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Dynamic Simulation: a Tool for Advanced Design and Operating Behaviour Prediction

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When dealing with transient conditions, standard process design approach may lead to poor equipment specification or even to a complete failure in evaluating the design reference conditions.
The three presented case-histories highlight the importance of dynamic process simulation as a design tool that allows both a targeted definition of the design conditions for equipment and an accurate prediction of the system behavior during transient operations thus enabling a predictive evaluation and validation of operating procedures. The three case-histories refer to different fields of application and to different levels of complexity, but in all the cases the power of the design approach based on dynamic simulation is demonstrated.
The first case-history is relevant to the design of instrumentation and relevant control scheme on a pump discharge. In a floating LNG regasification terminal, a small flow and high pressure pump used for header pressurization and vaporizers cooldown faced severe damage due to peak flow conditions during the initial phase of operation. Dynamic process simulation was used to design the flow orifice, the discharge maximum flow valve and to define the header's pressurization procedure.
The second case-history is relevant to the behavior prediction of a complex compressor system during the start-up phase. A large propane compressor in a multilevel refrigeration cycle is currently operated with a steam condensing turbine allowing smooth start-up. The plant's owner planned the turbine's replacement with an electric motor, reducing the start-up ramp from several minutes to few seconds. Dynamic model, following a field data tuning phase, was used to evaluate the behavior of the compressor system during the sharp start-up ramp and to validate the Compressor's vendor design for the control system.
The third case-history is relevant to the development of an innovative design approach. Following Techint's design and construction experience in LNG regasification terminal, a rigorous dynamic model has been developed in order to study the behavior of the Boil Off Gas (BOG) handling system during transient operations (LNG unloading and LNG Carrier reloading). The model can be tuned on existing terminals and used in identifying the real system bottlenecks during revamp studies as well as to optimize transient operation management. As a design tool, the model can be used in the future to optimize the BOG system design.

1. Case-history 1: Keep pump's operations under control

The Offshore LNG Toscana (OLT) Floating Storage & Regasification Unit (FSRU) is moored 12 miles off the coast of Livorno in Tuscany (Figure 1). The LNG regasification module has been built on top of an existing Moss® type LNG carrier of the 137000 m^3-class modified to operate as an FSRU permanently moored offshore. The FSRU is equipped with 4 LNG spherical Moss® type tanks with a total capacity of 137000 m^3 and 3 Intermediate Fluid Vaporizers (IFV) having a total vaporization capacity of 450 t/h of natural gas, delivered at 80 barg maximum on the Italian national grid through an underwater 32" pipeline. OLT FSRU is in operation since December 2013.

1.1 Background facts

The original design of the FSRU has been developed considering the initial pressurization and cooldown of the regasification equipment and header by using one of the large send-out pumps, having a capacity of 553 m^3/h. In a late stage of the design, a new small pump has been added in order to be operated only during the mentioned operation phases, deeming this smaller pump to be more appropriate and flexible for the requested procedure.

This new Small High Pressure Pump (SHPP) is equipped with a variable speed driver allowing an operating range between 5 and 35 m^3/h at a discharge pressure ranging from 31 and 105 barg. The variable speed driver has been designed in order to operate continuously at a rotation speed ranging from a minimum of 3600 rpm to a maximum of 6600 rpm according to the required downstream pressure. A schematic representation of the SHPP and of the relevant control system is indicated in Figure 2.

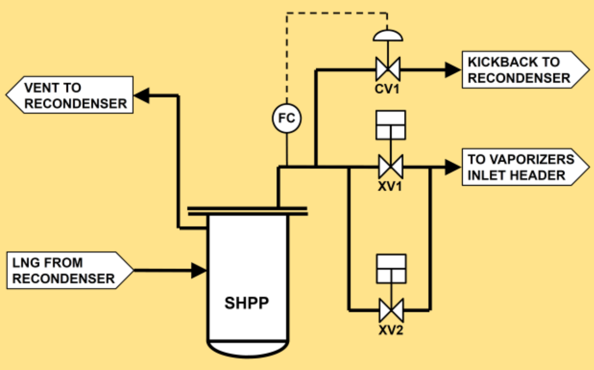


Figure 1: Offshore LNG Toscana FSRU.

Figure 2: SHPP original control scheme.

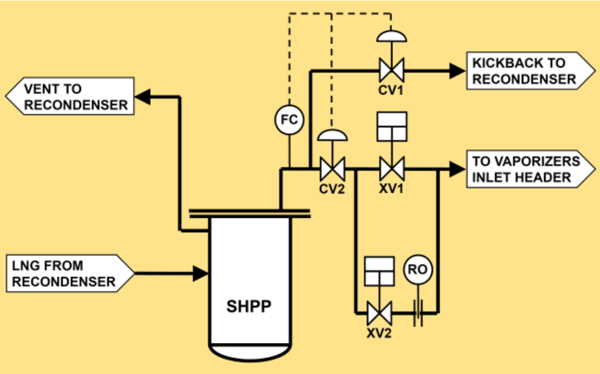
The operating procedure foresaw the start-up and alignment of the SHPP on full recycle operation through the spill-back line and control valve CV1 at the lowest operating speed, then the block valve XV2 on the pressurization line (having a reduced bore with respect to XV1) is opened allowing the initial pressurization at a pressure of 30 barg. Then the required pressure level was reached switching XV2 with XV1 and moving through the variable speed driver to a higher rotation speed.

Since the first start-up, the SHPP experienced severe and sharp flow rate variations at the pressurization line opening and during rotational speed increase steps. Such sharp flow rate peaks in some cases caused a partial emptying of the pump pot, driving to near-dry operation of the SHPP and consequent bearings overheating and damage.

1.2 Studied solution

A dynamic model of the existing pump's system has been developed in order to initially reproduce the actual behaviour during the pressurization and cooldown phases. Then the modifications to the control system and to the operating procedures have been analysed using the tuned model bringing to the final proposed solution represented in Figure 3. In order to limit the flow rate peaks during pressurization phase, a restriction orifice RO has been installed on the by-pass line of the block valve XV1.

SHPP is aligned on full recycle operation through the spill-back line and control valve CV1. Then pressurization phase starts at 30 barg with the opening of the block valve XV2 located upstream the restriction orifice RO. Once the pressure in the vaporizers header is equalized, then XV2 closes and XV1 opens. The new maximum flow control valve CV2 controls the pump's flow rate while vaporizers header pressure is increased up to 83 barg through 2 steps in pump's rotational speed during cooldown phase.



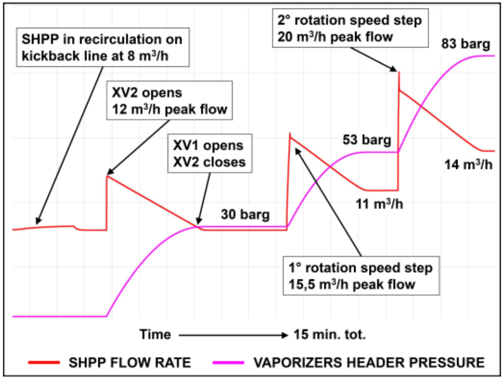


Figure 3: SHPP new control scheme.

Figure 4: Predicted SHPP operating behaviour

The dynamic model has been also used to design the flow orifice RO and to select the CV and the characteristic curve of the maximum flow valve CV2 as well as (Burns R. S., 2001), before the commissioning phase, to define the set of regulation parameters for the controller of the valve. The operating procedure for header pressurization has been modified as above described and checked on the dynamic model, as shown in Figure 4.

The studied modifications, once fully engineered by Techint, have been implemented by OLT on the FSRU during the first three quarters of 2016 and finally the SHPP with the modified configuration has been successfully started-up in October 2016 without incurring in any of the previously experienced upsets.

The SHPP behaviour showed a very good adherence with the dynamic model predictions.

2. Case-history 2: Replace a steam turbine driver with an electric motor.

ENI Refining & Marketing operates in Livorno (Tuscany) a refinery based on lube oil cycle. The Methyl-Ethyl-Ketone unit no. 1 (MEK1) has the purpose to remove the paraffins from the lube oil bases before final blending.

MEK is first used as solvent for paraffins crystallization and then paraffins are recovered through refrigeration of the Feed/Solvent mix in Chiller Evaporative exchangers, crystallization and separation in a vacuum rotating filter. Feed/Solvent mix refrigeration is obtained by means of a multi-level propane refrigeration cycle with a large propane compressor operated by a condensing steam turbine.

2.1 Background facts

The multi-level propane refrigeration cycle is operated by a large centrifugal compressor having power absorption of 3,5 MW, taking propane vapours at 3 pressure levels and discharging to a mixed air/water condensing system. The scheme of the refrigeration cycle is reported in Figure 5. The delivery pressure of the compressor is set by the condensing temperature, varying between summer and winter (the pressure maximum value is reported in Figure 5).

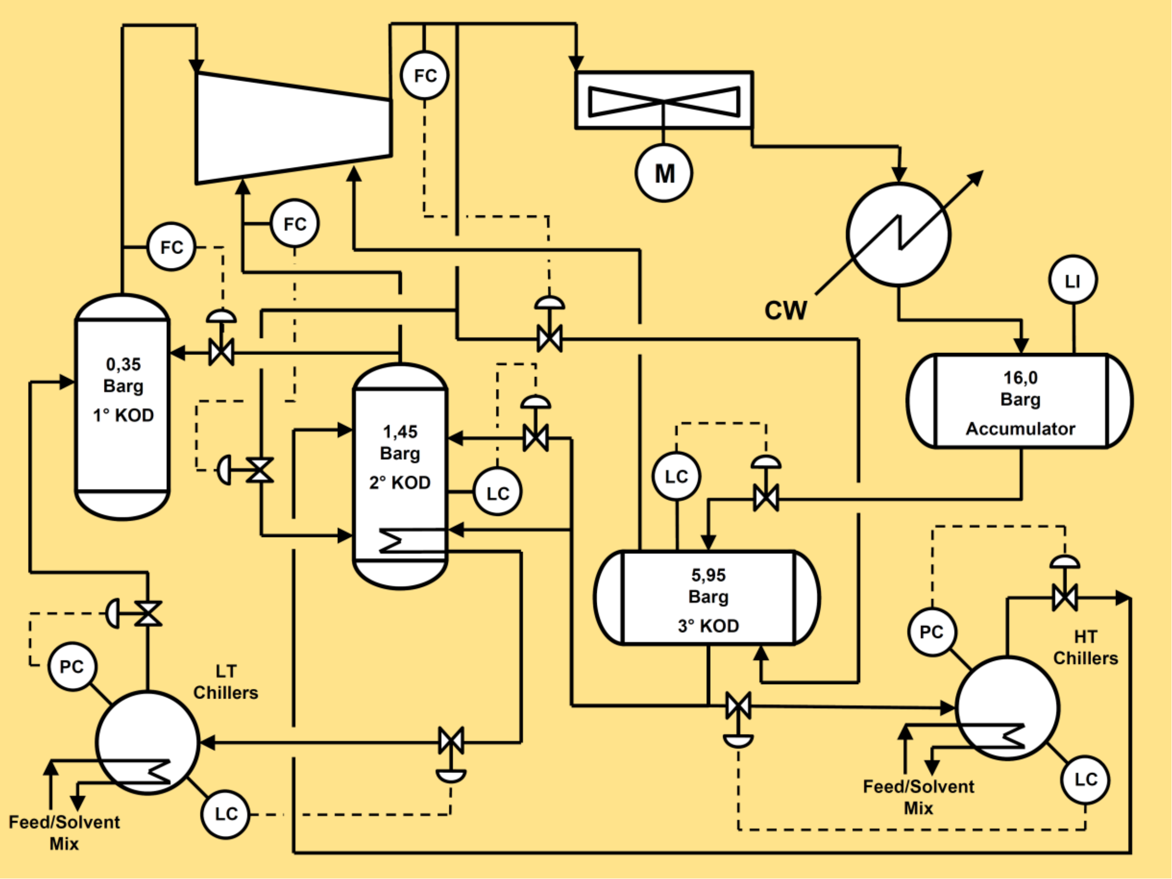


Figure 5: Schematic representation of refrigeration loop.

The liquid propane from the condensation system accumulator is flashed to an intermediate pressure into the Third KO drum, from where “High Temperature” (HT) liquid is delivered to the HT Chillers. A stream of HT liquid is subcooled through a coil inside the Second KO Drum where HT liquid propane is further flashed at a lower pressure. The liquid level control in the Second KO Drum guarantees that the coil is always submerged. “Low Temperature” (LT) liquid exiting the coil in the Second KO Drum is delivered to LT Chillers. Propane vapours from HT Chillers are returned to the Second KO Drum, while propane vapours from the LT Chillers are returned at near atmospheric pressure to the First KO Drum. The compressor is operated by a condensing steam turbine allowing a smooth start-up ramp through gradual rotating speed increase.

Following an internal consumptions optimization plan, the plant’s Owner planned to replace the steam turbine with an electric motor thus reducing the start-up ramp from several minutes to few seconds, going directly up to the rated rotating speed and posing some concerns on the future compressor behavior. Moreover, during start-up phases following operational shutdowns, the operators experienced sudden liquid entrainments in the First KO Drum, due to excess of liquid coming from chilling section as a result of malfunctioning of LT Chillers level control loop, leading to repetitive compressor shutdowns for high liquid level. This occurrence never posed problems when operating the compressor with a steam turbine, but in view of future operations, the use of an electric motor posed some concerns in case of repetitive start-ups due to expected motor overheating.

2.2 Studied solution

A rigorous dynamic model of the actual refrigeration circuit has been developed. Vessels and exchangers hold-up has been considered according to mechanical drawings, as well as piping volumes, calculated from sizes and lengths available on piping sketches and routing studies, also considering the presence of vertical piping runs leading to static head differences in case of liquid accumulation. The compressor has been simulated as a 3 stages centrifugal compressor, each stage having characteristic curves at different rotating speeds according to design specifications.

Following the model development phase, a fine tuning with field operating data has been performed, reaching a good adherence of the dynamic model behaviour with steady state field operation.

Once the model has been tuned, the following cases (each of them considering the steam turbine and the electrical motor) have been reproduced and analysed.

START-UP FOLLOWING GENERIC SHUTDOWN: this is the case where the compressor shutdowns for any operating reason different from malfunctioning of Chillers level control loop. The model showed some liquid accumulation and entrainment in the LP vapours return line to First KO Drum, mainly due to condensation of propane in cold return lines due to higher settling out pressure. The liquid entrainment was considerably higher in case of start-up with electric motor, if compared with the steam turbine case, but no operating upsets were detected.

START-UP FOLLOWING HH LIQUID LEVEL IN FIRST KO DRUM: this is the case where a malfunctioning of the Chillers level control loop leads to excessive liquid entrainment and accumulation in the First KO Drum. Simulating a fast operator response on the Chillers level control loop, re-establishing the automatic control mode, and a rapid restart of the compressor the cause for the excessive liquid accumulation in the First KO Drum has been identified in the response of Chillers restarting from a “high-level” condition. In particular, it has been demonstrated that restarting the Chillers with the level control valve closed in manual mode no excessive liquid entrainment was detected thus allowing compressor restart operation to be completed, provided that liquid in KO Drum has been completely drained. Moreover, starting from the analysis of process temperatures variations during the Chillers malfunctioning, it has been identified a temperature measurements showing a sharp drop well in advance with the start of severe liquid entrainment, thus giving to operators and useful advance warning on a potential major upset.

INTRODUCTION OF THROTTLING VALVES ON THE 3 COMPRESSOR SUCTION LINES: following the suggestion of compressor’s vendor to install a throttling valve on each compressor suction line in order to mitigate the motor start-up current, this case was analysed for both the two above described cases. It has been demonstrated that the introduction of the throttling valves with a gradual opening ramp mitigated the liquid entrainment phenomenon during the fast start-up ramp with electrical motor. On the other hand, the operation with the throttling valves effectively reduced the start-up current of motor. Nevertheless, while operating the throttling valves completely opened, the compressor operating point during the start-up ramp moved to stable condition staying close to the stonewall curve, with the introduction of partially closed throttling valves the operating point remained very close to the surge curve, leading to potential dangerous transient conditions for the machine. Several start-up cases were studied in order to identify the right initial opening position of the throttling valves (Burns R. S., 2001) as well as the most suitable opening ramp during compressor start-up, in order to keep the compressor operating point in a more comfortable zone of the characteristic curves field.

3. Case-history 3: Innovative approach in LNG Regasification terminals design.

Liquefied Natural Gas (LNG) Regasification Terminals (Mokhatab S. et al., 2014) can be considered a valid alternative to gas pipelines for natural gas supply, allowing receiving natural gas in liquid state through ships also from remote areas thus creating an important strategic diversification in energy supply. In particular for Europe, the construction in the last 10 years of 4 major terminals in France, Belgium, The Netherlands and Poland, resulted in a more flexible management of European energy supply grid, adding new gas production areas such as Middle East and Persian Gulf gas fields to the traditional areas of North Africa, North Sea and Russia already connected to the European gas supply and distribution network through pipelines.

3.1 Background facts

LNG is stored in tanks at cryogenic temperature very close to its boiling point at atmospheric pressure. During transfer of LNG from a tank to another, from a tank to a ship or from a ship to a tank (e.g. ship loading or unloading operation) a big quantity of Boil Off Gas (BOG) is generated due to heat-in-leaks in the system and the energy transferred to LNG from the pumps. As this huge quantity of BOG cannot be released to the atmosphere or flared, usually it is compressed and reincorporated in the liquid send-out stream through a Recondenser before delivery by means of High Pressure Pumps of liquid to the LNG Vaporizers and to the natural gas grid. During LNG transfer from tank to Carrier, the In-tank Pumps, through the LNG reloading line, deliver the LNG backward on the LNG unloading line. A schematic representation of an LNG terminal is reported in Figure 6.

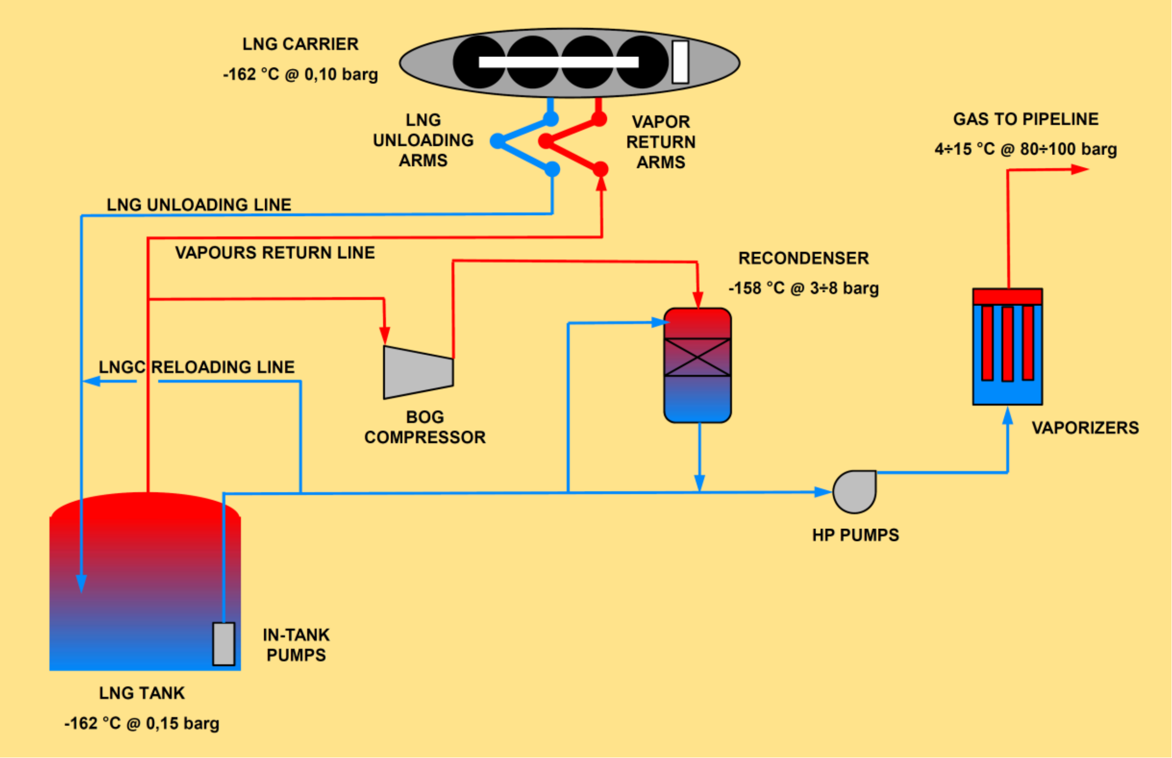


Figure 6: Schematic representation of an LNG Regasification Terminal.

Design of Liquefied Natural Gas (LNG) Regasification Terminals is based on consolidated process simulation procedures based on the application of steady state simulation, however the BOG formation during LNG transfer is a dynamic phenomenon that happens very far from equilibrium conditions and implies great variations both in flow rate and molecular weight during the transfer operations.

In the conventional design approach, based on steady state process simulation, many conservative assumptions are adopted leading to an oversizing of the system or to a specification of the BOG compressor's design point far from the real operating point, coupling conservative gas flow rate and molecular weight conditions resulting from operational scenarios not adhering to the real terminal operations.

On the other hand, the design approach based on dynamic process simulation is already recognized to better adhere to the real system behaviour during dynamic phenomena and it is currently used as a consolidated design or rating approach for complex flaring systems, fast or emergency de-pressuring systems, compressors anti-surge systems and flow assurance studies, just to mention the main applications.

3.2 Studied solution

Starting from the consolidated experience of Techint in design, construction, commissioning and operation of LNG terminals, a rigorous dynamic model of the BOG handling system (Mokhatab S. et al., 2014; Burns R. S., 2001) has been developed as part of the internal innovation program.

The dynamic model included LNG carrier, unloading arms, vapor arms, tanks, in-tank pumps, BOG compressor and all interconnecting piping. Recondenser and vaporizers were not currently included even if dynamic models for these sections have been developed separately for other projects.

Detailed design information from executive EPC projects (GATE, Dunkerque and Polskie) developed by Techint have been used to build the models of LNG tanks, pumps and compressors. Calculation of heat-in-leaks along piping networks has been based on real insulation thickness and piping diameters according to the executive design of the mentioned LNG terminals.

During the start-up and performance test runs of Dunkerque and Polskie terminals, detailed field data have been recorder to be used for the dynamic model tuning. This phase is currently under development.

Once tuning procedures will be finalized, then the dynamic model will be available as a design tool to be adapted on a case by case to the study of whole terminals, particular sections of a specific terminal or to the study of terminal behavior in case of modification of operating procedures.

The implementation of the dynamic process simulation and in particular of the dynamic model for BOG handling system of LNG terminals into the engineering phase is expected to allow a definition of the equipment design conditions much closer to the real maximum operating point. Moreover, the availability of the dynamic model will make possible off-line testing of the process control strategies without affecting plant’s safety or profitability as well as a deep investigation of the start-up and shutdown conditions, both during design and commissioning phases, thus optimizing commissioning and start-up phases duration. Such improvement in design strategies will reasonably allow a reduction of capital investment for equipment and an optimization of operating costs related to terminal’s commissioning and start-up.

The dynamic model will also allow the simulation of operational procedures and scenarios, providing indications on how optimize the existing terminal operations and relevant OPEX. This kind of dynamic model application is expected to become a powerful design tool in case of an existing terminal’s revamping or expansion, providing better indications on the real terminal’s maximum operating capability and identifying the real bottlenecks to be removed, thus bringing to the implementation of the minimum required modifications. As a further option in case of existing terminals revamp, the application of BOG peak-shaving operating procedures will also be verified on the dynamic model before proceeding with any evaluation of physical equipment or system modifications.

In the field of post-order services, the dynamic model has the potential for the application as core engine for Operators Training Simulators (OTS), thus providing LNG terminals’ Owners with a powerful tool for continuous training of personnel and the consequent improvement in operations’ safety.

4. Conclusions

The results obtained in the three case-histories confirm the validity of dynamic process simulation as the best applicable tool for the solution of design problems characterized by fast transient operating conditions.

The dynamic model is not only able to reproduce the normal operations of existing systems, but it is also an important tool in predicting the systems’ behaviour during transient conditions, giving useful indications to plant managers in day-by-day operations as an analytical and predictive tool for the optimization of operations as well as for the analysis of process upset and system malfunctioning.

As a future development, the dynamic process simulation can be used as a powerful design tool for plants characterized by transient and non-steady-state operations such as LNG regasification terminals.

Reference

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