DYNAMIC SIMULATION: A MAJOR CONTRIBUTOR TO FLNG PROJECT DEVELOPMENT

Benoit Laflotte
Audrey Laval
Vincent Tirilly
LNG Department - Process and Technologies Division
Technip

Juan Carlos Rodriguez
Aspen Technology

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ABSTRACT

The recent development of Floating Liquefied Natural Gas (FLNG) to monetize offshore resources has fostered new design concepts that answer specific constraints such as the impact of wave induced motion and the requirement for compactness. There is a need to innovate selectively, while building on the proven practices of the mature onshore LNG industry. Technip has completed the front end engineering design of several FLNG projects. One of these will be referred to as a perfect example of these new designs as it associates a front end NGL recovery unit comprising a deep LPG extraction with a Dual Mixed Refrigerant liquefaction process. One key engineering activity was to prove that the design is robust in responding smoothly and safely during transient operations and major upsets. This is of prime importance to enable safe, reliable and efficient operation throughout the FLNG lifetime. A detailed and integrated dynamic simulation model was identified as the appropriate tool to study the various transient scenarios. Technip and AspenTech pooled their knowledge and experience to achieve this. This poster will describe how the dynamic model was built, the main constraints and how they were successfully overcome. It will also present the important role of the dynamic simulation study in validating the process arrangement and optimising the control philosophy.

INTRODUCTION: GENERALITIES ON FLNG & DYNAMIC SIMULATION

The recent development of Floating Liquefied Natural Gas (FLNG) to monetize offshore gas fields has fostered new design concepts assembling technologies from offshore floating production units with the ones developed for onshore LNG Plants. Challenges unique to floating units revolve around installing on a moving structure (in a hull) of less than 2.8ha all the equipment and storages required to produce and export LNG that would take onshore land in excess of 50ha: While building on the proven practices of the mature onshore LNG industry, the need for compactness impacts all steps of design development from the selection of the process schemes, the design of the equipment to the detailed installation. Such selective innovations reinforced the need for design validation and dynamic simulation as a key step of validation of the process design at the Front End Engineering Design (FEED) stage.

In comparison with steady state models, the construction of dynamic simulation models requires more extensive design data including equipment and piping sizes and valve characteristics in addition to the control and the logics implemented for the operation and the safety of the unit. In the early days the scope of dynamic simulation models built for onshore plants was limited to the individual refrigeration systems and did not include any form of modeling of the cryogenic heat exchangers. Main Cryogenic Heat Exchanger (MCHE) models were introduced at a later stage. This allowed closing the loops between the liquefaction section and compression sections. Helper motors also had to be eventually modeled when required. More details were always being demanded by dynamic simulation users such as calculation of metal thermal inertias in vessels and pipelines to be considered. This led to the current high fidelity models of liquefaction.

Technip has completed the Front End Engineering Design (FEED) of several FLNG projects. One of these is presented as a perfect example of these designs specifically developed for offshore application as it associates a front end NGL recovery unit comprising a deep LPG extraction fully integrated with a Dual Mixed Refrigerant liquefaction process. The specific level of integration developed for the FLNG brings a new step of complexity of the dynamic simulation by modelling the full integrated process units of the FLNG and validating the process design based on very stringent design criteria fit for offshore application.

AN EXAMPLE OF FLNG WITH HARD CONSTRAINTS

Technip performed the FEED for a FLNG unit presenting several constraints that drove the design development with the objective to maximize LNG, propane and butane productions i.e. to reach the best available efficiency of production for a given quantity of feed gas. Aspen Technology Inc. was selected to develop the model and to perform the dynamic simulations of this project.

The FLNG was to be located in open sea with relatively harsh waves and wind conditions. The initial concept needed to be developed to minimize the effects on the safety and performances of the unit associated with the relatively large motions of the FLNG. Several liquefaction processes can be considered for such application, mainly divided between processes using refrigerant in vapour condition – then less sensitive to motion and processes with liquid refrigerant vaporised against the treated gas to liquefy. The Air Products Dual Mixed Refrigerant (AP-DMR^{TM}) process was selected for its high efficiency of liquefaction, its relative flexibility to balance power of refrigeration between the two refrigeration loops combined with its better ability to accommodate motions compared to other process with liquid refrigerant.

The selection of the drivers for the refrigeration compressors is a key step of the design development as indeed the arrangement of the compressor train, the lay out, the maintenance and the availability of the unit arise from this driver selection. Recognizing that such a project is carrying a number of first-of-a-kind technologies including development of new components, combinations of proven subsystems, marinization of onshore proven elements, the management of risk requires a careful attention to novelty in the design. Aeroderivative gas turbines were selected both as mechanical drivers for refrigerant compressors and for power generation. The refrigerant compressor arrangement included two parallel compressors (2x50%) for each refrigeration loop (refer to figure 1). This selection brought the best compromises in term of layout, cost, efficiency and management of risk and provided a high availability of the liquefaction.

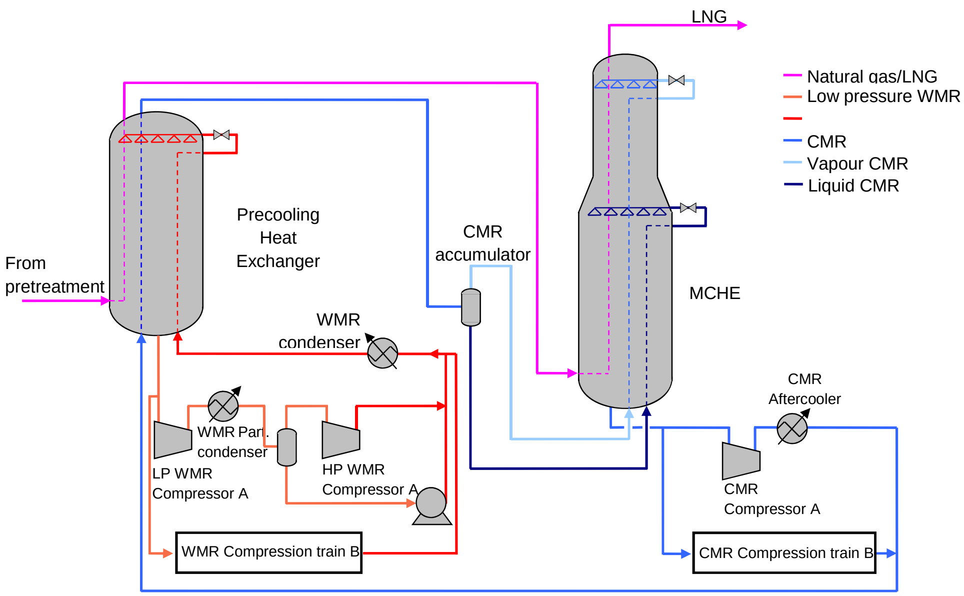

Figure 1: DMR with parallel arrangement of refrigerant compressors

The feed gas presented a large range of compositions with ethane content from 7% to 13%, propane content from 5% to 8% and butane content from 2% to 3%. Those ranges combined with the ability to meet different product specifications targeting both local and external markets requested the unit to be very flexible. The extraction of ethane in particular required variable ratios of LPG recovery from low to high recovery. A high recovery of propane and butane (>99%) was targeted for all operating cases. An NGL Recovery unit upfront the Liquefaction section was the primary choice:

- to produce a treated gas free from heavy components (including BTEX) to the Liquefaction section,
- to extract ethane, propane and butane to meet the LNG specifications,
- to produce a variable stream of ethane at a composition that could be used for make-up of the refrigeration loops,
- to maximize the C3 recovery in order to maximize revenues.

While NGL recovery technology is based on the cryogenic fractionation of the Natural Gas stream with the help of a turbo-expander, several different schemes can be considered with different levels of sophistications. In order to reach the above objectives, the FLEX-E scheme (part of Technip's Cryomax® family) was selected (refer to Figure 2). This patented NGL Recovery scheme allows variable ethane recovery through the addition of a reflux of ethane from the Deethanizer to the top of the recovery column.

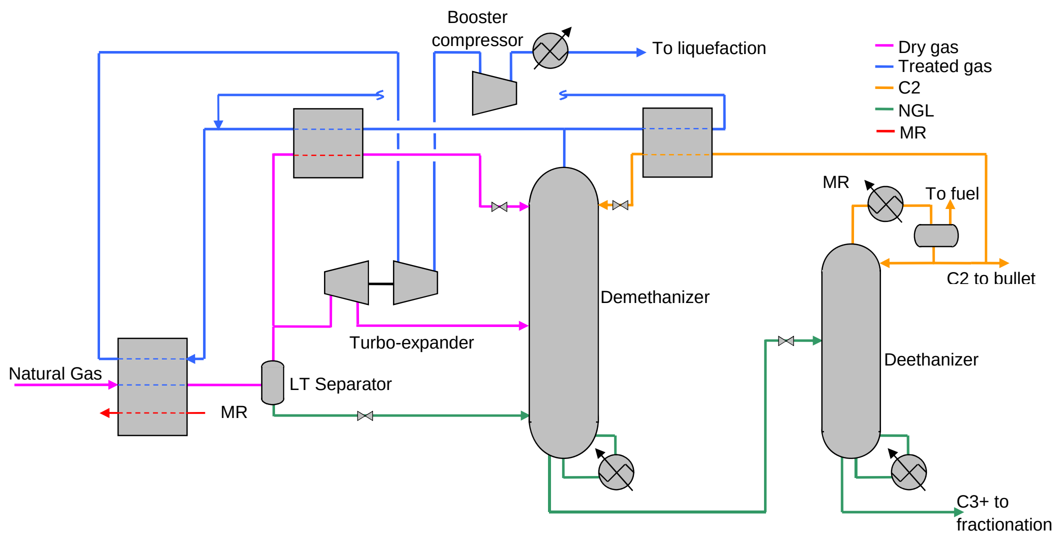

Figure 2: NGL Recovery Scheme

The NGL Recovery is integrated with the Liquefaction through several streams of refrigerant from the Liquefaction section. This configuration enhances the efficiency of the NGL Recovery and the integration of the two sections. This integration reinforces the need for a fully integrated simulation model.

A COMPLEX DYNAMIC SIMULATION MODEL

The model built for this project is an example of a fairly complex system modelled with high fidelity. The model covers all main process units in an integrated manner, and hence requires no assumptions and/or simplifications on the process dynamics at the boundaries of each section. The model has been constructed by AspenTech in Aspen HYSYS and Aspen HYSYS Dynamics, which is a simulation package for both steady state and dynamic simulation. Aspen HYSYS allows converting existing steady state models into dynamic models by specifying additional engineering details, or directly creating dynamic models without a previous steady state simulation (refer to figure 3 for some details on Aspen HYSYS dynamic capabilities).

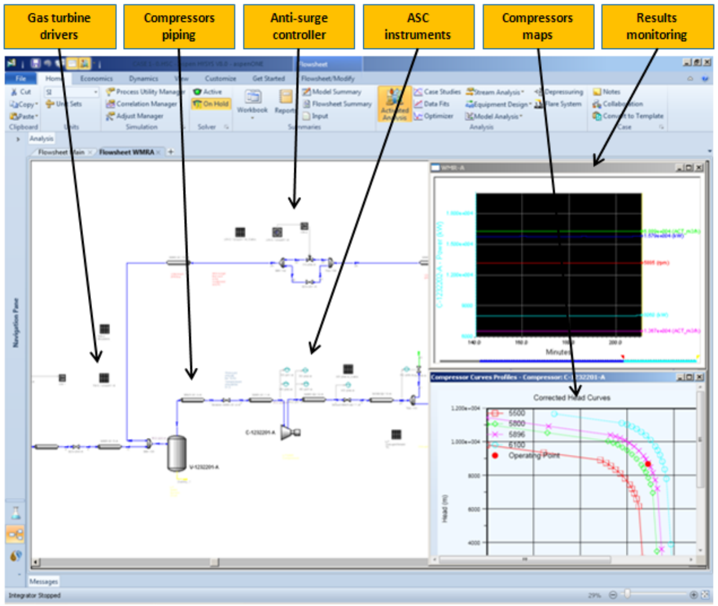

Figure 3: Aspen HYSYS tools

The model comprises the following units (refer to figure 4):

- NGL Recovery and Fractionation sections.
- Liquefaction section, including the LNG turbine, the flash gas drum and flash gas heat exchanger.
- WMR Compression circuit, with both compression trains explicitly modelled.
- CMR Compression circuit, with both compression trains explicitly modelled.

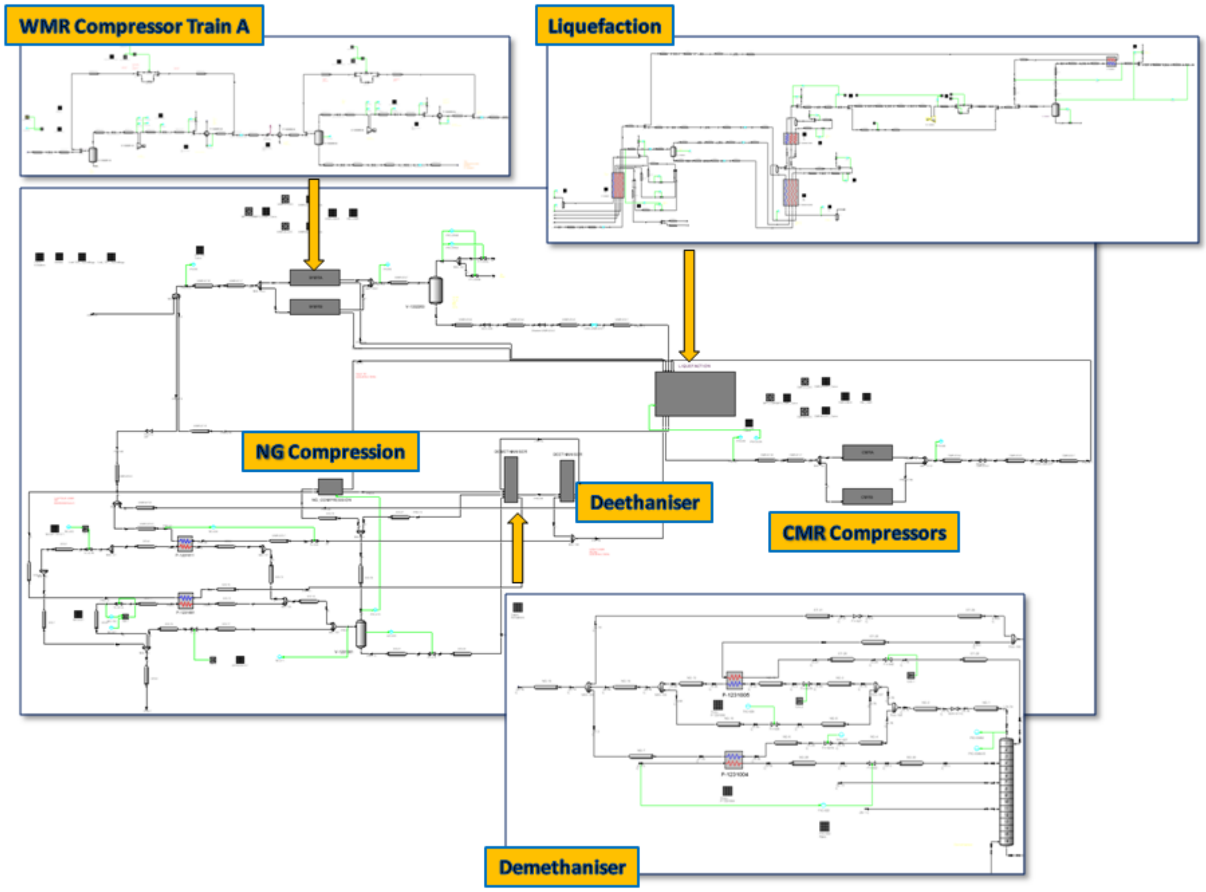

Figure 4: Aspen HYSYS Dynamics simulation model

In order to provide the best possible representation of plant dynamics as wells as to be able to re-use the model for later project phases, the following fidelity aspects were taken into consideration:

- Separators were modelled according to their design mechanical datasheets in what concerns volumes, sizes and normal liquid holdups.
- Shell and tube heat exchangers were configured by imposing the design UA values and with tubes side and shell side volumes calculated from the mechanical datasheets.
- Plate-fin heat exchangers and printed-circuit heat exchangers were configured by adjusting the geometry of the exchangers to provide the correct fluid volumes in both sides (hot and cold) and by adjusting the U value to get a good match with the design heat and material balances (HMB) outlet temperature values.
- The fractionation columns were modelled using the actual diameter and number of theoretical separation stages. The height of each separation stage was calculated based on the data available from the process design sheets. Void spaces in between beds were modelled as an additional separation stage, with a very low efficiency value to achieve the correct volumes without affecting the fractionation.
- Parallel compressors were modelled according to the manufacturer's provided compressor maps. Inertias of the compressor, driver and connecting equipment were taken into account.
- Compressor controllers were emulated using AspenTech's proprietary representations of the anti-surge, load sharing and master performance control blocks (figure 5).
- Detailed piping characteristics for a total of more than 250 pipelines were included.
- Control valves, on/off valves, check valves and transmitters were rigorously modelled, including actual characteristics and actuator time constants.

- All unit operations within scope were rigorously modelled according to design and manufacturer's data.
- The performance of the turbo-expander was closely matched to the manufacturer's data.
- All relevant control loops were modelled and tuned.

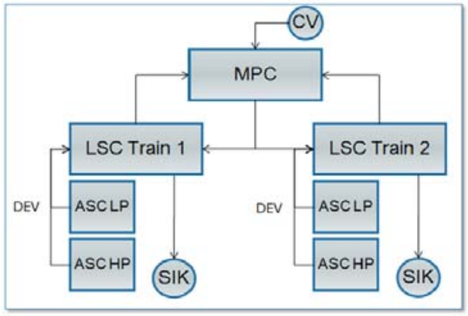

Figure 5: ASC-LSC-MPC compressors control arrangement (as modelled)
ASC: anti-surge controller, LSC: load-sharing controller, SIK: speed controller, MPC: master performance controller, CV: controlled variable (e.g. compression ratio)

The configuration of the coil wound heat exchanger models deserves special attention, since this is a critical piece of equipment of the unit. The exchanger was modelled using the HYSYS LNG unit operation block. The two coil wound heat exchangers were modelled using the HYSYS LNG unit operation block, each one configured according to the following premises:

- Volumes of the different fluids inside the exchanger were calibrated to best match the available data.
- Internal characteristics were modeled to achieve a correct prediction of shell side fluid densities. Possible accumulations of MR at the bottom of the exchangers during process upset situations were also considered.
- The variation of heat transfer coefficients inside the exchangers as a result of changes in the flow regime during plant transients was considered. Different U values were dynamically applied along the tubes length depending on the fluid phase present at each time interval. The dependency of U values with fluid flow rates was also considered.
- Temperature differentials in the warm ends of both cryogenic heat exchangers were monitored and override control actions implemented to prevent thermal stress on the tubes.

The integrated dynamic simulation model was validated against the design heat and material balance sheets, providing average error values lower than 2% for all stream properties other than temperature. The errors in temperature values were below 2 °C.

The built-in Aspen HYSYS Dynamics event scheduler and spreadsheets were used to configure the cascade of actions corresponding to each simulation scenario. Approximately 1000 process variables were monitored and recorded over a period of three hours in each run. The model was configured to run with a time step size of 0.5 seconds for the slower transients and 0.01 seconds for the faster rotating machinery trip transients. The model required no special hardware and runs in a fairly typical laptop computer.

DYNAMICS OF THE DMR PROCESS WITH PARALLEL REFRIGERATION TRAINS

The selected Dual Mixed Refrigerant (DMR) process includes one refrigeration loop for pre-cooling with Warm Mixed Refrigerant (WMR) followed by the refrigeration loop for liquefaction and sub-cooling with Cold Mixed Refrigerant (CMR). One key objective from selection of DMR with a parallel arrangement of compressors for the two refrigeration loops is to be flexible in case of unavailability or trip of one out of the four refrigeration compressor trains. The dynamic simulation has been used to study and to validate the design upon different scenarios as follows:

1. Trip of one CMR compression train in normal operation,
2. Start-up of one CMR compression train while the three other compression trains are in operation,
3. Trip of one WMR compression train in normal operation,
4. Start-up of one WMR compression train while the three other compression trains are in operation.

Dynamic simulation runs have confirmed that both WMR and CMR compressors can be re-started from settle out conditions without the need of depressurization and that the parallel compressors can safely be lined out to restore the unit design capacity after a trip of one of the compressors. Figure 6 shows the trip and start-up trajectories of the WMR compressor B.

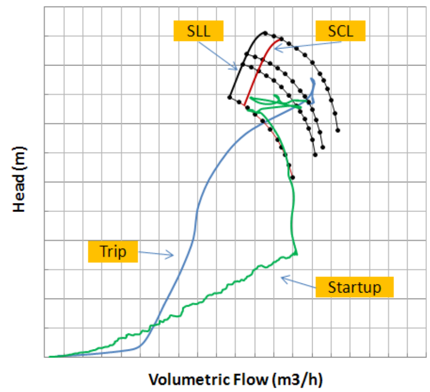

Figure 6: Low Pressure (LP) stage WMR compressor B during trip and startup

Figure 7 shows the balance of flows of the two compressors during the CMR compressor B start-up. The plant is operating initially at reduced capacity. At a time approximately equal to 1500 seconds, the discharge flowrate of both CMR compressors equalises and remains balanced while the FLNG unit throughput is progressively increased to full capacity. After approximately 2200 seconds the FLNG unit is operating steadily at full capacity.

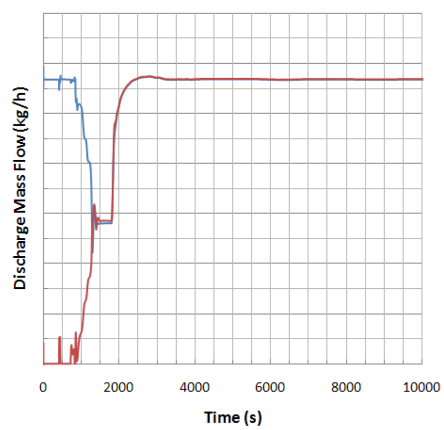

Figure 7: CMR compressors A and B discharge flow rate during CMR-B startup

When one refrigeration compressor trips, it is necessary to force a decrease of LNG production (approximately 50% capacity) since the control system does not provide a fast enough response for avoiding major disturbances in both refrigeration loops, which may result in losing the liquid levels in the WMR and CMR accumulators. This is achieved by reducing both the WMR and CMR circulating flowrates with a pre-set ramp down which forces the set points of WMR and CMR Joule-Thomson (JT) valves around the cryogenic exchangers to close in the range of 50-60% of their normal set points.

Figure 8 shows the CMR flowrate variations after the trip of the WMR compressor B. Following the trip event, the openings of CMR JT valves are reduced to limit the unit capacity and the refrigeration loop circulating flow to maintain the unit under steady conditions at a reduced capacity.

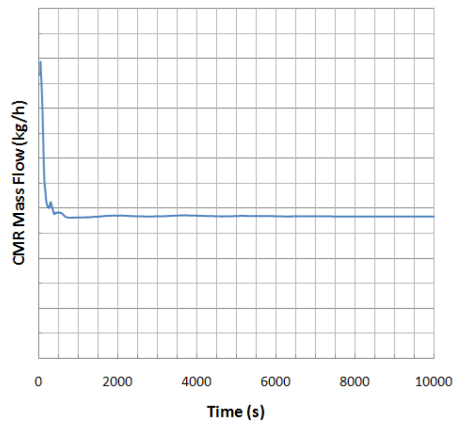

Figure 8: CMR flow rate during WMR-B trip

Figure 9 shows the performance of the LP stage of the CMR compressor A after the trip of the CMR compressor B. Following the upset event, the operating point of the CMR compressor A moves to the right side of the performance map, which is subsequently compensated for by the forced reduction of the refrigerant flowrates.

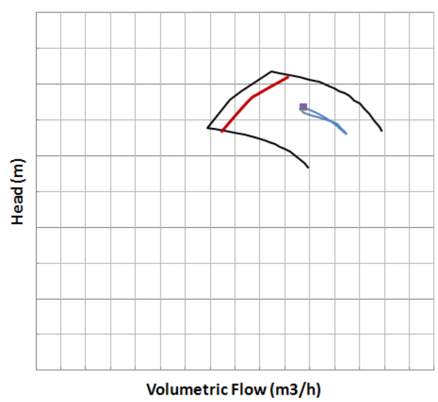

Figure 9: LP stage CMR Compressor A performance during CMR-B trip

UPFRONT NGL RECOVERY UNIT, FLEXIBLE AND ROBUST

The NGL Recovery section is tightly integrated with the Liquefaction section. Dynamic simulation has been used to ensure the operability of the system and to monitor the responses of the FLNG unit for the range of different operating conditions confronted with different scenarios of failure and a variety of different start-up operations. The dynamic model was used to study the dynamics of the whole integrated NGL Recovery and Liquefaction sections, as indeed, any disturbance in one section affects the other section.

Two major upsets of the NGL Recovery are presented with their analysis and consequences on both sections.

The most impacting upset for the NGL Recovery is the trip of the turbo-expander which provides a significant part of the refrigeration duty necessary to the NGL extraction. Once tripped, the flow through the expander is diverted to the JT valve. The NGL Recovery unit operates with a lower duty of refrigeration, resulting in off

specifications LNG production. The unit capacity shall be decreased to be able to maintain the specifications of the produced LNG with this lower duty available in JT mode.

A key parameter to increase cooling duties during expander trip is to increase the WMR at the inlet of the NGL recovery to cool down the inlet feed gas before entering the LT separator. The figure 10 below shows the variation of temperature at the inlet of the LT separator following an expander trip.

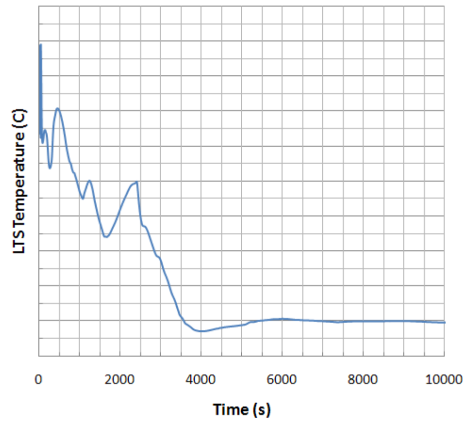

Figure 10: LT Separator temperature during turbo-expander trip

The consequence of the expander trip in the NGL Recovery needs also appropriate actions in the Liquefaction section.

Following the turbo-expander trip, the pressure profile is modified through the NGL Recovery and Liquefaction sections: First the flow rate to the Demethanizer falls quickly to 10% and then, after the pressure profiles reach a new steady state, the flow rate progressively increases to around 74% of the initial normal operating capacity.

The control of the LNG temperature at MCHE outlet limits the LNG throughput and the flow rate of treated gas to a value of around 50%. This point corresponds to the new and final steady sate. Figure 11 shows the plant inlet NG mass flowrate after the turbo expander trip.

When the turbo-expander trips, the controllers keep the speed of the compressors at their design set point values while the vapour CMR flow rate is reduced by half of the design flow rate. Figure 12 shows the CMR mass flowrate after the turbo expander trip.

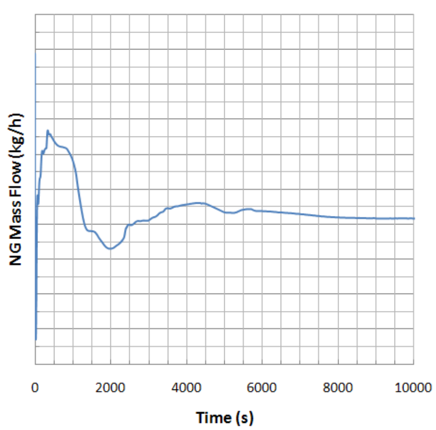

Figure 11:
Inlet NG flow rate after turbo-expander trip

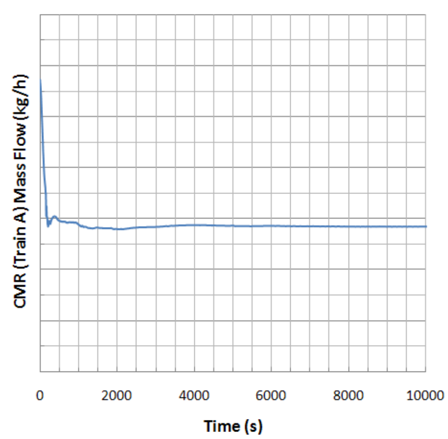

Figure 12:
CMR mass flow rate after turbo-expander trip

Among the different scenarios, the NGL Recovery booster compressor trip is the most representative of the integration of the NGL Recovery with the Liquefaction.

When the treated gas booster compressor trips, the liquefaction capacity decreases as the pressure of liquefaction drops.

Figure 13 shows the treated gas fall of pressure at the inlet of the liquefaction after the booster compressor trip. After approximately 2 minutes, the pressure in the liquefaction has decreased enough to equalise with NGL recovery treated gas pressure: The natural gas flows through the booster compressor bypass and the liquefaction pressure quickly stabilises.

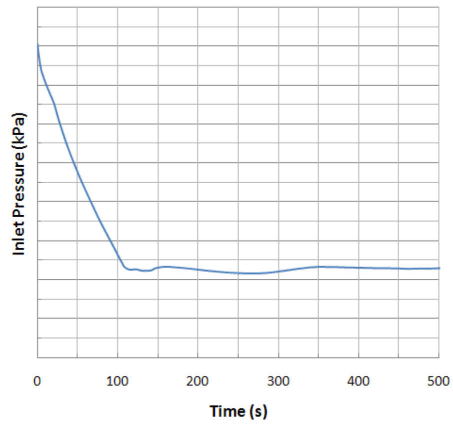

Figure 13: Liquefaction unit inlet treated gas pressure after Booster compressor trip

Once the pressure in the Liquefaction section has dropped sufficiently and forward gas flow is re-established through the booster compressor bypass, the incoming gas flow rate from the NGL Recovery section progressively reaches a new steady state value of 40% of the design capacity as shown the figure 14 below. The LNG flow rate profile at the outlet of the MCHE follows the same pattern as the demethanizer treated gas flowrate.

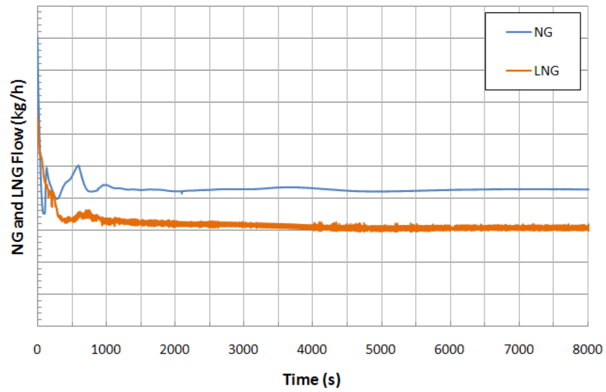

Figure 14: Inlet NG flowrate during the booster compressor trip

During the dynamic run, the controllers from the Liquefaction section are all maintained in an active state. The CMR compressor speed set point is maintained at its design value. The capacity of the two trains progressively decreases as a result of the lower CMR demand (figure 15). At the end of the run, both CMR compressors are equally loaded in recycle mode.

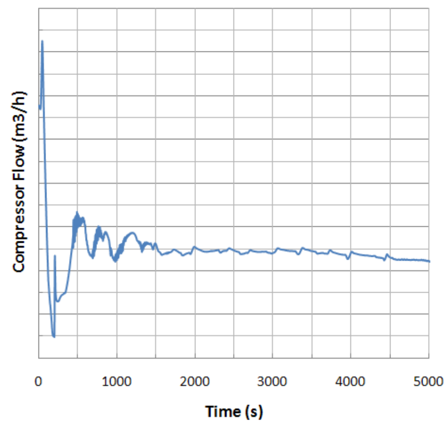

Figure 15: CMR volumetric flowrate

The NGL Recovery booster compressor restart scenario needs also a careful analysis of the transient phenomenon to restore the liquefaction pressure to its initial value and progressively increase the unit throughput to full capacity.

Figure 16 illustrates the booster compressor restart performance while figure 17 shows the variations of LNG production capacity after booster compressor restart.

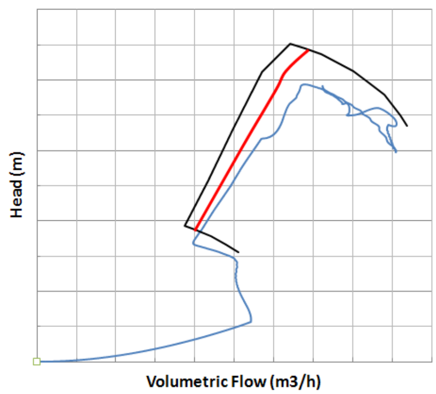

Figure 16: Booster compressor performance during startup

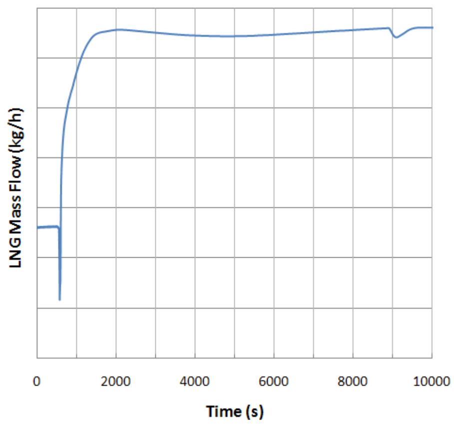

Figure 17: Produced LNG flow rate at the top of the MCHE during the booster compressor restart

CONCLUSIONS

Aspen HYSYS Dynamic models have proved in this and previous studies to be able to provide very valuable insight on the operability of LNG plants under upset and transient situations. The models can be used early in the design process to detect operational issues which can be more easily fixed during the design phases to avoid later expensive operational issues, as well as to optimize the control and operating strategies. The models are fully re-usable during the project life cycle[1,2]. A model created during the design phase of the project can be easily upgraded with final design data and with plant test data during the EPC phase prior to plant startup.

One important conclusion was to demonstrate that the process control systems allow LNG production to continue, albeit at a reduced rate, following any machinery trip in the NGL recovery or liquefaction sections. The use of a turbo-expander based cryogenic NGL recovery unit upstream of liquefaction is becoming increasingly common for reasons that include the high pressure liquefaction as a source of improved efficiency. Whereas the advantages of such schemes are increasingly recognised, the additional machinery is a potential source of reduced reliability: The dynamic simulation study performed during the FEED stage has served to confirm the operability and controllability of the FLNG unit in case of major disturbances. It has also supported the Reliability, Availability and Maintainability (RAM) analysis by providing values for start-up periods and partial productions. It finally highlighted few aspects of the control strategy and some opportunities for optimisation to improve the control which are of real value to the project, considering that a unit with stable operations, few trips and rapid start-up will offer higher annualised production and is particularly advantageous for offshore operations where modifications and maintenance are more costly.

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