Automation technology opportunities in natural gas transmission - pipelines and LNG

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ABSTRACT

Natural gas transmission systems - pipelines and Liquefied Natural Gas (LNG) systems offer some unique challenges to automation technologies not seen in other application areas such as the process industries. Maybe the most unique automation solutions for natural gas pipeline systems (NGPS) are on-line dynamic simulation with integration (assimilation) of true pipeline operating data, leak detection algorithms and on-line real-time optimization, the latter still being under-utilized and more or less still in a development phase. LNG systems seem to benefit more from off-line optimization of LNG shipping schedules with some opportunities for optimal management of the boil-off gas always accompanying the liquid phase.

1. MONITORING AND CONTROL OF PIPELINE SYSTEMS

NGPS's may have thousands of kilometres of pipes and they must be equipped with compressor stations (CS) typically every 50…100 km in order to keep the gas flowing (Figure 1) to all gas off-takes where the consumers are entitled to receive a certain amount of gas above some minimum pressure and fulfilling some quality limits eg. with respect to heating value. A Supervisory Control and Data Acquisition (SCADA) system has it's central processing unit in a control room and connects to sensors (F=flow, P=pressure in Figure 1), gas quality analysers and local compressor station control systems, part of which are remotely located w.r.t the control room. What makes control of an NGPS special is, that there may be hundreds, or thousands, of kilometres from the control room to a sensor or actuator, so the control room operators must be able to trust the SCADA because they have limited opportunity to do manual checks "out in the field".
A feedback control task can be formulated as: keep gas pressures at defined pipeline locations above specified (contractual) minimum limits under varying gas off-take flow rate conditions (= the disturbance variables) by manipulating CS discharge pressures in such a way that total energy used for gas compression is minimized. The control problem is constrained by not only the minimum pipeline pressures but also the operating envelopes of each compressor machine in operation. The operating points of compressors must always be within the envelopes which are defined as non-linear curves in the pressure ratio - gas flow coordinate system.

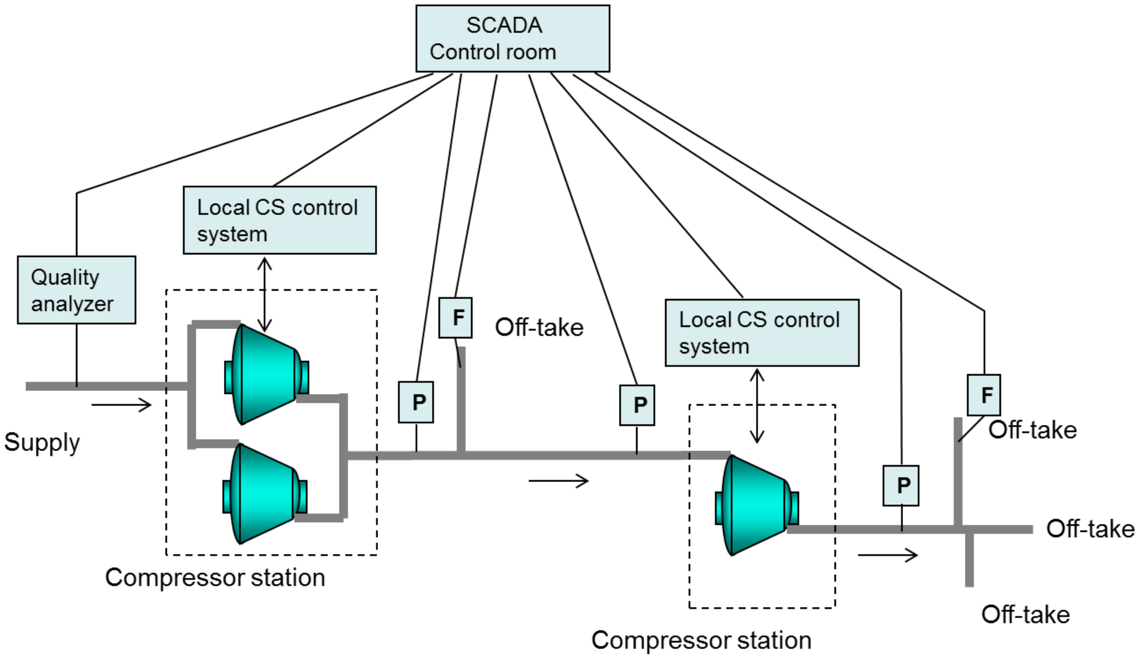

Figure 1. Natural gas pipeline system with two compressor stations, one with two parallel and one with one single compressor. A few pressure (P) and flow (F) sensors are shown.

This control task is usually handled manually by experienced operators with varying success. The dynamics of only a pipeline segment between CS's is very slow and so is the dynamics of a whole NGPS. Slowness gives time to react but it is also difficult to control the system accurately.

2. REAL-TIME SIMULATION

The NGPS community uses the term "real-time simulation" to describe dynamic, first-principles simulators which takes the initial state from the true NGPS and simulates the system behaviour over a defined future time period with user supplied (changes in) supply and off-take flows together with projected operative decisions such as CS discharge pressure profiles. Because of this, also the term "Look-ahead simulation" is used. Contrary to the typical situation in the process industries, real-time simulation usually works well in practice because the simulation models can be made accurate and the current state as derived from measured pipeline values can be calculated rather straightforwardly [1, 3]. The reason for this good situation can be attributed to the fact that no chemical reactions occur in a pipeline given that the gas has been relieved from heavier hydrocarbons which might give rise to mild reactions such as hydrate formation. Thus, the dominating phenomena in a gas pipeline are fluid flow in pipe and thermodynamics. If the temperature in the pipeline is not constant, a non-isothermal dynamic model must be used which adds complication but different simplification and decoupling strategies are available [2]. In order to perform accurate simulation, the model needs to be initialized with the correct initial and boundary conditions, part of which are derived from noisy and sometimes erroneous SCADA measurements and part of which are estimated from measurements. The initialization is a kind of data reconciliation task which can be solved by optimization [3]. The initialization, launch of simulation and storage of simulation results may be done manually or by automatic periodic timing.

3. LEAK DETECTION

Many methods are available for leak detection, according to [4]. Camera monitoring and fiber optic cables require equipment installations along the pipeline system. High-frequency sampling of pressure signals enable analysis of the pressure waves in the pipeline and enables estimation of the size of the leak (estimated volume flow) and the location of it. This method may require replacement of pressure sensors and secured fast data transmission from sensors to control room. If an accurate non-isothermal dynamical pipeline model is available, mass balance difference computation enables an estimate of the leak which is an unknown, undesired gas flow component - an "extra off-take". The model-based leak detection requires that the mass balance error is integrated over time and reliable leak detection alarms can be triggered only after some hours of integration time. Of course, undetected leaks always means loss of money, and major leaks, such as rupture in a high-diameter pipeline segment are also include major safety risks which implies fast detection of the leak.

4. TRANSIENT OPTIMIZATION

4.1. Optimal control of pipeline systems

The control task of pipeline pressures defined in Section 1 can generate substantial benefits for the pipeline system operator if it can be automated. The optimum pressure control principle for pipeline systems with simple structure - see figure 2 -has been known since 1961 , [5] : maximize the gas pressure in pipeline segments between CS's within compressor station constraints and minimize the pressure in the pipeline segment after the last CS against gas delivery contract (minimum pressure) constraints. This control strategy minimizes total gas compression energy in the system. Because an NGPS typically has a very slow dynamics, variations in gas consumption along the pipeline makes the control task very challenging. Gas consumption forecasts, if available and accurate enough, can make the control problem tractable in particular when Model-Predictive Control (MPC) in [6] is used.

The simple principle above does not apply for more complicated networks with significant gas flows in branches or if loops exist. In such cases, *Transient Optimization* (TO) can be used to simultaneously control the pipeline pressures accurately and operate the gas pipeline at an optimum.

Figure 3 from [6] shows a simulated result where the gas pressure is close to ideally controlled to the minimum constraint by TO which tried to minimize the discharge pressure of the nearest upstream CS according to the above principle.

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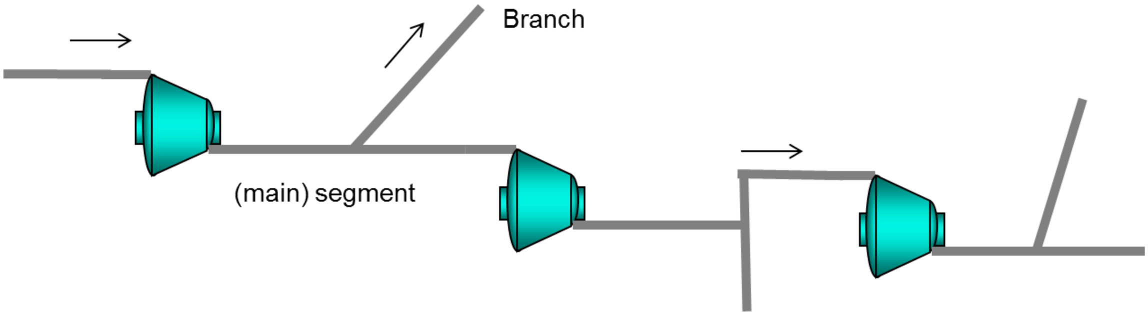

Figure 2. Simple NGPS, often called "gunbarrel" with branches with rather small gas flows

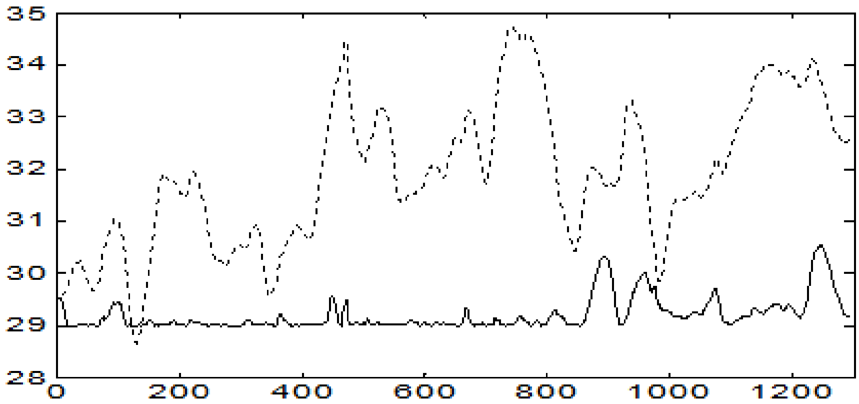

Figure 3. Control of gas pressure at the end of a pipeline segment. Dashed line = real pressure with manual control, solid line = simulated MPC control result. Time axis is in ticks of 10 minutes.

4.2. Transient optimization of pipeline systems

The TO problem was defined in the previous section 4.1. as an extension to optimal control for minimization of total compression energy, i.e. the sum of the energy consumption of all compressors in the system over the prediction horizon while respecting constraints on pressures and flow in CS's, off-takes and other defined points in the pipeline. Alternatively, TO may be used to maximize the throughput of gas or to minimize the violation of gas delivery contracts ("Load curtailment") [7].

When applied on a gunbarrel pipeline, TO automatically implements the old principle in [5], so it is easy for the users to follow the decisions of TO contrary to more complex NGPS's. Accurate gas consumption forecasts are a must for TO in order to achieve good results in particular if *closed-loop TO* is used which means that TO sends control setpoints (CS discharge pressures for instance) directly to the SCADA.

Non-linear dynamic NGPS models are still commonly used within TO, but model simplification and reduction are seen as necessary [7], although linearization is rarely seen in the literature. MPC has been successfully applied in the process industries over decades. MPC is based on *receding horizon* minimization of the predicted control error and if the control error is replaced with a cost function reflecting the total compression energy we arrive at receding horizon optimization [6]. This represents a considerably simplified TO if linear dynamic models, the mainstream of MPC, are used.

Closed-loop TO is used marginally, if at all, in NGPS's because of complicated non-linear models which mean long execution times of optimization [7] and rules related to operations of the NGPS, which are partly introduced by legislation in particular in USA [3, 8]. The operating rules state that whatever optimization is done in the NGPS, the gas content in the system ("Linepack") must be closely followed up and kept above some minimum values at prescribed points in time normally defined as the beginning of a "gas day". The division of the time axis into "gas days" introduces a kind of periodic, or "batch-like" thinking which makes it confusing to think about applying receding-horizon TO for the purpose. The operations planning and short-term optimization (on hourly basis for instance) have been mixed together which favors the mind-setting to use off-line (planning-like) tools instead of closed-loop TO.

5. LNG LIQUEFACTION

The transmission of natural gas in an LNG system is completely different to an NGPS because LNG is transported in "batches" using big tanker ships between sending and receiving LNG terminals. The sending terminals require large-capacity liquefaction which consumes large amounts of energy. The design and configuration of the liquefaction process may vary but the principle remains the same i.e. repeated let-down of gas through a Joule-Thomson valve which successively cools down the gas and leads to a phase change in the end. The control of the liquefaction is not necessary a complex task but locating the sensors optimally and pre-tuning the PID control loops can be significantly supported by dynamic simulation. Moreover, the control structure, or "control loop pairing" which determines what sensors are used for manipulation of what actuators by PID control loops may turn out to be somewhat counter-intuitive but optimal in the sense of the self-optimizing control principle [9].

6. LNG LOGISTICS

The LNG transport by ships between the terminals, the supply of gas to sending terminals and the truck delivery traffic as well as possible gas pipeline operation at the receiving terminals can be formulated as a non-linear programming problem with integer decision variables included, i.e. NLMIP [10]. Depending on the case, it needs to be multi-period, i.e. take into account the time evolvement for instance so that the logistics optimization problem is solved over a one-week total time period divided into half a day periods. This is a high-level optimal planning problem with little real-time relevance except do the need to base the initial values for optimization on an accurate estimate of the current situation (LNG inventories in terminals and at sea).

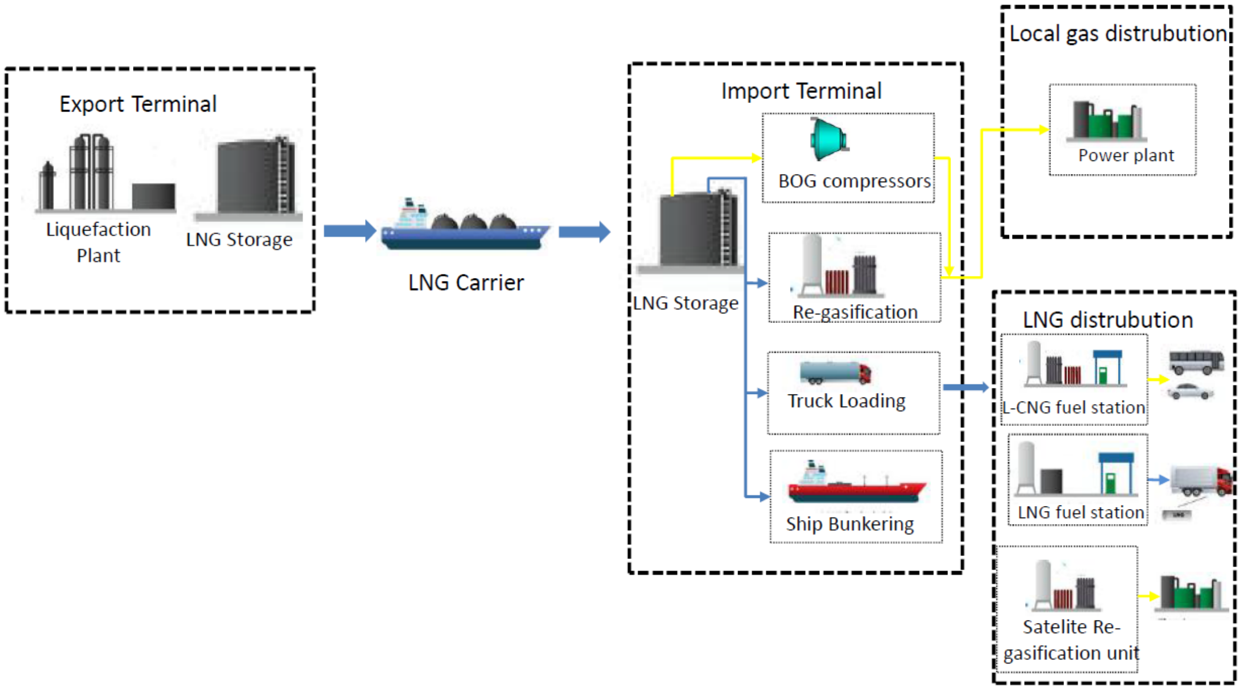

Figure 4. Typical LNG supply chain. CNG = Compressed natural gas.
Adapted from http://cryonorm.com/liquefied-natural-gas'

7. LNG BOIL-OFF GAS MANAGEMENT

Because of heat flux through the walls of an even well-insulated LNG tank, there is always some degree of vaporization (boil-off) in the tank. This boil-off gas must be removed so that tank pressure does not increase excessively. The boil-off gas (BOG) is subject to significant increase at LNG ship unloading [11] and a dynamic simulation model of the LNG terminal, liquid and gas pipes and boil-off gas compressor makes it possible to find an optimal profile of the LNG tank pressure in order to minimize BOG loss. However, even for a big LNG receiving terminal the monetary annual benefit remains quite modest.

LNG storage tanks may suffer from fast vertical liquid movements caused by density and temperature differences between upper and lower part of the liquid space being too large [12]. The upward flowing low-density liquid partially vaporizes near the liquid surface and causes a fast increase of BOG which increases the tank pressure unless let out. Excess BOG outlet means economical loss because it can typically not be allocated to any gas consumer with short notice and this it is flared. LNG tanks can be equipped with vertical traversing density end temperature measurement devices and calculation algorithms for prediction and alerting of roll-over conditions.

7. SUMMARY

For NGPS, one important enabler for higher level automation and optimal control is the detection of the current state of the pipeline system using measured values from SCADA and some models for estimating non-measured variables. Another important thing is to have available reasonably accurate gas consumption forecasts which are updated frequently and are accessible by real-time applications. Having these, the probability of success increases when implementing real-time simulators, simulation based leak detection, optimal control and transient optimization.

The transient optimization and planning tasks need to be separated to allow efficient closed-loop TO to be implemented. The separation is necessarily not easy and the limit between TO and panning may vary from case to case, but there is no reason to delay start of working on this because while waiting, in particular NGPS operators acting close to maximum gas throughput lose money because they do not operate at optimum efficiency.

BOG minimization in LNG terminals could benefit from quickly adaptable and low-cost procedures, with or without dynamic simulation for determining the optimum LNG tank pressure profiles in different situations.

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