditioning skids represent the weak point of centrifugal compressors in term reliability, and roughly 80% of the lack of availability of centrifugal compressors for Upstream applications are linked to the malfunctioning of DGSs. In addition to that, the continuous leakage of process gas exiting the DGSs inboard seal is either released unburnt to the atmosphere or routed to the flare system contributing to Green House Gas (GHG) or CO_2 emissions. As a rule of thumb, the primary seal gas leakage for a compressor is roughly 5 Nl/min/bar (suction pressure to be sealed) and for High Pressure applications the corresponding emission is not negligible.

Thanks to the development of HSEMs see Fig. 12 with a fully laminated rotor inside a High-Speed balancing machine, and AMBs see Fig.13, the Stand-Alone solution for motor compressors can be made fully Integrated and Hermetic without any gas leakage, see Fig.14. To do so, the DGSs of the compressor are removed, and both AMBs and HSEM are directly cooled using the process gas at the suction pressure of the compressor.

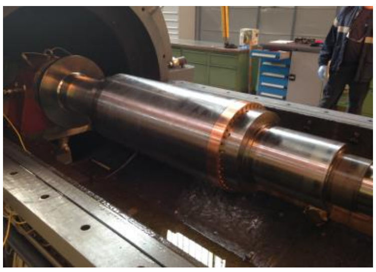

Figure 12 - HSEM Fully laminated rotor with AMBs

Figure 13 - AMB static parts

Figure 14 – ICML during Factory Testing

Of course, the material used for HSEM and AMBs shall be able to withstand any corrosion attack from process conditions due to the potential presence of contaminant such as CO_2, H_2S, Mercury or liquid Water. A particular attention shall be paid during stand still conditions at the settle out pressure due to possible water condensation while the temperature of the pressurized gas inside the machine decreases below gas dew point.

Another concern is related to the High and Low voltage connections respectively for HSEM power supply and AMBs control/command system, and some deep qualification processes are required to fully validate the sealing and the tightness of these electrical passages and connectors.

In 2007, TotalEnergies was the first Oil & Gas Operator to qualify the technology from Baker Hughes Company (BH), so-called ICL™ for Integrated Compressor Line. The HSEM and the AMBs are respectively provided by GE/PC and SKF/S2M. The technology was first qualified for "Commercial, Dry and Clean" gas applications. Few years after the qualification was extended to "Water Saturated Gas" applications including some contaminants such as CO_2 and H_2S. More recently TotalEnergies extended furthermore the qualification to the "small scale" integrated compressors line from BH, so-called ICL-LV™, technology using Low Voltage permanent magnet HSEM running up to 30 000 rpm and targeting Flare Gas Recovery applications.

In 2022, TotalEnergies pronounced the qualification of the Hermetic Oil Free technology from MAN-ES company so-called Sealed -HOFIM™ to enhance its portfolio of hermetic solutions and favor competition.

The main advantages of the Integrated and fully Hermetic compressor packages are summarized as follow:

- No leakage of natural gas to the atmosphere or to the flare system
- No Lube Oil system with all auxiliaries, and no speed increaser Gear Box
- No Dry Gas Seal and associated conditioning system
- No requirement for Cooling Water nor Nitrogen
- Low noise package thanks to the high speed and the HSEM casing thickness
- Only few remaining instruments, instead of tenth, to monitor the package
- Drastic reduction of weight and footprint
- "Plug and Play" pre-commissioned packages
- Less spare parts
- Better reliability and availability compared to conventional packages
- Lower maintenance and associated downtime

Due to the process conditions, including but not limited to gas, pressure, temperature, the compressor architecture is always a Project specific and different cooling loops can be implemented. The impact of the cooling loop either "quasi-closed" or "fully close" shall be properly evaluated from a performance standpoint during the design phase of the Project as the windage effects are directly linked to the geometry, the velocity, and the gas density. The specific heat capacity of the gas is key parameter as it governs the cooling flow requirement. Full Load String Test (FLSTs) as strongly recommended for hermetic packages with AMBs, not only to check its mechanical behavior and integrity but also to confirm the performance in term of electrical power consumption. It is a standard requirement within TotalEnergies.

For all new TotalEnergies projects, either Brownfield or Greenfield, Onshore or Offshore, the integrated and seal less technology is selected as the base case. One limitation is coming from the suitability of the AMBs and HSEM components versus the process gas and associated contaminants, if any. Another limitation is coming from the high pressure to sustain the aerodynamics excitations coming from the gas density, as a rule of thumb, the suction pressure of the compressor is limited to roughly 100-120 bara. This limitation is also driven by the low stiffness of the AMBs compared to tilting pad bearings. As another rule of thumb, AMBs are roughly 10 times softer than hydrodynamic bearings. In addition, the higher the compressor pressure, the higher the windage motor losses are, and the integrated solution can be discarded due to excessive power consumption.

In 2015, TotalEnergies commissioned and started two (2) ICL Booster compressors of 4.5 MW in Bolivia, each handling 7.5 MSm3/d of process gas from 73 to 106 bara and running at 12000 rpm, see Fig. 15. The compressor is equipped with a single impeller directly clamped to the motor without any flexible coupling. The cooling gas loop is ensured thanks to a dedicated fan directly mounted on the Non-Drive End (NDE) side of the motor to circulate the process gas inside the motor/stator and the AMBs before to be reinjected hotter at the inlet of the compressor. After 9 years of operation, these ICLs will be retrofitted in 2024 from parallel operation (high flow / low pressure ratio) to "in series" mode (lower flow / higher pressure ratio) to better comply with the depletion of the gas field.

In 2016, another ICL compressor of 9 impellers in back-to-back arrangement was installed in the south of France for an ethylene transportation project, see Fig. 16. The compressor is a two-stage machine of 2.8 MW running at 11 000 rpm and handling 0.8 MSm3/d from 13 to 97 bara. The cooling principle for this multistage compressor is more conventional. The cooling gas is taken from a dedicated internal stage, without any fan, to circulate the ethylene through the HSEM and the AMBs before to be also rejected hotter at the inlet of the compressor.

Figure 15 – Both compressors in Operation at site In Bolivia

Figure 16 – Ethylene compressor in Operation

The construction of a new ICL is on-going for a Low-pressure phase Project in Brunei. The compressor of 10.8 MW and running at 8 500 rpm will handle 3.8 MSm3/d of gas from 13 to 59 bara. It will be a new world first as the AMBs and HSEM will be cooled and submerged in the Water Saturated Gas, impacting the technology and the material selection.

Many other Projects, all based on Integrated and Hermetic compressors are under discussion to meet TotalEnergies objectives in term of Carbon Footprint Reduction (CFR). Some of them are related to the electrification of existing facilities (either onshore of offshore) with the decommissioning of large Turbo Compressors and their replacement by Integrated and “Green electrical” packages. Other are related to the recovery of Flare Gas to directly decrease the CO_2 emissions.

4. Lessons Learn and Expectations from AMB systems

Thanks to the number of Rotating Equipment and Turbomachinery’s operated by TotalEnergies and fitted with magnetic bearings, from turbo-expanders to electrical motors and including compressors. With more than 30 years’ operating equipment with AMBs, TotalEnergies has developed a large experience on the technology.

The following lessons learnt and expectations from AMBs are based on Projects, qualification programs, testing activities, commissioning, and site operation:

4.1 Lack of stiffness and damping at low frequency

The machines equipped with AMBs may suffers of sub-synchronous vibrations with a very low frequency content. The frequency spread may vary from few hertz to tenth of hertz and corresponds to the frequency domain where the AMBs are very soft compared to conventional hydrodynamics bearings. The AMBs are usually ten time softer than sleeve or tilting pads lubricated bearings. These sub synchronous broadband vibrations are often observed for Turbo-Expanders is case of liquid formation due to gas expansion across some internal labyrinths of passages.

The common way to cure this sub-synchronous vibration is to work on the process conditions to avoid any liquid, but stiffer AMBs especially at low frequency would be beneficial to limit sub-synchronous activity during upset and transient conditions.

4.2 Sub-synchronous Instability – Forward but also Backward…

Some sub-synchronous rotor instabilities may also occur on the first natural frequency, either in forward or backward motion, for medium and high-pressure compressors. The API-617 for centrifugal compressors focusses on rotor stability as it is the main concern for HP compressors, reference is made to API-617 Part 1 Annex D. The stability analysis deals with the forward motion of the first natural frequency that could be self-excited by aerodynamic due to internal gas velocity in the direction of the rotation. To avoid the aerodynamic effect and to increase the damping (logarithmic decrement) of the first natural frequency, many stabilizing devices can be implemented to limit cross coupled stiffnesses affecting the forward mode:

- Impeller eye swirl breakers to limit and decrease the circumferential gas pre-swirl at seal entrance
- Axial balance drum equipped with either Honeycomb or Hole-Pattern seals with pressurized cells
- Shunt hole at the balance drum inlet to also cancel pre-swirl at the inlet.

All previous practices are well-known to ensure stability of HP compressors, but what is beneficial for the forward motion is detrimental for the backward one. TotalEnergies experienced a pure sub-synchronous instability of the first natural frequency in backward direction while the compressor equipped with AMBs was reaching the maximum pressure and maximum speed. To cure the issue, the internal parts of the compressor had to be modified removing some stabilizing devices for the forward mode to not destabilize the backward one. The transfer functions of the AMBs were also modified to bring additional damping in the frequency area of concern. The same HP compressor equipped with hydrodynamics tilting pad bearings would never have demonstrated any sub-synchronous instability in backward due to the higher impedance of the lubricated bearings (stiffness and damping) versus AMBs.

Recommendation is made for medium and high-pressure compressors fitted with AMBs to not only focus on forward stability analysis as per API requirement but also to take care of the backward motion first natural frequency. References is also made here to a very interesting paper (Bidaut, et al., 2006).

4.3 Load capacity and requirement for thrust magnetic bearing

The capacity of AMBs is much less compared to hydrodynamics bearings and some efforts are also recommended in that direction to accept higher loads, and this applies also in the axial direction for the active magnetic thrust bearings. A centrifugal compressor is always equipped with a thrust bearing to contain the aerodynamic residual load. Electrical motors are usually not equipped thrust bearing as the stator core magnetic centering is sufficient to axially locate the rotor in a stable position. For high pressure applications of integrated compressors with high density gas, the cooling flow rate may induce an axial load requiring also a thrust magnetic bearing. Having a thrust magnetic bearing on both compressor and motor linked together with a flexible coupling may induce mechanical and vibratory uncertainties during transient events as start-up, loading and coast down.

All efforts shall be deployed from a design standpoint to not installed a magnetic thrust bearing for high-speed motor.

4.4 Process gas compatibility and qualification

For Integrated and Hermetic solutions, and as the AMBs and HSEM are submerged inside the process gas, some efforts are still needed to make the components more robust and suitable whatever the contaminants. Qualification programs and acceptance criteria shall be mutually agreed between parties: AMBs & HSEM sub-supplier, Original Equipment Manufacturers (OEMs) and Operators.

4.5 Auxiliary bearings

Auxiliary bearings are used to support the rotor at rest and to protect the AMBs to avoid any contact with sensitive parts and laminations (actuators and sensors). The clearance of auxiliary bearings is typically 30% of the AMBs clearance and special roller bearings are usually used. The concept of “soft” and “hard” landings is often used by AMBs suppliers or OEMs, and it should be revisited. In addition, the justification for auxiliary bearing replacement shall be fully justified.

Furthermore, it is not recommended to perform any AMBs delimitation during Factory Acceptance Test, and this applies either during Mechanical Running Test of single equipment or during String Test of complete package.

4.6 Rotordynamics analysis

API-617 mainly refers to lateral unbalance response analysis. As different types of synchronous filters may be proposed to optimize the rotordynamics lateral behavior, the unbalance responses shall be run with and without synchronous filter including a narrative and a justification of their use. In addition to the stability analysis as specified in the API Standard, the Campbell’s diagram without any synchronous filter shall be part of the lateral analysis. All lateral natural frequencies, with associated mode shape, either forward or backward, and damping (logarithmic decrement) shall be clearly identified up to two (2) times the frequency corresponding to the trip speed and the analysis shall be run up to the trip speed. The lateral analysis shall also include the stiffness and damping properties of the AMBs versus the frequency and resulting from the Transfer Functions.

The axial rotordynamics analysis of the complete train shall be part of the torsional, and this applies independently of the number of thrust bearings present in the shaft line.

4.7 Tuning of AMBs

The tuning of AMBs, either during Factory Acceptance Test (FAT) or during site commissioning activities, represents a constraint in term of Project management and scheduling. The initial and pre-implemented Transfer Function within the AMBs control system shall be ONE used for the rotordynamics analysis as it governs the stiffness and damping characteristics. Any modification of the transfer function shall be justified and documented by the AMBs supplier and by the OEM responsible of the complete package. If some tuning activities are nevertheless required, the rotordynamics analysis needs to be rerun based on the true implemented transfer function. In addition, and in case of identical equipment and packages, the transfer function shall be the same whatever the package, and in case of bundle or rotor replacement at site, no AMB retuning is foreseen.

AMBs shall not be considered as "Black Box" and to make them fully democratized, the AMBs shall be as simple as hydrodynamics bearings in term of Operation.

4.8 Acceptance Criteria during Factory Acceptance Testing

The acceptance criteria for AMBs, as specified in the API-617 – Annex-E, mainly focus on the direct (global) vibrations and are only based on the auxiliary bearing clearances. These criteria should be revisited to also consider the following:

- one per rev (1X) component including its thermal vector change and repeatability check especially for electrical motors. If API-541 provide some rules it is recommended that the one per rev (1X) vector change does not exceed 25% of the direct overall criteria, and the reading shall be repeatable to confirm rotor thermal stability
- some limitation for low frequency broad band signature
- none sub-synchronous or super-synchronous instability corresponding to any undamped natural frequency shall be accepted
- some current limitations to anticipate any saturation issues. As a criterion, 75% of the maximum current that the amplifiers can deliver by axis is proposed

Criteria shall mutually agree between parties: AMBs & HSEM sub-supplier, OEMs and Operators prior FAT, and in any case, including package Full Load String Test, the criteria shall be lower that Alarm Limits at Site.

4.9 Spare Parts Strategy & Obsolescence

If it is recognized that no capital spare parts are recommended for the hardware of the magnetic bearing, either rotoric or statoric components, some other spare parts are highly recommended. Of course, one or two sets of auxiliary bearings including rotating sleeves are recommended. For what concern power electronic and control, cables, connectors, batteries if any… the capital spares shall be discussed on Project basis based on reliability numbers and considering obsolescence constraints.

4.10 Cost acceptability of the solution

As energy must remain affordable, the cost of the installations, thus the equipment is particularly challenged during project preliminary phases. Expensive technologies make projects non economical and unsuccessful, preventing the very same technology from being used, confronted with field use, and improved. To be successful, the AMB technology as any developing technology must offer technical benefits while remaining affordable to purchase and to maintain.

5. Conclusion

This publication gives an overview of TotalEnergies Strategy in term of evolution to comply with climate challenges with the objective to reduce CO_2 and GHG emission, the final goal being "Net Zero" in 2050.

Active Magnetic Bearings are clearly identified as part of the solution to address this exciting challenge.

Thanks to its experience for more than 35 years and the combination of Active Magnetic Bearings with High-Speed Electrical Motors, TotalEnergies is very confident that Integral and Hermetic compressors will be part of the future. The numerous advantages also make the solution very attractive for brown field offshore Projects including electrification and retrofit of turbo compressors.

This paper also provides some technical recommendations and expectations, and all the actors from AMBs suppliers to Operators passing thru OEMs must to keep in mind that to make the solution fully attractive, some efforts are still required in term of development, simplification and democratization of the "Black-Box".

References

API 617:2014 (2014) Axial and Centrifugal Compressors and Expander-Compressors.

API 541:2014 (2014) Form-wound Squirrel Cage Induction Motors – 375 kW (500 Horsepower) and Larger

Bidaut Y, Somaini R and De Lima Rugue MA (2019) Stability considerations of centrifugal compressors equipped with active magnetic bearings, Proc. 48th Turbomachinery Symposium, Houston, 2019