A SUCCESS STORY OF STEAM TURBINE REPLACEMENT BY HIGH SPEED ELECTRIC SYSTEM DRIVEN COMPRESSOR

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Abstract – Thanks to the development of high-speed induction motors and voltage source inverters, standalone electric drivers are today an alternative to the traditional train driven by steam and gas turbines when regulating the operating speed of compressor, improving the system efficiency and reducing significantly the emission of greenhouse gases as requested by the new European regulations. This will be developed in the first introductory part of this paper. The second part of this paper describes the main expectations and challenges of the end-user in term of project time line, reliability, inter-changeability and site electrification based on an actual business case in Nederland operating at 5.7MW @ 6,400rpm. The third part overviews the selected architectures of electric systems delivered to the end-user, including the induction motors and Voltage Source Inverters technologies. The last part is dedicated to the key technical milestones, during the design phase, Factory Acceptance Tests, and commissioning with a focus on the mechanical integration when using oil lubricated bearings. The conclusion highlights the learnings and the win-win cooperation of this project.

I. INTRODUCTION

In the past, gas and steam turbines have been natural drivers for compressors in most the Oil & Gas processes, from offshore applications to refineries. For some years now, electrical drives (Fig.1) have been selected for new plants and/or new compressor trains as they provide a more efficient, environment friendly and flexible solution [1]. For existing equipment, the decision on how to replace an ageing steam turbine is primarily dependent on the plant steam balance. If the plant has an excess of produced steam by the other processes, the replacement by a new steam turbine could be relevant even if we start to see replacement by electric motors in regions where environmental incentives are in place despite that steam production is not necessary. However, if no steam is available and steam production from boilers would be require investment for continued operation then the replacement by an electric motor must be seriously considered. This could be quite challenging in the way that the footprint of the electric motor must fit the existing environment. Classical arrangements, based on industrial speed motors (1500/3000 rpm-50Hz or 1800/3600 rpm-60Hz) driving the compressor through a gearbox to match the compressor speed, are usually too large to be accommodated in lieu of the turbine to replace. The development of high-speed electric motors driving directly the compressors enables a drastic reduction of their size and their weight, opening doors to the electric solution. We will illustrate, through real cases, the benefits of the electrical solution.

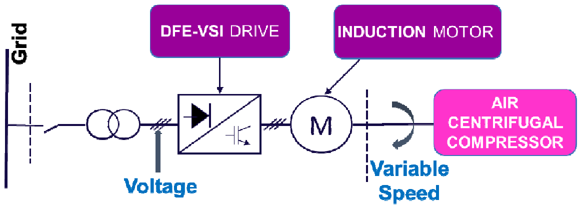


Fig. 1. Electric System

A. Global efficiency

Most of the time, the operation costs are a key point in the selection of the replacement solution. If we consider for instance an islanded station, it does not seem obvious that replacing a turbine driving a compressor by a complete electrical system is more efficient. In such a system, the electric power is produced by gas turbines as prime movers driving generators. Part of this electric power is used to supply the compressor driving motor through a Variable Speed Drive (VSD) and a transformer [2]. Nevertheless, the electrical solution is more efficient with an average improvement of 15% compared to the conventional one. Even though there are losses in the different components of the electrical chain, i.e. generators, transformers, VSD and motors, the efficiency of condensing steam turbines taking in account an optimistic assumption of 80% for the efficiency of the condensing steam turbine and adding it's boiler to generate the steam we obtain an overall efficiency of the steam turbine system below or equal to 45% (Fig.2). Taking equivalent and pessimistic values for the electric motor system chain, the overall efficiency is 6% better (Fig.3).

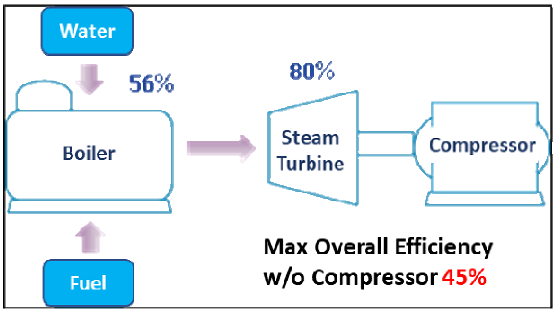


Fig. 2. Optimistic efficiency of a steam turbine system driving a compressor

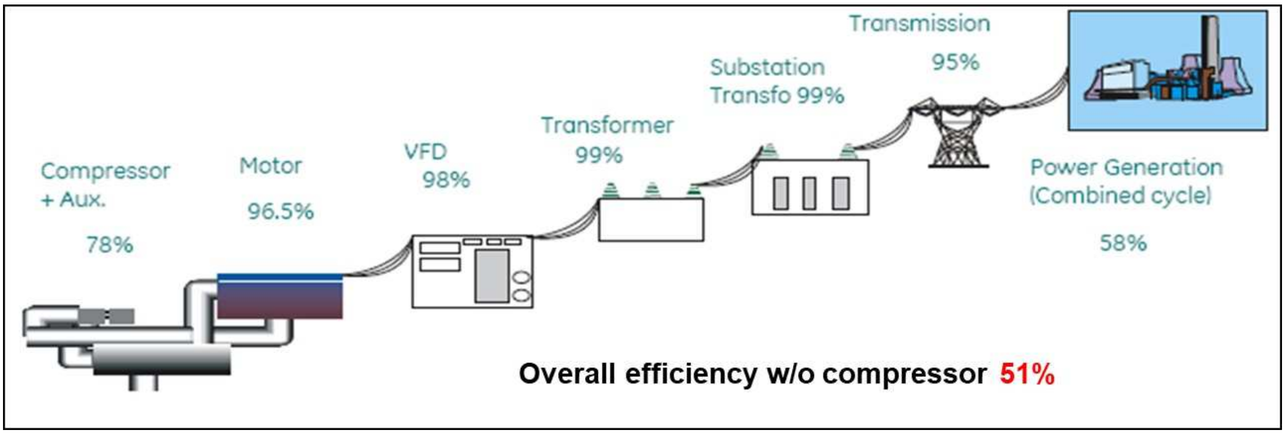


Fig. 3. Overall Electric System and Distribution Efficiency

B. Environment, Health and Security

Environmental regulations are becoming more and more stringent in larger parts of the world. For instance, the NL Klimaatakkoord law reduces Industrial GHG emissions by 60% by 2010. CO2 emissions produced by variable speed turbines directly coupled to compressors are much higher than the produced by fixed speed turbines used in the electricity generation plant. The electrical solution enables plant operators to reduce by around 30% the amount of their plant CO2 emissions.

Noise emissions produced by an electric motor are also lower than those produced by a turbine, typically -12 dB(A). In a world that pay increased attention to the wellness of workers, this advantage can represent a high value.

C. High Flexibility

High speed motors driven by Electrical Variable Speed Drive offer high flexibility compared to most other solutions. In a few seconds, the motor can be operating at full speed and with full torque, without having to wait for any thermal cycle. The starting current is always limited by the VSD to the motor rated current, thus increasing its lifetime. The number of starts and stop sequences is therefore nearly unlimited.

D. Operation cost

Thanks to the higher efficiency of the electrical solution, the operation costs related to fuel consumption are drastically reduced. An electric motor does not require much maintenance, which is even more the case if the motor is fitted with active magnetic bearings. For an electric motor, the time between major overhauls is usually 15 years, compared with 10 years for a steam turbine. Lube oil consumption is reduced and can even be eliminated with a magnetic bearing solution. In cases where an oil lubricating unit is totally removed, site potential risks are reduced, thus leading to a safer environment for the operators - and usually the site insurance premiums are also reduced.

Finally, a condensing steam turbine consumes a tremendous amount of treated water which has a very high cost for the plant. While motors and VFD are also cooled by water, the cooling water flow required is much lower driving lower operating costs.

E. Key enablers of the electrical solution

One of the major difficulties faced in the past was that any new equipment that pretended to replace the steam turbine had to be of a compatible size with the existing environment. With the classical solution, i.e., an electric motor running at a conventional speed and driving a compressor through a gearbox, this condition was difficult to reach especially on elevated locations. Fundamental physics dictates that the power delivered by an electric motor is the product of its torque multiplied by its rotational speed. Given that the size of an electric motor is proportional to the torque it delivers, it therefore follows that, for a given output power, the higher a motor's speed, the generally smaller its size. For many years now, a new technology of high-speed electric motors has been developed. A full range of power is available from 1 to 80 MW, running between 3,600 and 18,000 rpm. More than 150 units are known to be operating around the world in various Oil & Gas applications, most of them in Midstream for transportation and gas storage and Downstream in refineries. The return of experience from millions of hours of operation has proven how reliable and how efficient this solution is. Another difficulty has been to develop a new type of Variable Speed Drive (VSD) to supply the electric power to such motors, whose rated frequency is up to 300 Hz due to their high speed. A new converter topology, using new high-performance power electronic devices, has been selected to build a full range of Medium Voltage Variable Speed Drives. A modular concept is used to provide a power range from 1 MW to 100 MW with rated voltages from 3 kV to 11 kV.

II. THE END USER OPPORTUNITY

In May 2017, the end-user organization identified the opportunity to reduce their site's energy footprint and variable cost by replacing a high-pressure steam driven turbine of an air compressor by a 6 MW high-speed electric drive (Fig.4). At that time there were two main options being considered. The first option was the construction of a full new train consisting of an electric motor and a compressor, replacing the existing turbine-compressor train. The second option was the replacement of the steam turbine with a new electric motor and keeping the existing compressor and associated utilities.

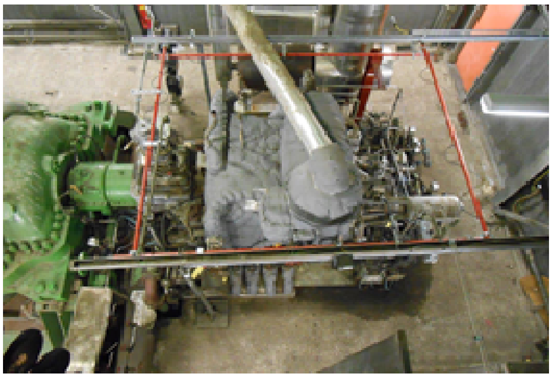


Fig. 4. Compressor (Left) - Steam Turbine (Right)

By replacing the steam turbine with an electric motor, the high-pressure steam consumption of the site is minimized. Steam is typically generated by fossil fuels, whereas electricity is produced by a mix of sources, including renewable energy. It is the first step in the site's journey from 'molecules to electrons' and important demonstration of how electrification technology can change our industry.

An economic and technical evaluation between the two options showed that building a new train was not viable in this case. While replacing only the steam turbine made sense from an economical perspective, it also introduced many risks such as schedule pressure, potential reduced plant availability and deep brownfield interfaces. The project team had a challenging task to balance expenditure, speed in project delivery and quality.

TABLE I

Summarized evaluation of replacement options

	Option 1: Replace with motor-compressor train	Option 2: Replace turbine with electric motor	
Civil structure	-	+	Plot space needed for option 1 while option 2 will re-use existing turbine location
Tie-in duration	+	-	Minimal downtime needed to tie-in new train
re-use existing auxiliaries	-	+	Option 2 to reuse lube-oil system
Cost	-	+	

A project management strategy was introduced to realize the site's aspirations. This included combining of project phases, incorporating the equipment manufacturer into the integrated project team very early-on during front-end design, use of critical path analysis and pre-funding of long leads to fast-track schedule. In addition, a decision was made to build a modular substation (instead of stick build), which allowed parallel construction activities.

This made it possible to engineer and construct most of the project scope within a timeframe of 16 months, except for the actual steam turbine replacement which was executed during a scheduled maintenance stop (6 days/week and 10 hours/day).

III. 1st CHALLENGE - RAMS AND SYSTEM SELECTION

A. The End-user Requirement

The key challenge during engineering (and construction) was to find a design that could integrate into the existing brownfield site without compromising on plant reliability and availability. The air compressor delivers air to one of the production units and is not redundant, meaning that the complete production facility will need to shut down in case of compressor trip. It is therefore of utmost importance to have a very reliable machine, including the electric drive of the compressor. Three key aspects were worked out further to ensure brownfield integration. Firstly, a stringent MTBF (mean time between failure) of 6 years was given as a requirement for the combined system (Motor + VSDS + Transformer + connections), to match with plant shutdown intervals.

B. The Manufacturer Solution

After a first project of steam turbine replacement by an electric system operating at 2.4MW @ 10700rpm, in Singapore, with the end user, the equipment manufacturer carried out a detailed RAM study in which we identified the "weak links" of the system. A RAM (Reliability Availability Maintainability) analysis is performed, and the details are given below. The reference documents used to perform this reliability study are:

- IEEE 493–2007 standards: IEEE recommended practices for design of reliable industrial and commercial power systems,
- FIDES guide 2009: Methodology of calculation for reliability of electronic systems,
- MIL-HDBK-217F standards: Reliability prediction for electrical and electronics equipment,
- GRIF Tree: Interactive graphical software tool for reliability calculation using fault tree method,
- IEEE Calculation tool: New Model 280 Propst plus Dong Elec Reliability Model.

Each of the items of the system is analyzed as a single device in term of failure rate expressed in FITS which is the number of failures per billion hours. Once performed, it can be extended to the entire system by summing all the single devices failure rates to obtain the global failure rate. Finally, the MTBF is obtained from the failure rate on standard system. The MTBF calculation is more complex for the other type of systems such as reparable systems or systems with device redundancies. Final goal is to determine which configuration was able to meet customer expectations in term of reliability and availability. The different equipment studied are:

- The 2x 3 winding 24-pulse transformer connected to the 30kV supplying grid,
- The drive including Diode Front End Rectifier
- The induction motor driving the compressor.

The study focuses on failures that causes a motor stop as it was the main criteria for this customer. For redundant devices or blocks that are reparable or replaceable while the system is running, we consider that the MTTR is short compared to the MTBF of the system. This hypothesis is realistic since the MTBF of the system will be at least several years.

Most of the electrical single devices failure rates considered in this study are those given by the IEEE Std 493™-2007 but when they are known, the single devices failure rates given by the manufacturers are considered (e.g. for Injection-Enhanced Gate Transistors - IEGT). Measuring the number of failures over time provides a failure rate (λ). The failure rate that occurs during one billion device hours is called the Failure In Time (FIT). The Mean Time Between Failure (MTBF) is the distribution for a population of components. MBTF can be determined by taking the reciprocal of FIT (λ).

TABLE II
System Reliability Optimization

24-pulse Transformer	**Failure rate (FIT)**	**Comment**
Standard	4,415	
Reinforced Reliability	< 4,334	Could avoid spare transformer, description of the reinforced reliability options is not described in this document

VFD - Cooling	**Failure rate (FIT)**	**Comment**
Standard	17,360	
Oil & Gas application	7,350	
Reinforced Reliability	2,091	Recommended option, description of the reinforced reliability options is not described in this document

VFD - Control	**Failure rate (FIT)**	**Comment**
1st generation	12,352	
2nd generation	6,480	
Current generation	4,349	
Fully redundant control	438	Highly expensive solution
Redundant CPU	1,755	Recommended option

VFD - Power	**Failure rate (FIT)**	**Comment**
1st generation	7,399	
2nd generation	6,432	
2nd generation w/o pre-magnetization	5,652	
N+1 IEGT cell redundancy	2,006	Recommended option

Motor	**Failure rate (FIT)**	**Comment**
IEEE 493	4,554	
High speed motor with Reinforced Reliability	< 3,791	Recommended option

Failure rate (FIT) with standard options	**Failure rate (FIT) with recommended options**
28,451	13,977

A new computation is done with two configurations: the one that was provided at the initial stage (Version 1) and a new one that includes the redundancy of the CPU (Version 2). The redundancy of the CPU increases the MTBF by more than 1 year. As the MTTR of the control is low, the Availability and the Forced downtime are not significantly changed, but the Probability of failure is reduced from 15% to less than 13%. The Medium Voltage components are not subject to wear and therefore they do not require any specific maintenance during the 6 years of continuous operation. One can then consider that their Probability of failure is constant during the 6 years (in other words, the probability to fail in the 6th year is not higher than the one to fail in the 1st one). It is not the case for the auxiliary circuits such as the cooling system, UPS, etc. for which it is necessary to perform a regular preventive maintenance (usually every year) to avoid that their Probability of failure increases with the time (in other words, a preventive maintenance activity “resets” the Probability of failure at its initial value). In conclusion, this study clearly shows that, with a MTBF of the complete system at almost 8 years and an associated availability of 99.92%. The goal of a continuous operation for 6 years is achieved, selecting the recommended options associated to the preventive maintenance program.

C. Electric System Selection

Only Voltage Source Inverter (VSI) drive can control an induction motor at a requested power factor, maximizing the torque generation by an optimum vector control. The requested power below 7MW allows the use of a simple DFE 3-level IEGT Neutral-Point Piloted (NPP) converter without an additional heavy current harmonic filter on the rectifier side (Fig.5). The IEGT VSI technology has been applied to many applications in a wider power capacity range. VSI drives can now deliver tens of MW with a small number of such components, which gives them a high reliability. In the system speed range, the 7-pulse synchronous control of the inverter reduces significantly up to the 15th and 17th time harmonics of the currents fed into the motor, limiting the stator joule losses and the torque pulsations. The NPP topology for the valves of the inverter downsizes the cooling unit of the drive. The clamping diode valves are replaced by IEGT ones giving additional controllability. Each valve is commutating with only half the DC bus voltage, reducing the devices commutation losses by three. 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. As shown on Figure 5, the 5kV 3-Level NPP inverter has 3 IEGT in serial arrangement per half phase plus 1 IEGT for redundancy thus #ph =3(+1), and 2 IEGT in back to back arrangement at neutral point location plus one IEGT for redundancy thus #np = 2(+1) + 2(+1). A sinus filter is necessary to avoid any risk of electrical resonance between the inverter and the stator via the cables and to reduce the IEGT transient switching voltages below 3 kV/µs to protect the inter-turn insulation of the stator coils as requested by the IEC60034-18-42.

The grid design does not require power regeneration from the motors to the grid to brake the driven load of the compressors. For this reason, it makes sense to use a Diodes Front End rectifier which requires some capacitive reactive power from the grid to commutate the diodes with a lagging power factor greater than 0.95 at full load conditions. A multiple bridge 24-pulse arrangement generating harmonic currents above the 23rd rank of the grid frequency is compatible to the Current THD requirement of the end-user and the limited power needs for designing the cables and the step-transformers with limited weights and layouts.

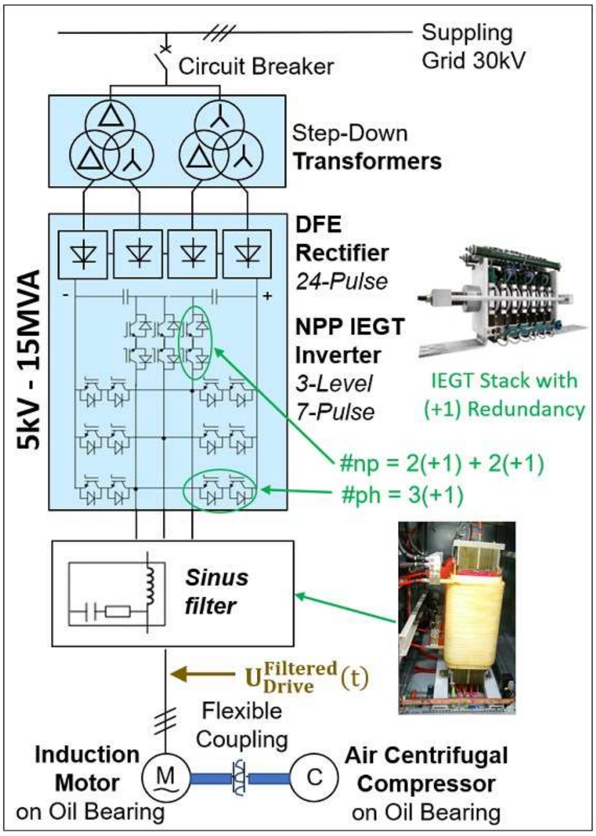


Fig. 5. System Architecture for Moto-Compression DFE NPP 3-Level VSI

IV. 2nd CHALLENGE - DRIVER INTERCHANGEABILITY

A. The End-user Requirement

It was critical for the customer to not touch the existing compressor and foundations. The power to deliver is 5.7MW@6400rpm. The plot space dimensions, and allowable weight were clearly established, giving the project team the task to design a machine that would fit over the bolt locations of the existing machine. As the machine is standing on a concrete tabletop, the full scope of steel base frame and electric motor was given as one scope to the equipment manufacturer. This allowed detailed stiffness calculations to be carried out and keeping the scope definition with one party only, limiting organizational interfaces. The static and dynamic behavior of the new train (electric motor and compressor) was an important design parameter as there was a concern that the new electric motor would be too heavy, would not fit the existing footprint or would vibrate too much. Several studies were carried out to assess the static and dynamic behavior of the new configuration. Lastly, a very detailed inspection and test plan was worked out with the integrated team (owner, engineering contractor, equipment supplier, installation contractor). This ITP identified several attention areas and key hold points throughout the construction, commissioning, and start-up.

B. The Manufacturer Solution

Special attention has been given by the manufacturer to be able to integrate the electric motor with the 4 main existing interfaces:

- *Interface #1:* Maximum available volume,
- *Interface #2:* Axis height & Rotor of the compressor,
- *Interface #3:* Re-use of the oil system for the bearings,
- *Interface #4:* Existing 10-point of fixation by tie-rods in the foundation.

According to the volume constraint of the Interface #1, the compressor is directly driven by the high-speed air-cooled induction motor (Fig.6). The advantages of the induction motor compared to the synchronous motor include no excitation system and simplified rotor construction, leading to longer run-time with fewer maintenance issues. The cooling with motor-fans is chosen for a better operability especially at low speed using the electric motor for the compressor barring. The stator insulation is customized for high speed VSD: Class H (180°C) Insulation, Class F (155°C) Temperature Rise, Vacuum Pressure Impregnated (VPI).

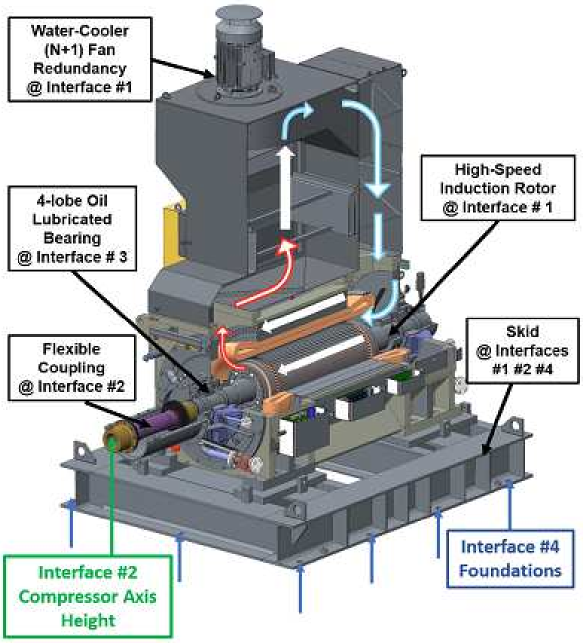


Fig. 6. Electric driver general view

The rotor construction is customized for conditions of high centrifugal stresses up to peripheral speed of 180 m/s, especially the squirrel cage and the laminated ferromagnetic part hooped (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}.

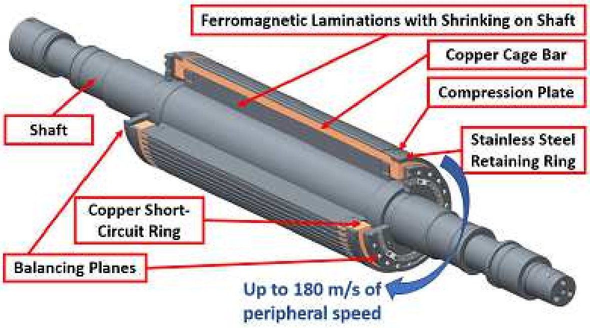


Fig. 7. Induction Rotor Technology up to 180 m/s

V. 3rd CHALLENGE – MOTOR INTEGRATION

A. Full Compression Train Torsional Analysis

Conventional trains present complex torsional behavior. Their equivalent models contain multiple inertias and stiffnesses (motor, low speed coupling, gear wheel, gear pinion, high speed coupling, compressor). The combination with the high motor shaft inertia results in high modal density at low frequency that must be checked carefully. On the contrary, the high-speed moto-compressor presents a very simple torsional model, consisting of the motor shaft and compressor shaft inertias, coupled by the coupling stiffness. As the interface #2, the compressor manufacturer provides the torsional model of the air compressor. The motor manufacturer performs the torsional study of the full shaft line. The first global torsional mode around 22 Hz, while next modes are rejected above 295 Hz without any risk of excitation by the torque harmonics (Fig.8).

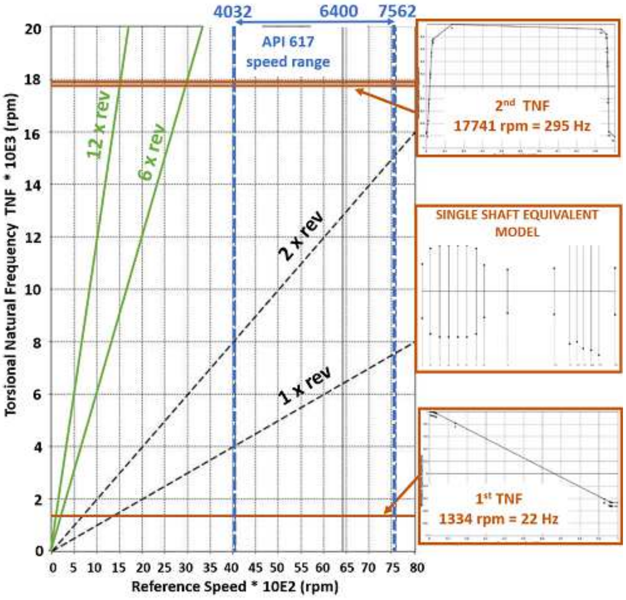


Fig. 8. Torsional Shaft Line Campbell Diagram

Because of the DC energy stored in the VSI DC capacitors, the VSI induces overall very low torque ripples to the motor (Fig.9) and does not produce significant inter-harmonic interactions in between the grid and the motor as for torsional sub-synchronous excitation improving a lot the system reliability. Significant torsional shaft excitations are unlikely to occur.

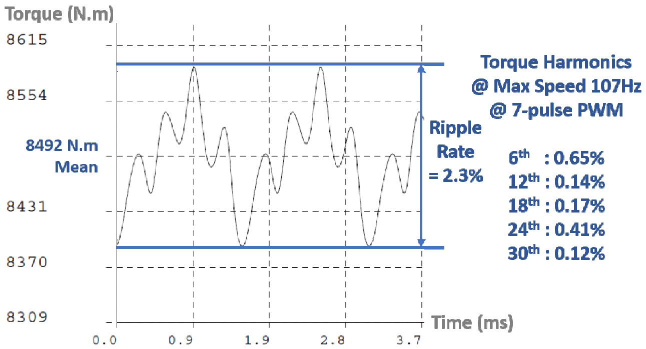


Fig. 9. Torque vs Time @ 6,400 rpm

As the VSI inverter generates voltage harmonics V_h to the motor, the higher the motor impedance Z_h is, the lower the harmonic currents are ($I_h = V_h / Z_h$). The design of the motor can thus be freely done so that the short-circuit torque is reduced. Because of the 7-pulse PWM control of the inverter coupled to the sinus filter, the harmonics of the torque remain low, mainly driven the 24th rank around 0.41% of the mean torque.

B. The Skid

The skid is the keystone and the adjustment variable of the mechanical system. Indeed, the constraints of integration related to the axis height of the compressor (interface # 2) and the re-use of the 10 fixing points of the foundation define the input interfaces for the design of the skid. The skid must be also perfectly designed and modeled in terms of dynamic interfaces for the lateral analysis of the electric rotor. The use of lubricated oil bearings (Fig.10), answering to the need of the Interface #3, strongly couples the dynamic of the rotor, operating above its first bending modes, with the static structural part of the motor through the stiffness and the damping of the oil film and the skid.

Fig. 10. Assembly of the Induction Rotor with Oil Bearings

The contractual speed range of the motor is 4,480rpm to 6,880rpm with a rated speed at 6,400rpm. The acceptance criteria of vibrations are 2.3mm/s rms on bearing housings and 4.5mm/s rms in all directions on the motor frame including main terminal boxes. Based on the bibliography, the structural design will be under control if the following design rules are satisfied:

- No natural frequency of rotor bending in the 1X variable speed range.
- No natural frequency of the end-shields of the frame in the 1X and 2X variable speed range.
- No global “reed” mode of structure bending (horizontal or axial) in the ½X, 1X and 2X variable speed range, or close to the rotor bending natural frequencies avoiding any risk of modal chaotic couplings and rotor instability.
- Skid vibration near the motor feet to be less than 30% of the vibration measured at the bearings [3].

The methodology of the manufacturer is to find the minimum stiffnesses of foundation by conducting a sensitivity study on the stiffness of the anchoring points. This allows to know very early in the design phase the necessary stiffnesses of foundation that can be discussed and validated with the end-user and the EPC partner in charge of the civil works.

The full motor, including the skid and the rotor with the bearing's symmetric stiffness and damping matrixes, is modelled with a mix 3D/shell FE model predicting the vibrations when the structure is excited by the rotor unbalances and the stator by the pole passing frequency at 2 times the inverter fundamental frequency.

The sensitivity study of foundations shows the needs of stiffness of foundations above $10^9 \mathrm{N/m}$ for the anchoring points to avoid significant resonances in the 1X and 2X range of speed (fig. 11).

In addition, the overall structural modes named A, B and C are not in the most probable ½X frequency range of use (i.e. 52Hz-54Hz) corresponding to a speed variation between 6,250rpm and 6,450 rpm.

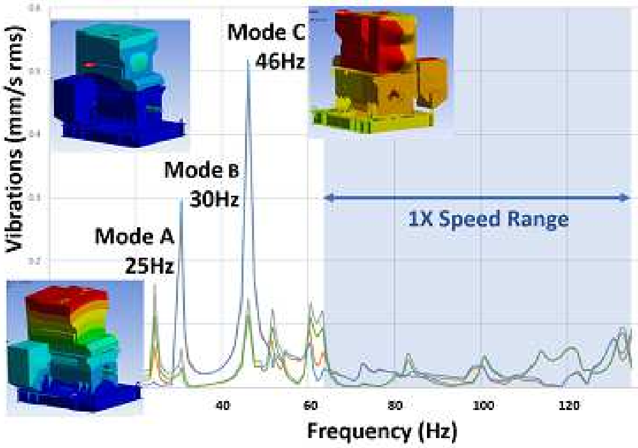


Fig 11. Dynamic response at the bearing housings location

The 3D-FEA model also allows the computation of the dynamic stiffness necessary for the rotor lateral analysis at the interface of the bearing housing (Fig.12) [4]:

$$K_{ij}^{dyn}(\omega) = K_{ij} - \omega^2 M_{ij} = F_i(\omega) * \frac{\overline{U}_{Re,j}(\omega)}{\overline{U}_{Re,j}^2(\omega) + \overline{U}_{Im,j}^2(\omega)} \tag{1}$$

$$C_{ij}^{dyn}(\omega) = -\frac{F_i(\omega)}{\omega} * \frac{\overline{U}_{Im,j}(\omega)}{\overline{U}_{Re,j}^2(\omega) + \overline{U}_{Im,j}^2(\omega)} \tag{2}$$

Where $\overline{U}_{Re}$ and $\overline{U}_{Im}$ are real and the imaginary complex averaged displacements at the nodes of the interface of fixation and i,j={x,y,z}.

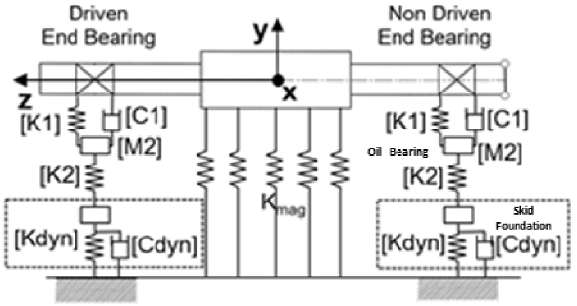
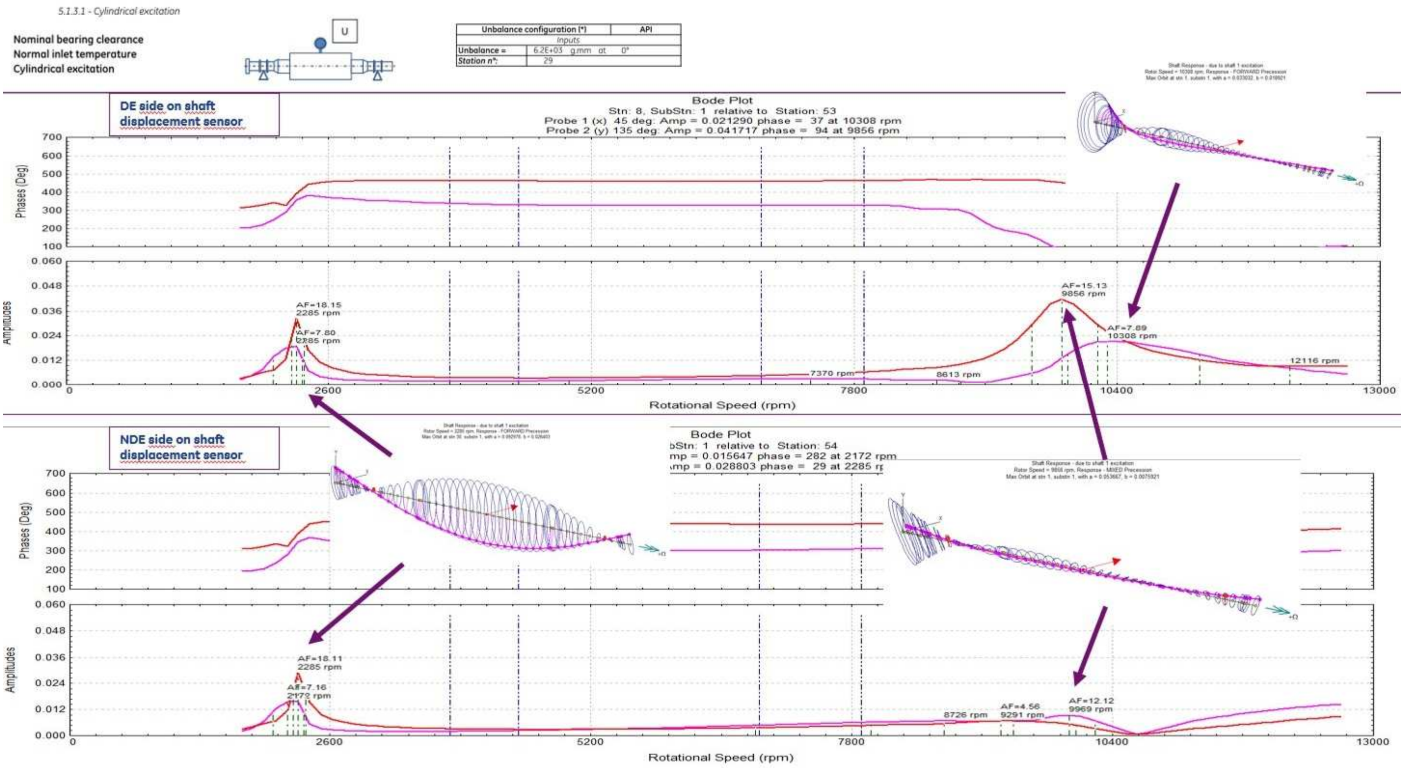


Fig. 12. Rotor Dynamic Model for FEA Lateral Analysis

The motor is compliant to the End User Specification and also the API 541 for the shaft displacements, and the bearing and frame vibrations, considering the stiffness and damping matrixes of the 4-lobe bearings at minimum, rated and maximum temperature of oil and the minimum, rated and maximum clearances of the sleeves (Fig.13).


5.1.3.1 - Cylindrical excitation

Nominal bearing clearance
Normal inlet temperature
Cylindrical excitation

Unbalance configuration (*)		API
Inputs		
Unbalance =	6.2E+03 g.mm at 0°	
Station n°:	29	

DE side on shaft displacement sensor

Bode Plot
Stn: 8, SubStn: 1 relative to Station: 53
Probe 1 (x) 45 deg: Amp = 0.021290 phase = 37 at 10308 rpm
Probe 2 (y) 135 deg: Amp = 0.041717 phase = 94 at 9856 rpm

NDE side on shaft displacement sensor

Bode Plot
bStn: 1 relative to Station: 54
mp = 0.015647 phase = 282 at 2172 rpm
mp = 0.028803 phase = 29 at 2285 rp

Fig. 13. Dynamic response of the Driven End (DE) & Non-Driven End (NDE) shaft displacements

C. Specific Motor Tests

After an overspeed test useful for relieving the stresses inside the rotor, a rotor heating test [5] is carried out for this type of a high-speed motor:

- Helping the rotor in relieving all residual stresses, reaching stable vibrations over the time in cold and hot conditions,
- Checking centrifugal and thermal expansion of the different components especially at the interface of the copper bars and the ferromagnetic laminated shaft, respectively having coefficients of thermal expansion of 17.10^{-6} K^{-1} and 12.10^{-6} K^{-1},
- Checking residual unbalance.

During a partial load test (Motor + Skid + Test Bench VSI), an Operational Deflection Shape (ODS) combined to a Bump Tests campaign is carried out to identify all the principal natural frequencies (Fig. 16 & 17) and to quantify of the dynamic stiffnesses at the different interfaces of fixation of the system. The motor outputs including vibrations are summarized below (Fig.14 & 15):

TABLE III
Main Outputs of the 2-pole Motor Performance

Parameters	Measurement
Power	5.7MW
Rated Speed	6,400 rpm
Speed Range	4,480-6,880 rpm
Rated frequency	107.1 Hz
Fundamental Voltage	4.7 kV rms
Current	866 A rms
Motor Efficiency fed by VSI	97.3%
Motor Weight	12 tons
Stator RTD Temperature	< 120°C
Bearing Vibrations @ full load	< 2.3 mm/s rms
Structure Vibrations @ full load	< 4.5 mm/s rms
Run Out	< 12.5 um pp
Thermal Unbalance	< 5 um pp
Shaft Displacements @ Full Load	< 20 um pp

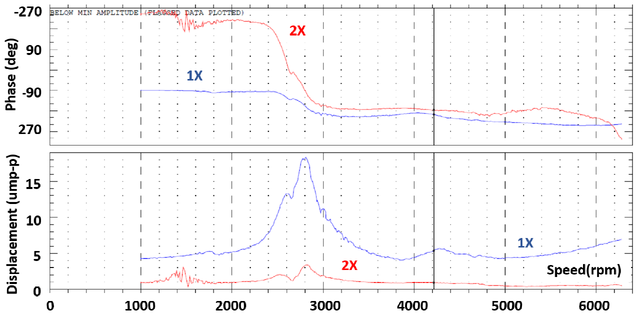


Fig. 14. 45° Left NDE Shaft Displacement vs Speed

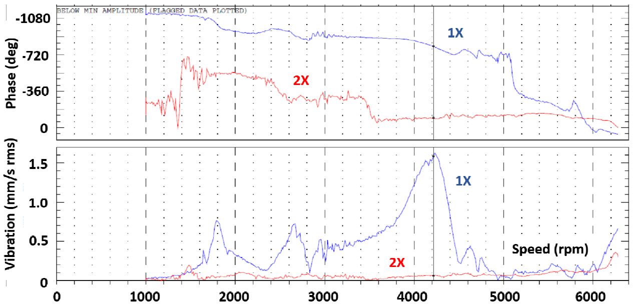


Fig. 15. Horizontal DE Seismic bearing Housing Vibration vs Speed

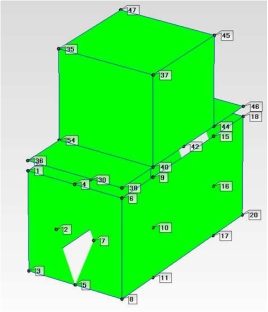


Fig. 16. ODS Mesh

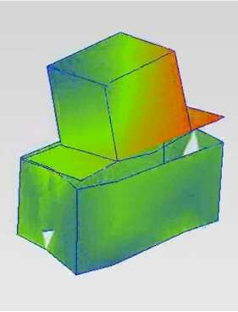


Fig. 17. Mode A @ 25Hz

VI. 4th CHALLENGE – CONSTRUCTION AND START-UP

The final investment decision of the project was taken in February 2018 after which construction started in April 2018 with excavation of the trenches for the main high voltage routing. This consisted of 1.3 kilometers of high voltage cable. In parallel with the cable installation, the underground infrastructure for the new modular substation was prepared, which consisted of tubex piles, concrete, and steel on which the new substation could be placed. The substation itself was completely built off-site, which allowed to integrate the electrical equipment into the substation prior to on-site installation. The key electrical equipment inside the substation consisted of 30kV switchgear, a water-cooled variable frequency drive, low voltage motor control centers (MCC), a HVAC system and fire and gas protection. In September 2018, the substation, transformer and cooler for the VSDS arrived on site and were hoisted onto the foundation. After this the E&I connections were made and the project scope prior to the maintenance stop was completed (Fig.18).

Fig. 18. Substation Module Lift

The only item left to install was the actual steam turbine replacement with the electric motor which took place during a maintenance period between April 29th and June 18th, 2019. The demolition scope at the start of the turn-around was extensive. It required expertise to remove the piping as well as the old steam turbine. The key challenge was to separate it from its foundation without damaging the concrete so that the tabletop could be re-used without too much civil works (Fig.19). Once the concrete surface was cleaned and prepared, the new steel base frame was hoisted into position, aligned with laser, and grouted (Fig.20). It is vital to get the grouting right. Thus, several flow tests were done to determine the right mixture and viscosity of the grouting before actual under-grouting the steel base frame (skid). Afterwards, the new electric motor was installed and aligned with the compressor and the mechanical and E&I connects were made after which commissioning began (Fig.21).

Fig. 19. Replacement of the anchoring tie-rods

Fig. 20. New Grouting

Fig. 21. Motor (L) - Compressor (R) after replacement

VII. LEARNINGS & CONCLUSION

There were two key lessons learned during the commissioning phase of the project. Firstly, the existing oil lubrication system delivered an oil flow that was too large for the bearings of the new electric motor. It was assumed that the flow would be regulated through installation of new restriction orifices. Unfortunately, the required orifice size would have been unacceptably small to reach the desired oil flow. This caused a late scope change during commissioning to achieve the required oil flows for both the electric motor and existing compressor. It is highly advised to thoroughly study the lube oil system during the engineering phase, up to the last detail of orifice restriction size and assess whether the existing lube oil system is fit-for-purpose. In the case of this motor-compressor, the existing system was too big and should have been partly re-sized as part of the project. This is a difficult trade-off between scoping, schedule, expenditure, and operational flexibility.

Secondly, as part of the commissioning process, there was an extensive test-run of the coupled configuration, blowing air to atmosphere for a period of 4 days, prior to lining-up the air to the reactors. During this test run, the diodes in one of the Diode Front End stacks of the variable frequency drive failed. The project team decided to replace all diode stacks preventively, this was resolved within 2 days. A root cause analysis concluded that the failure was caused by a fabrication defect. Looking back, the end-user had high expectations for this electrification project with many stringent requirements on minimum scope, minimum cost, schedule, logistics, plot space dimension, reliability, and availability. After the post implementation assessment, it was concluded that this project as a success, having delivered the project without any safety incidents, on time, below budget and started-up the unit “first-time-right” with no trips to date. The motor-compressor train has delivered more value than originally anticipated in the business case and reduces the site’s CO_2 footprint with 13 ktpa.

A win-win contribution from an environmental and economical perspective. A win-win collaborative success story for the end-user, the Engineering Procurement Company (EPC) and the Electric System manufacturer.

VIII. ACKNOWLEDGEMENTS

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