

DESIGN, MANUFACTURE, AND TEST CAMPAIGN OF THE WORLD'S LARGEST LNG REFRIGERATION COMPRESSOR STRINGS

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ABSTRACT

Increasing demand for LNG has driven the requirement for a significant increase in LNG plant capacity. Qatargas II (QGII), a joint venture initiated by Qatar Petroleum, is committed to accomplish this while reducing plant emissions and making more efficient use of energy resources. The Qatargas II LNG project has applied the AP-X™ process for two large LNG trains (7.8 MTA) presently under construction in Qatar at Ras Laffan Industrial City (RLIC). Approximately 280 MW of refrigeration compression will be required to achieve this goal. This paper addresses the design, manufacture, and test campaign of the world's largest LNG refrigeration compressor strings.

INTRODUCTION

The economy of scale incentives highlighted the Frame 9E as the ideal mechanical driver for the refrigeration strings. However, a significant qualification effort was required to adapt the Frame 9E power generation gas turbine for variable speed mechanical drive service. System reliability was improved through a focused design program that targeted reduction of the number of components. In addition, considerable effort was concentrated on reducing plant emissions through the qualification and use of Dry Low NOx (DLN) burner technology suitable for the low BTU, LNG mechanical drive application.

Further improvements to efficiency required a solution to address the impact of diurnal and seasonal ambient temperature variations on the gas turbine power output. This requirement was accomplished through the development of a unique, variable-speed, electric motor/generator. The motor/generator enables pressurized starting of the compressors, ensures adequate power for refrigeration compression, and exports

surplus power as electricity into the plant grid to fully utilize the capability of the gas turbine.

This paper also discusses the challenges of design, manufacture, and full-load string testing for the six main refrigeration compressor casings. Experience called for the development of single-piece manufactured impellers. Extensive use of CFD simulation and modeling was used to authenticate the aerodynamic design. Finally, advanced sealing technology was developed for refrigerant sealing at very large shaft diameters.

INTEGRATED TEAM APPROACH

An integrated team approach was employed to develop the design concepts for the refrigeration compressor strings. This team engaged engineering and operational expertise from QGII, in conjunction with the Design Team and Equipment Supplier's Team.

The need for 280 MW of refrigeration required not only understanding technology gaps, and designing the system to minimize these gaps, but also achieving the desired capacity and required reliability and availability. These challenges required initiating studies and design work earlier than typical projects.

Refrigeration was designed around three process services: propane pre-cooling, mixed refrigerant liquefaction, and nitrogen sub-cooling. This process was presented in [Qatargas II: Full Supply Chain Overview](#) at LNG 14. The refrigeration strings depicted below in Figure 1 are an innovative design. Each string utilizes a Frame 9E single shaft gas turbine driving through a motor/generator, powered by a variable frequency drive (VFD).

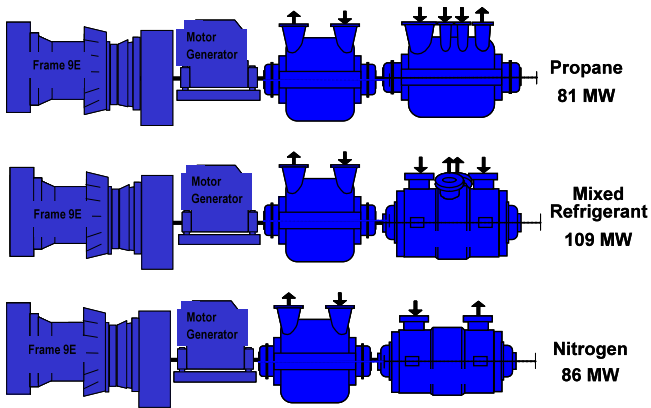


Figure 1. Refrigeration Strings

These strings were designed to meet demanding reliability and availability required for LNG production while in the high ambient environment of Qatar. “Flat” LNG production was a key design target along with simple starting and minimized flaring. The design concept selected achieved these objectives by utilizing a large motor/generator with a VFD that is capable of pressurized starting of the compressor strings and providing helper service during high ambient temperatures when the gas turbine power is limited. This permits 100% of design refrigeration requirements to be met at any ambient condition in Qatar. It also allows “one button” starting without depressurizing refrigeration loops around compressors in most cases. Pressurized starting eliminates flaring refrigerant and significantly reduces starting times.

String layout was designed to facilitate maintenance of the compressors and gas turbine without requiring removal of any casings. The inboard compressors are all horizontally split, allowing vertical rotor removal. Outboard compressor rotors are either removed vertically or horizontally as bundles. The motor/generator is designed to be removed for servicing. A typical string design is shown below in Figure 2.

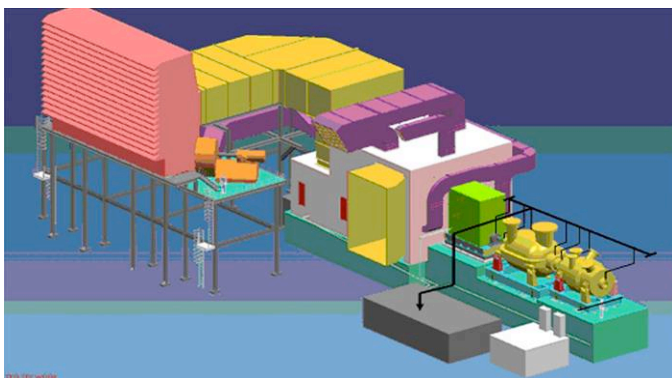


Figure 2. Typical Refrigeration String

One innovative design is that the strings are capable of speed variation, required to optimize LNG production while producing high quality electrical power as a by-product to the plant throughout this speed range.

Additionally, heat recovery steam generators (HRSG) were added to the C3 and MR strings, making more efficient use of untapped energy sources, improving plant efficiency while reducing emissions. This low cost steam was utilized on numerous Steam Turbine Driven Compressors throughout the Plant, eliminating additional VFD Motor drives, further reducing plant electrical power demand and Ras Laffan emissions at the IPP.

The Design Team’s proprietary qualification processes were utilized to manage the technical risks associated with this string design. The following designs and new technologies were validated not only using these qualification processes but also through customized design validation efforts:

- Frame 9E as Mechanical Drive customized for LNG
 - Variable Speed
 - Dry Low NOx (DLN) , Inlet Bleed Heating (IBH) and Fuel Flexibility
 - Augmented Starting Power
- Large centrifugal compressors and associated casings
 - Impellers and Casings
 - Dry Gas Seals
 - Couplings
 - Anti-Surge Protection
- Large motors and VFDs
 - 60 MW VFDs (4X15 MW)
 - Torque Ripple
 - Active Front End (AFE)
 - VFD Redundancy/ 4-Winding Motor
 - Break Away Torque
 - Pressurized Starting
 - Drive Through Motor
 - Exciter/Overspeed Protection
 - Turbine Auxiliary Services
- Common oil system
- String Integration and Reliability
 - Gas Turbine, VFD, DCS and Power Management System Controls
 - String Torsionals

FRAME 9E GAS TURBINE

Speed Studies

The MS9001E (Frame 9E) gas turbine has an extensive operating history in power generation applications since 1978. The Design Team initially qualified the Frame 9E for mechanical drive LNG service based on 100% constant speed and fuel gas with 38% nitrogen content. The Design Team then performed a study to customize the Frame 9E for variable speed operation without compromising maintenance intervals or life expectancies. The speed study assumptions were:

- Operating ambient temperature from 4 deg C to 49 deg C

- 5 to 30 starts per year (mature design at 5 per year)

With above assumptions, the following components were assessed to verify life expectancy over a speed range of 2850 rpm (95% speed) to 3150 rpm (105% speed):

- Axial compressor rotating and stationary blades
- Turbine rotor and buckets
- Gas dynamics in the combustion cans and transition pieces
- Gas flow disturbances in the combustion system, exhaust diffuser and collector

Gas turbine components are subject to a number of failure mechanisms such as low cycle fatigue crack initiation, cycling crack propagation, disc burst and creep. All of these failure modes were evaluated at baseline conditions and at 105% speed.

A finite element analysis (FEA) model was developed based on parameters that defined the thermodynamic behavior of the unit (power output, pressure ratio, mass flow, speed ramps, etc.). The FEA model was then used to calculate temperature distribution, aero mechanical loads, inertia loads, etc.

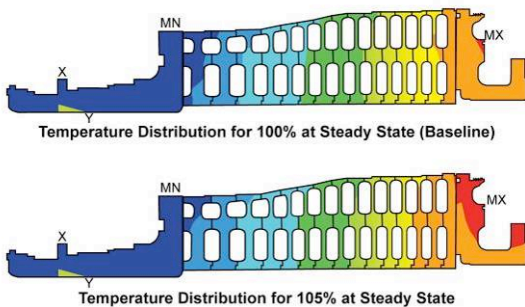


Figure 3. Rotor Thermal Model

The thermal model indicated in Figure 3, was used to calculate transient temperature distribution that was then mapped on the structural model together with the rest of load conditions. After completing the structural analysis, low cycle fatigue (LCF), and creep life was evaluated and all found to be well within design requirements.

Another part of the study evaluated the Frame 9E compressor airfoil rotor and stator blades ability to operate in the 95% to 105% speed range. An FEA analysis was performed on all rotor and stator blades with the appropriate constraints and loads. The rotor and stator blades were also analyzed at zero speed with no pressure and temperature load to simulate a ping test environment. Ping tests were then conducted to validate the modal analysis. The conclusion was that stresses remained within allowable limits. Torque ripple effect contributions from the VFDs were also assessed and considered a low risk to the compressor blades. This analysis, coupled with the operating experience of the Frame 9E compressor rotor,

confirms that the Frame 9E can operate continuously as a mechanical drive in the speed range of 96% to 102 %.

Hot gas path components were analyzed for aeromechanical (modal) creep and LCF capability. Modal analysis revealed that resonance is avoided between bucket natural frequencies and high strength drivers at rotor speeds between 95% and 105% speed. Creep resistance of the rotor was evaluated against the 200,000 hours limit for Frame 9E gas turbines. The turbine rotor dovetails exhibit sufficient margin to operate at 49 deg C at continuous speed up to 105%.

Finally, the effect of variable speed up to 105% operating at 49 deg C ambient temperatures was analyzed using FEA modeling to identify and quantify LCF rotor components life. The life requirements were set at 300 starts over the life of the rotor for this application (10 starts per year, 30 years operation). Results showed the components have margin beyond the conservative 300 starts requirement.

The study concluded a speed range between 96% to 102% was suitable for continuous operation and transient excursions up to 105%.

Fuel and Emissions Studies

The Frame 9E is equipped with a DLN combustion system for emission abatement (DLN-1). In a normal application this system is capable of 25 ppmvd of NOx and requires a variation of no more than +/- 5% from a given Wobbe Index target value for the fuel gas. WI is the ratio between the fuel lower heating value (LHV) and the square root of specific gravity multiplied by fuel temperature. This can be thought of as a measure of the energy density of the fuel.

The QGII fuel gas is supplied by the LNG process and supplemented during various modes of operation. The fuel gas may have a WI variation as high as +/- 26%. The WI range and rate of change is limited to ensure adequate pressure ratios across the fuel nozzles. If the pressure ratio is too low, then the combustion dynamics amplitudes can increase to unacceptable levels leading to shortened operating life and poor reliability.

Combustion testing was performed to verify the combustion hardware was capable of handling fuel gases ranging from 4% up to 48% N₂. Additional lab tests were performed to verify that the selected fuel nozzles and the selected combustion chamber design stayed within acceptable performance limits. The following diagram (Figure 4) illustrates the layout of the DLN-1 combustion system:

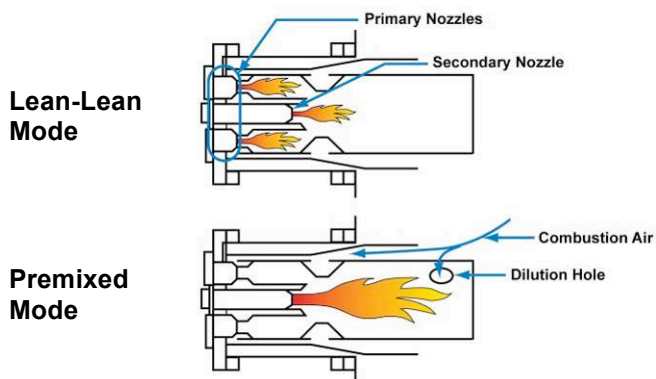


Figure 4. DLN-1 Combustion Modes

The system incorporates two main fuel circuits: one feeding the secondary nozzles, and the other feeding the six primary nozzles. The pressure ratio of both must be carefully observed to understand which is contributing to any measurable combustion dynamics. Five combinations of primary and secondary nozzles were tested over the entire expected operating range with the principle goal of establishing the pressure ratio boundaries of each circuit.

Combustion air is split between the dilution air and the air that goes to the head-end of the combustors. Reducing the head-end air (i.e. the air in the main reaction zone) increases the equivalence ratio and the reaction temperature. Higher flame temperatures yield higher NO_x emissions, but yield lower CO emissions. This increases the margin from the blow-out region, achieving a more robust design with a wider operating envelope.

Different dilution holes were also tested to determine the best trade-off between emissions and combustion stability over the operating range. Critical testing was performed at the Gas Turbine Manufacturing Facility to change combustion boundary conditions and set points independently. Test parameters included: air inlet temperature, inlet pressure, fuel composition, air-flow and/or exit temperature.

NO_x emissions reduce as the N₂/CH₄ ratio in the fuel gas increases. While this effect is beneficial for reducing emissions, it can have a negative impact on the reliability of the combustion system. Extremely low NO_x emission values for this combustion system can indicate a very weak flame, which in turn could lead to a combustion blow-out or high combustion dynamics. To compensate for the high N₂ fuel content, the dilution area of the liners was increased to achieve a robust flame over all operating conditions.

This liner modification, coupled with the redesigned fuel nozzles, produced test results that concluded the combustion system can operate throughout the required QGII range. The NO_x is expected to be less than 25ppmvd while running on fuel gases with 25% to 42% nitrogen.

Complimentary to the combustion design changes was the addition of Combustion Reliability Upgrade Technology, maximizing availability.

MOTOR/GENERATOR, VFDS SYSTEM

Design Basis

The design basis of the motor/generator, VFDS system was to support flat LNG production by providing sufficient string torque under all ambient conditions. The design and operability of the string was validated during Back to Back (B2B) and String testing.

The synchronous motor/generator incorporates integral shaft flanges that mechanically connect the Frame 9E and the centrifugal compressors. This design is based on a theoretical limit that allows the turbine to transfer full power to the compressors at the same time the motor/generator also supplies full power (45MW, 143KNm base, 60 MW, 190KNm peak) to the compressors.

The VFD's are designed to not only support a base full motor power (45MW, 143KNm) in either generation or helper motor modes. They are also designed to provide peak power up to 190KNm of motor starting torque (corresponding to 60MW@3,000rpm) for 90sec. This enables pressurized starting of each string, significantly reducing starting time as well as emissions.

15MW VFD Limit, Parallel Operation and Redundancy

High availability flat LNG production requires a 60MW system design. Since the VFD technology selected was limited to 15MWs per drive ("threads"), 4 drives were required for each compression string. However, the 15MW limit provided an opportunity for system redundancy. Each motor is normally fed from 4-VFDs with each VFD feeding a separate motor/generator stator winding. The design using 4 parallel drives, not only supports the 60MW requirement for pressurized starts, but can also operate continuously at 45MW in motor/generator mode with only 3 VFDs. To provide a double level of redundancy the VFDs are designed so that a single VFD can provide full power (15MW) with one of the power cells out of service in each phase (total 3 cells out on different phases) or 2 power cells out in any one phase. It is also important to note that only two VFDs are required to permit depressurized starting, flat LNG production, and turning gear operation.

Even the simultaneous trip of all 4 VFDs does not necessarily imply a string trip interrupting LNG production. With the VFDs tripped, the motor simply acts as a coupling between the turbine and the compressors. Once the VFDs are available, they can be restarted without requiring shutdown of the Frame 9E.

The simultaneous trip of all 4 VFDs only affects the MR string operation during the hottest portion of the day in the summer months when the motor is operating in helper mode (Figure 5 below).

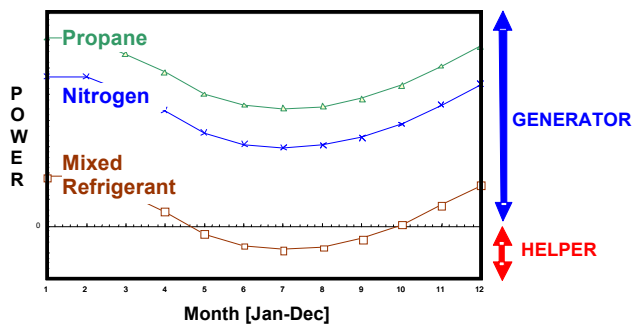


Figure 5. Monthly Power Variation for One Year

Turning Gear Function

The VFDs and motor/generator were developed to provide the strings turning gear function. This replaces the standard accessory base functions of breakaway torque, slow roll turning, purge, starting, water wash and cool down. A dedicated emergency low power circuit has been incorporated into the design to permit 300 rpm turning gear operation in the event of a plant blackout.

Back to Back Testing

Back to Back testing was performed at the Motor Manufacturing Test Facility. The purpose of this testing was to validate the system design and compare its performance with predicted and guaranteed values. The B2B configuration consists of mechanically coupling two motors with each motor fed by 4-15MW VFDs (Figures 6 and 7 below). Operating conditions were simulated while validating redundancy. High Speed test data was recorded during both the B2B and string testing for system performance evaluation.

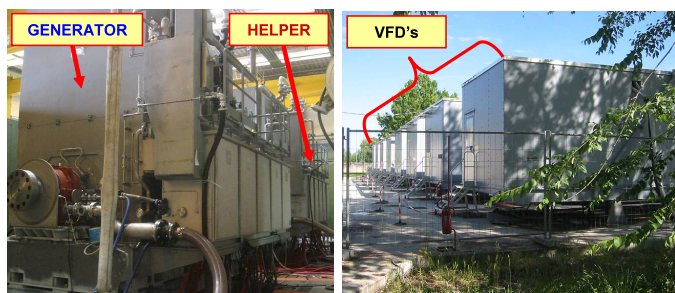


Figure 6. B2B Motor Config. Figure 7. B2B VFD Config.

During this testing, one of the units was operated as a motor simulating the turbine by providing positive torque. The second unit was operated as a generator converting mechanical energy from the first unit to electric power. This configuration required that the utility supply only enough electric power to cover system losses as indicated in the test one-line configuration below (Figure 8).

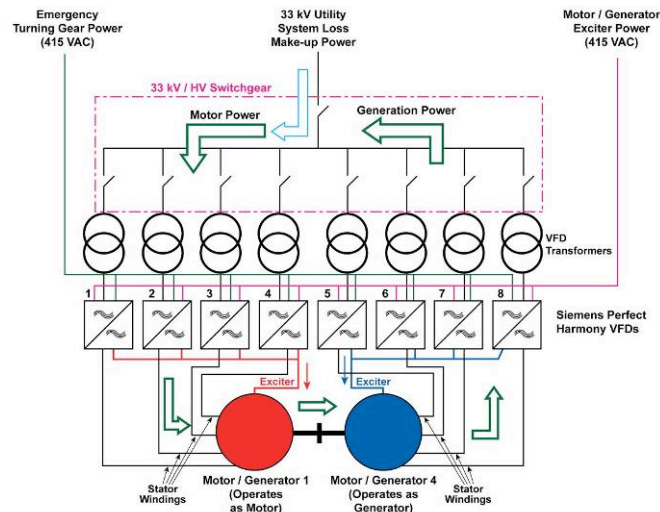


Figure 8. B2B Test One-Line Configuration

B2B testing confirmed system performance not only met guaranteed values but also exceeded the less conservative predicted values. For example, the motor/generator was required to operate below a class F temperature rise at full load (45MW) with only three VFDs (i.e. one “failed VFD”). However, B2B testing determined actual temperature rise was significantly below this value and in fact below a class B temperature rise. This data would not be available without B2B testing and may allow increased motor/generator loads if required in the future.

One unanticipated benefit of B2B testing was realized during an unexpected motor/generator failure. An over-voltage in the motor/generator field delayed B2B testing until the root cause was identified and eliminated. Without B2B testing, this problem would not have been detected until commissioning where a failure would have impacted LNG production.

Compression String Power Generation

Each VFD is provided with an active front end (AFE) capable of supplying real power or reactive power to the plant grid, whenever excess turbine power is available.

Real power to the motor/generator is controlled by adjusting the VFD output current phase angle with respect to motor/generator voltage. This controls the direction of motor/generator torque and therefore MW power flow to or from the motor/generator. In a similar manner the active front end controls power flow from the grid by retarding the current angle relative to system voltage to draw power out of the QGII distribution system, or advancing this angle to push power into the QGII distribution system. Reactive power is also controlled by the AFE by adjusting voltage to control the export of reactive power to the plant grid. Since VFDs isolate the motor/generator from the plant grid by converting plant power from 50cycle AC to DC and then to a variable AC, power flows between the plant grid and the motor/generator are independent of motor/generator shaft speed.

Each compression string is capable of supplying up to 45MW of real power, depending on excess turbine torque

availability, and 30MVAR reactive power to the plant electrical grid on a continuous basis, at variable speed.

Power Management System (PMS)

Excess power from each string is controlled by a power management system (PMS). The PMS controls real and reactive power from all plant power producers (steam turbine generators, gas turbine generators, LNG power recovery generators) distributing the loads as required. One unique feature of the QGII power management system is its ability to scale the size of VFDs power availability based on compression string excess torque availability.

PRESSURIZED STARTING

On most gas turbine mechanical drive applications the centrifugal compressor load (function of process loop pressure) at string start-up usually is maintained as low as possible. The compressors are then loaded once the turbine reaches the minimum continuous speed. The same concept is applied to generator drive units (normally single shaft units), where the gas turbine reaches full speed in an unloaded condition. This allows reducing the size of the starting devices and reduces loading of the gas turbine axial compressor during the start up transient phase. In an LNG plant this depressurized starting method results in:

- loss of refrigerant to depressurize refrigeration loops after any plant shutdown
- flaring
- increased plant downtime (approximately 8 hours required to complete plant start-up)

As a consequence, pressurized starting capability can help increasing plant availability by greatly reducing starting times. The incentives of pressurized starting capabilities led to a significant development effort.

An initial feasibility study was used as the basis for starter motor sizing. Since the required start-up torque is a function of compressor load/loop pressure and rotating inertia, it was critical to fully understand the complete compression system as well as the Frame 9E and motor.

A rigorous dynamic simulation was later performed to take into account the Frame 9E transients using the Turbine Manufacturer's proprietary model based on Frame 9E actual control software and cycle deck performances. The simulation included the electric motor supplied torque, compressor load and train inertias. Pressurized starting was considered feasible using a 45 MW motor with 60 MW peak load capability.

Dynamic simulations performed by the Compressor Manufacturer using site conditions, showed the need for extra-torque from the Frame 9E for speeds above 82% for N₂ and C₃, and above 70% speed for the MR train.

Additional starting torque was obtained by modifying the standard turbine generator drive start-up sequence: increasing

fuel flow rate and anticipating the turbine inlet guide vane opening. This resulted in a dedicated augmented start capability test campaign designed to explore higher Frame 9E axial pressure ratios.

A non-standard development engine approach was used to explore the new operating line limit (OLL). In order to take into account engine deterioration with accumulated operating hours, and engine to engine variation, a 10% margin in terms of pressure ratio was considered necessary to validate the final OLL. This margin forced a higher level of pressure ratios during the test campaign.

The major concerns of the tests were sudden compressor surges and possibly incipient rotating stall resulting in aero-mechanical vibration (nodal diameter stimulus).

To mitigate these risks, the axial compressor was fully instrumented with pressure probes to 1) detect aero-mechanical disturbances and rotating stall and 2) laser probes to evaluate airfoils alternating stress values.

The newly defined OLL was then used as a pressure ratio protection line for the new start-up control sequence, resulting in successful pressurized starting.

In summary the initial project objective of pressurized starting at nearly all site conditions was achieved. This not only simplifies starting, greatly improving plant availability, but also minimizes plant emissions.

WORLD CLASS CENTRIFUGAL COMPRESSORS

Centrifugal compressor design development has been shared between Design Teams from very early stages of the project. The Shareholder Technical Group performed technical reviews covering many aspects of the compressor design.

QG II compressors are the largest centrifugal compressors designed by the Compressor Manufacturer for LNG applications. Although the compressor architecture is not completely new, several innovations were introduced to mitigate risks associated with the manufacturability, performance, and field maintainability of these extremely large compressors.

The process compressors are split into two bodies on each string. The inboard compressor connected to the motor/generator is a drive-through horizontally split casing (MCL type). The outboard compressor is either an MCL type or a barrel type (BCL) depending on the pressure rating. This arrangement was chosen to improve the maintenance on the machines.

The large, horizontally split compressors were designed for ease of maintenance by separating the upper half diaphragm from the upper half casing to significantly reduce the heaviest maintenance lift and avoid the need to rotate the upper half casing to service upper half diaphragms. Removal of the upper

half casing leaves the upper half diaphragm in place. The diaphragms are then removed to reveal the rotor (Figure 9).

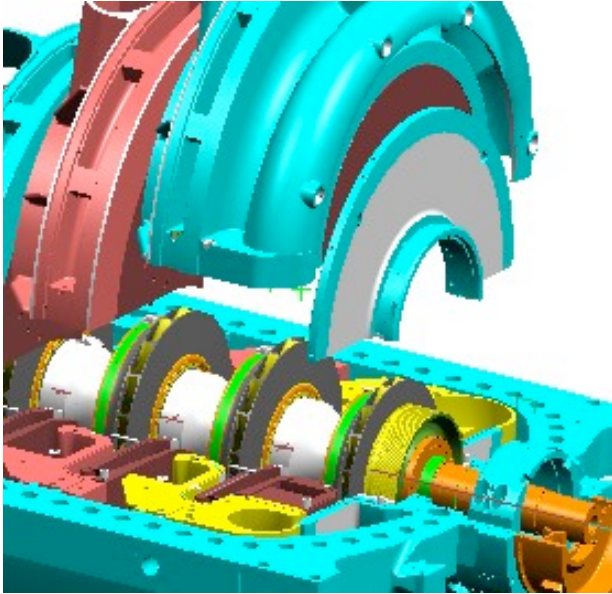


Figure 9. Horizontally Split

These barrel compressors are the largest ever built by the Compressor Manufacturer, with a maximum weight of 115 Tons. Machining and handling of these large single piece forgings required world class manufacturing capability.

The barrel casing is opened by removing the end wall and pulling the inner bundle out on rollers. The roller design, together with the overall stiffness of the structure, is crucial to ensure easy removal of the bundle (Figures 10 and 11)



Figure 10. Barrel Internals



Figure 11. MR Barrel Compressor

Single Piece Impellers

The QGII compressors are equipped with three-dimensional impeller machined from a solid forging. Each impeller blade is machined using a 5 axis milling machine eliminating the need for welding (Figure 12).



Figure 12. Single Piece Impeller

This manufacturing process provided excellent control of the blade geometry without reducing tensile properties associated with weld joints. This technology also increased steel alloy options without the constraints of material weldability.

Each impeller was then checked on a computerized measuring device to assess the possible impact of geometrical deviations. The single piece impeller method guarantees repeatability and improves performance.

QGII compressors were designed to optimize both rotordynamics and aerodynamic performance. In particular, propane compressors are often limited by impeller-eye Mach number resulting in premature choking of the stage.

Splitting the propane compressor into two bodies allowed the high pressure section to have a smaller shaft. This solution reduced the impeller-eye Mach number, avoiding premature choke.

The propane compressor side stream injection design was assessed using wind tunnel tests. These tests were performed on a scaled model reproducing the original geometry, which confirmed the calculated losses (Figure 13). The design was also validated during the string testing through the use of extensive internal instrumentation.



Figure 13. Scale Model Test in Florence, Italy

The complete flow path was analyzed with the help of multistage Computational Fluid Dynamics (CFD) using the Compressor Manufacturer’s proprietary code. The effect on stratification of side to main flow was assessed as well. The use of CFD (Figure 14) allowed for fine tuning of the design during the final assembly of the compressor without impacting the overall schedule. In particular, the diameters of some stages were reduced to meet the process requirements.

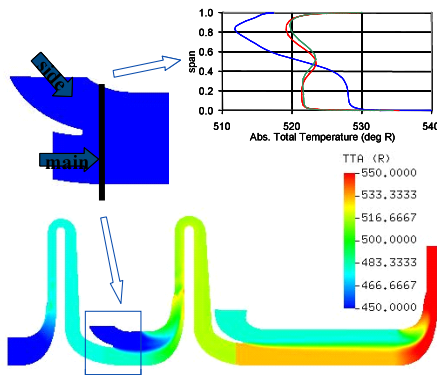


Figure 14. CFD Analysis

A larger flexible coupling was needed to accommodate the significant amount of power required by the string. The coupling manufacturer provided a detailed study to guarantee the life of the flexible unit. In order to transmit 125 MW of power, a new hydraulically fitted hub was developed. The hub

was validated by using a full-size fixture during the early stages of the project.

All barrel compressors completed aerodynamic performance testing at the Compressor Supplier’s Manufacturing Facility. Due to their large size, the horizontally-split compressors were aerodynamically tested while in the string configuration at the Compressor Supplier’s String Test facility. Barrel compressor performance was revalidated during the string tests to ensure consistency of testing results between sites. The results were excellent and showed better than expected efficiencies. A broad operating range was demonstrated between surge and overload as shown in Figure 15.

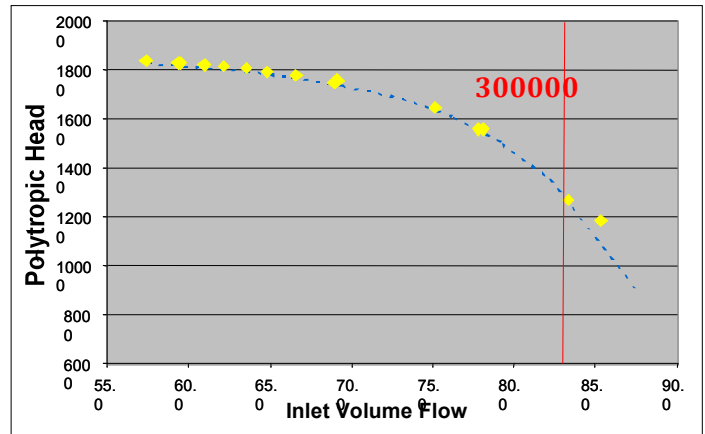


Figure 15. MCL1805 Head Curve

DRY GAS SEAL

The large compressor shafts required tandem dry gas seals (DGS) of 350 mm, which are larger than the current reference of 330 mm. A qualification program was developed that started with understanding the operational modes and conditions. It included dynamic simulation of normal operating conditions as well as start-up, shutdown and “turning gear” modes. The program included detailed analysis and testing of static and dynamic cryogenic conditions to establish boundary conditions of pressure and temperature at all modes of operation, especially during transients. Key concerns of seal lift off speed, depressurization during coast down, shaft axial shuttling, particle ingestion and reverse rotation were all addressed in the design analysis and testing campaign. Particular attention was paid to understand how conditions change during process upsets.

The qualification program was successfully completed on the Dry Gas Seal Manufacturer’s tandem seal (Figure 16). Through design audits and extensive testing the 350 mm DGS and supporting system design was qualified. The design includes:

- Intermediate labyrinth with interstage labyrinth purged with N₂ to eliminate fugitive emissions
- Seal protection from reverse pressurization damage while operating in sub-atmospheric

service by adding a secondary control loop for the primary seal gas control system

- Reliability improvement through addition of secondary seal high differential trip
- Use of abradable type seals on the gas side labyrinths to minimize seal gas consumption
- Use of a buffer gas amplifier system to protect the refrigeration loops from contamination of non-refrigerant buffer gas sources during settle-out conditions
- Other measures were taken to ensure the seals were protected from lube oil ingestion and potential issues of seal gas condensate formation



Figure 16. 350 mm Dry Gas Seal

COMMON LUBE OIL SYSTEM

The standard generator drive Frame 9E utilizes an accessory base arrangement, incorporating the string lube system, the drive for the main oil pump and other functions such as turning gear, starting and cool down.

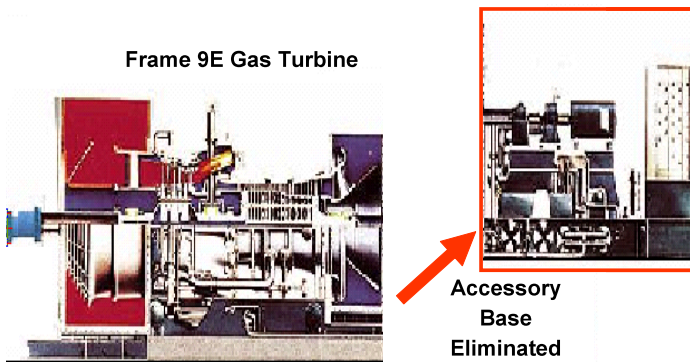


Figure 17. Frame 9E Standard Accessory Base

The initial issue of the standard accessory base was inadequate lube oil supply and storage capacity. This forced the requirement for an off-base lube oil system to supply the compressors and motor/generator. The integrated project team saw an opportunity to use the motor/generator to supply the turning gear and starting functions and allow elimination of the standard accessory base (Figure 17 above). This led to a common oil system which provided the needed additional oil capacity while avoiding a second oil reservoir, set of pumps,

coolers, filters and associated instrumentation (Figure 18 below). Elimination of the accessory base also eliminated the associated coupling, gearbox and turning gear drive. Both tasks had the underlining goal of increasing string reliability by decreasing the number of components.

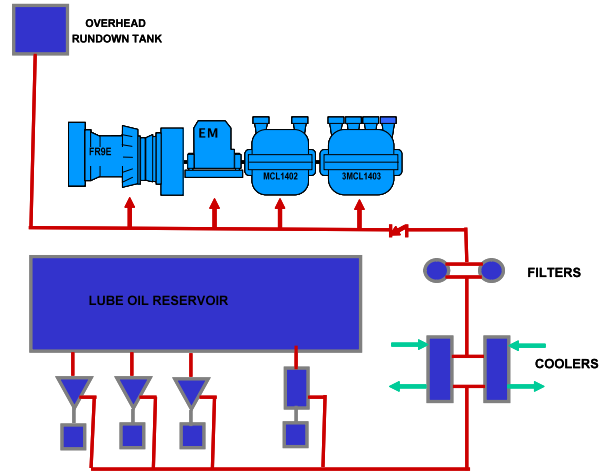


Figure 18. Common Lube Oil System

COMPRESSOR MANUFACTURER'S STRING TEST

As final validation before shipping, a full power string test was performed on each of the three compressor strings at the Compressor Manufacturer's String Test facility. Moving from the current Frame 7EA size refrigeration trains to the QGII Frame 9E driven compression trains required a complete upgrade of testing facility capabilities. Feasibility studies resulted in a substantial upgrade of the facility infrastructure such as the plant cooling water system, a new 132 kV/33kV 96 MVA shop transformer and a new fuel gas supply line.

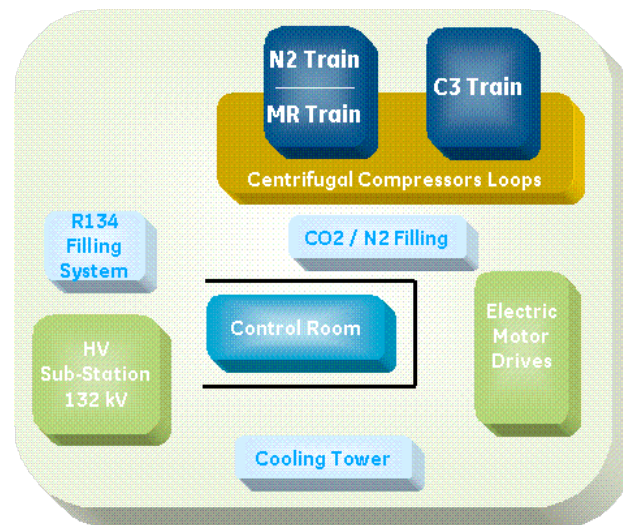


Figure 19. String Test Configuration

The string tests were designed to replicate as much as possible the plant site configuration. Figure 19 shows the block diagram of the two string layout. Two test beds were utilized to

allow setup of one string while testing another (Figure 20). The contract Frame 9E gas turbine, compressors, motor/generator and associated VFDs were all used. It also included subcomponents such as inlet air filtration system, Inlet Bleed Heating, oil system and the DGS system. The only difference with the site configuration was the use of a temporary on-base Frame 9E enclosure instead of the contract off-base enclosure.

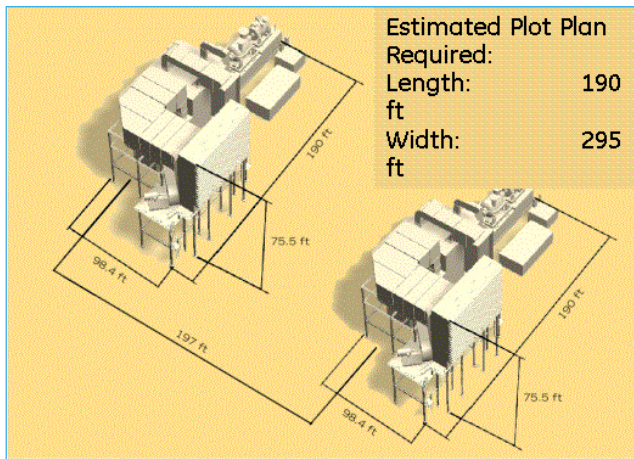


Figure 20. Dual Strings Plot Layout

Detailed pre-commissioning functional checklists were used to reduce spurious trips during the string testing. This “Red Flag Review” process allowed reduction of the total number of unexpected trips during the entire three string tests to only 4 events. This method was also incorporated into the site commissioning plan.

A large portion of the string testing was dedicated to the final validation of the VFDs system and its integration with the main equipment as well as with the power supply grid. Shaft torque ripple (a well known weak point of variable frequencies systems) and the amount of harmonic disturbances injected by the system into the surrounding electrical grid was closely monitored by a third party via an advanced recording system. Results validated low torque ripple, well within the design basis, therefore not requiring external suppression.

Main Testing Achievements

The oil system was fully validated through flow measurement at each bearing inlet as well as bearing temperatures throughout various operating conditions.

Simulated loss of complete AC power under full load was performed at the test facility. The emergency oil pump and overhead rundown tank provided adequate oil to protect the string during coast down and cool down. The system also demonstrated the capability to maintain minimum lube oil pressure with only one of the 3x100% AC pumps running. This pump was ultimately connected to the Plant Emergency Power Buss at the site, while the relatively small overhead rundown tank provided the oil supply coverage needed to rack in the

electrical switchgear (2 minutes).

The load test was the final validation of the train alignment procedure (especially for the rigid shaft line Frame 9E + motor/generator supported by 5 bearings). In addition to the contract string bearing vibration monitoring system, an extensive temporary vibration monitoring system was installed on the piping, casings, bearing pedestals and support structure. This provided a complete picture of the string rotordynamics. All measurements were well within specified limits, validating lateral analysis studies.

The Frame 9E is equipped with DLN-1 NOx combustion system and IBH to improve system operability. DLN-1 system allows very low NOx emissions provided that all combustion control parameters are properly adjusted to take into account site conditions and unit to unit variations. The IBH takes air from the axial compressor discharge and feeds it to the Frame 9E inlet to enlarge the load window the DLN-1 can run in premix mode. The DLN-1 system tuning is normally done at site as one of the commissioning activities. In this case, a pre-tuning was performed at the String Test Facility to demonstrate the system capability in terms of operability and emissions. This has the additional benefit of reducing commissioning schedule. Measured NOx emissions were well within the 25 ppmvd target over a wide load range.

The commissioning sequence of the main equipment started with the motor solo run where the electric motor is disconnected from the Frame 9E and from the compressors. For this operation, a temporary thrust bearing was added to the motor shaft.

Similar sequence with functional checks and vibration readings were done with the motor connected to the Frame 9E.

Finally the string was coupled and a first demonstration of the motor capability to start in depressurized (0.5 barg) condition was performed. The motor was accelerated to 450 rpm (crank speed for Heat Recovery Steam Generator purge at site). Once the purge sequence was completed the motor decelerated to 300 rpm and the Frame 9E was then fired, accelerating the string to minimum continuous speed (2880 rpm). The string was then released for various load and operational mode testing as shown in Figure 21 below.

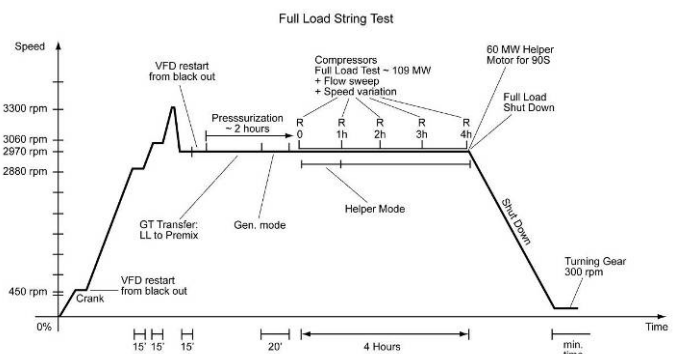


Figure 21. Full Load Test Sequence

In the turning gear mode, the motor turns the string at 300 rpm. This speed was identified as the better compromise between motor cooling capacity (that would be not sufficient at lower speed) and DGS reliability (low speeds are normally not enough to create the necessary lift phenomena).

Figures 22 and 23 below show the tested motor/generator operating modes. In particular Figure 22, indicates motor load step up to 43 MW at 96% speed. Figure 23 indicates the capacity to generate power into the grid (50 Hz constant) at variable speeds (from 2880 to 3060 rpm).

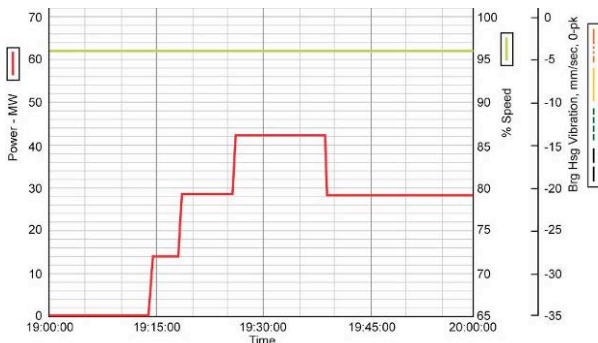


Figure 22. Motor Mode - Load vs Speed

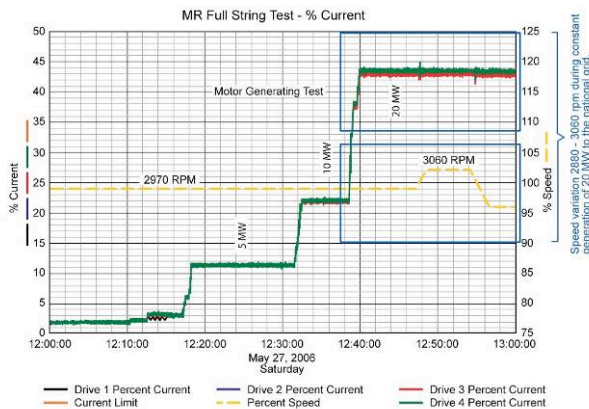


Figure 23. Generator Mode - Power vs Speed

The VFD system has two levels of redundancy. In the loss of the VFD, the Frame 9E can continue to operate with the motor used simply as a rigid coupling. Figure 24 (below) shows the transient caused by a VFD trip while the motor was in helper mode at 45 MW power. The Frame 9E was tested to determine capability of recovering from the loss of a helper motor without going into an underspeed “bogdown trip” condition, a situation that will cause a trip of the entire string.

The Frame 9E showed excellent response as expected at low power. This response, combined with peaking mode will be utilized in the field to avoid tripping of the MR string during loss of VFDs when in helper mode.

Additional tests were carried validating VFDs double level

of redundancy, in particular the capability to supply uninterrupted power (45 MW) with one cell failed in one thread and a second one in a second drive, as well as with a complete thread (VFD) out of service (Figure 24).

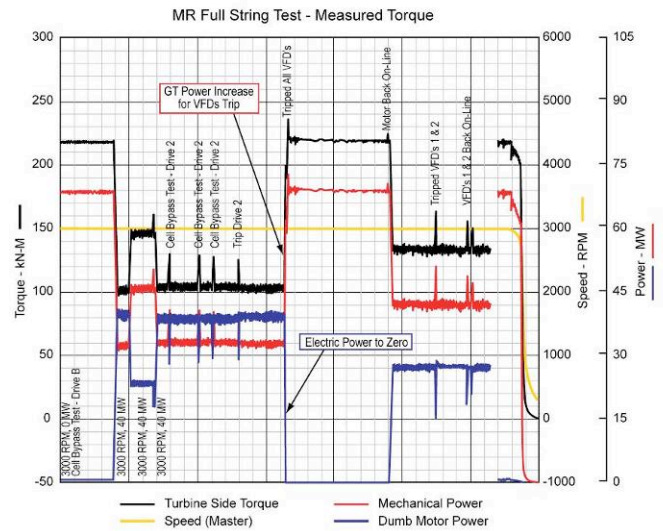


Figure 24. Frame 9E & Motor/Generator Measured Torque

The normal stop sequence on this string causes the Frame 9E to reduce speed to 300 rpm for cool down. During coast down the system proved it is able to resynchronize at 300 rpm, maintaining the whole string at turning gear speed to complete the cool down sequence.

A dedicated test campaign was carried out to validate system capabilities to restart in case of VFDs troubles. Restarting of the VFDs in all modes of operation was successfully demonstrated. Additionally, restart capabilities were demonstrated with only two out four VFDs in operation, increasing plant reliability over conventional designs.

CONCLUSIONS

The integrated team approach was successful in qualifying large LNG refrigeration strings for the QGII project. All three strings (C₃, MR, N₂) were designed, manufactured, and tested at the Compressor String Test Facility, passing extensive internal/external reviews as well as stringent performance/reliability requirements. The measured approach to qualifying new technology has led to pressurized starting capabilities, lower gas turbine emissions and optimized LNG production/power generation. These compressor strings will supply 280MW of refrigeration needed to produce the world’s largest LNG plant of 7.8 MTA.

ACKNOWLEDGEMENTS

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