Optimizing linepack usage and intraday operations of a gas transmission network, a new approach on GRTgaz network

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ABSTRACT

GRTgaz operates, maintains and develops a 32,000+ km-long natural gas transmission system in France. In the last few years, GRTgaz has experienced challenging evolutions in the regulations and in the behaviours of its shippers. This has changed the way of operating the network and lead to a need for intraday decision help tools, helping operators on a real-time basis to perform an optimization of operations.

GRTgaz and the CRIGEN, GDF SUEZ main research center for gas and renewable energies have developed a tool, called HELP (Hourly Enhanced LinePack) that builds hourly schedules of flows and linepack usage. This paper will present thow this software is used on a daily basis and what gains it has brought. We will also discuss the main difficulties of building such a tool and enhancing it to have more accurate and complete transient optimization of operations.

NEW TOOLS FOR A CHANGING WORLD

Since 2005, there has been many evolutions for GRTgaz. Since GRTgaz network is at the crossroads of European gas networks, it is currently going through a 4bn€ investment program to enhance fluidity between the different European Gas markets.

The network is changing, and the way shippers use it also . Back in 2005, following European regulations, Gaz de France split its transmission system, storage, LNG terminals, distribution network into different subsidiaries. GRTgaz, the transmission system company then worked as an independent TSO. The number of shippers using GRTgaz network has increased oversince, to more than 110 shippers by the end of 2013. Therefore, from a transmission network including storages and used by only one company with a predictable supply behavior, GRTgaz now faces many different shippers who can hourly change their position according to European gas markets: harder to anticipate.

Moreover, since storages and transmission network are operated by different companies, there are new – contractual – complexities, especially for intraday operations. If the transmission system needs some extra gas at some point of the day, it may contractually have to pay the storage operator for that service, it is therefore a key issue for the TSO to optimize its linepack usage so as to reduce those flexibility costs.

While operating safely its network, keeping transmissions secured, GRTgaz also needs to be efficient, minimize storages expenditures AND other operating costs. Therefore, a whole compilation of tools and new processes had to be adapted or put in place.

We will first describe the multiple challenges of operating GRTgaz network on a daily basis. We will then discuss the main issues that arose building the hourly optimization of GRTgaz operations. We will then discuss the main principles of HELP and of its solutions.

I. OPERATING GRTGAZ NETWORK

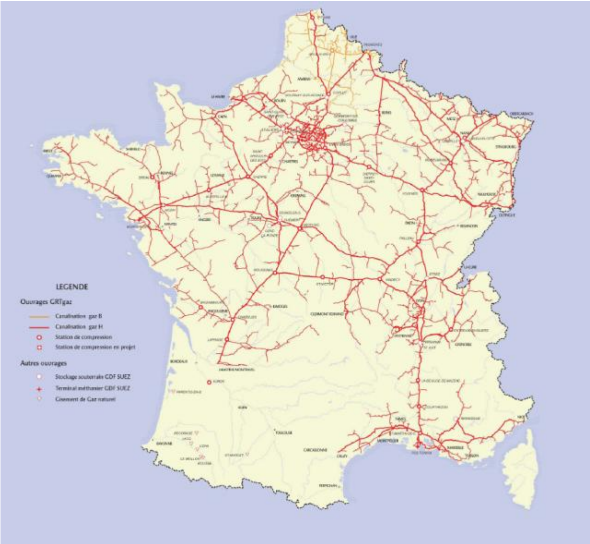

Figure 1: Overview of GRTgaz's physical network

A) A COMPLEX AND HIGHLY MESHED TRANSMISSION NETWORK

The GRTgaz network is highly meshed, for historical reasons. It has 5 interconnection points with other TSO, 3 LNG terminals and 13 underground storage facilities. The transmission system is divided into the main transmission system and regional networks. The main transmission system (pressure from 40 bars to 90 bars, pipeline diameter from 500 mm to 1200 mm) supplies big industrial customers and the regional networks that deliver the gas to the remaining final consumers. The latters (pressure from 20 to 40 bars, pipeline diameter from 80 mm to 400 mm) supply industrial customers and distribution networks. While regional networks are operated by – regional – divisions of GRTgaz, this paper focuses on the main part of the transmission system.

The main network has 30+ interconnection stations, that are nodes where there valves and for some compressors (26 compressors stations containing several compressor units) so as to be able to direct and regulate flows and pressures within the network. Due to the number of entry/exit points and the possibilities offered by meshes and interconnection stations, there can be a great variety in flow patterns in the network.

It is therefore very hard to find a good balance between safety (obviously priority number one) and cost optimization while operating the network. This is the reason why GRTgas has started to work on a decision help tool for the Grid Dispatching, joined by the CRIGEN for further development.

B) DAILY CAPACITIES AND BALANCING RULES

The shippers use a contractual network in which only contractual capacities are published. This network is based on 2 interconnected balancing zones. They pay on an entry-exit basis within each balancing zone, independently of the distance between entry point(s) and exit point(s). Each balancing zone is supposed to be completely fluid. The connection between the two zones is limited by a link capacity. Nominations are done on a daily basis, which means for each shipper and each zone, the total of entries during the gas day in that zone has to be equal to the total of exits in the same zone, with a tolerance. As consumptions are only fully known the day after, there is a tolerance for shippers, the difference between entries and exits being billed by the TSO to each shipper using a market price.

Therefore, though entries are to balance exits on a daily basis, meaning the average flows during the day could be computed using steady state computations, operations are always transient and unbalanced: physical and contractual pressures constraints have to be met during the whole day, in an unbalanced network.

C) ORGANIZATION OF THE GRID DISPATCHING

In order to handle its operations, GRTgaz has structured its daily routine. Putting aside maintenance, customer contact and remote-piloting of the different devices, there are two different supervising roles :

- driving the network following a road map, making adjustments if necessary
- planning the day ahead.

Both these roles need tools that are similar :

- Forecast flows, on day / hour basis
- Decide the networks configuration (compressor station to turn on, how to configure interconnection stations and their evolution during the day, and how to pilot the different devices (pressure set, flow set, open/closed …)
- Decide what is going to be asked to external operators in terms of flexibility sourcing

The main different levers that those tools use to cope with the different operational constraints are :

- the configuration of interconnections stations and the compressors that are activated,
- the flows that are directed through valves and compressors that can be piloted remotely

D) OPTIMIZATION = FINDING A GOOD TRADE OFF

Optimizing the operations means finding a good way of piloting the network (safe and sure) and minimizing compression and flexibility costs. On a network such as the one of GRTgaz, with an important combinatory of choices of interconnection setting and compressor set up, it is too hard to try at first to do everything with the same tool. Everything means optimizing an unbalanced network ruled by mathematical complex fluid mechanic equations (transient, time-dependent) on an hourly basis and deciding how each interconnection is going to be set up and which compressor turned on. The mathematics and the number of variables of the problem make it a very hard problem to solve.

A multistep approach is used : since the whole day is balanced and fluid mechanic equations for steady state have explicit and simple formulae, a first optimization phase is performed by a tool named MinOPEX : based on the dimensioning flows at the entry/exit points, consumption forecasts, it determines which compressors will be on during the day, which really dimensions costs and gives a good average for the day, but does not take into account the intraday unbalances.

The compression scheme is then an input for the other software that this article presents : HELP. This software builds an hourly planning of flows within the network : hourly flows are determined so as to handle unbalances during the day and optimize on an hourly basis linepack usage, taking into account the constraints due to the compression scheme. The optimization is on an hourly basis because HELP is a decision help tool, not an automatic pilot for the network. In particular, operational aspects or constraints may imply to adjust and deviate from the hourly trajectory determined by help because of the reality of operations : models give hints and help do better but they still are models with imperfections, and data for instance consumption forecast is not 100% accurate so reality will be different, yet the tool suggests operators “good” decisions.

HELP will act like a networks GPS, giving the hourly trajectory of the network from the current position to a desired target. A map of flows in the network for a given hour is “the direction” for this hour: this is the set up of the network for that hour. Thus, having a serie of set ups gives operators the view of the network and how it evolves during the day. It is like a movie with 24 images, each image being an hour.

II. Key questions defining the core of HELP

HELP is like a GPS, so questions that will need be answered are basically the ones of a GPS :

- Where am I ?
- Where do I want to go ?
- What do I want to optimize ?

A) Current position ?

The current state of the network is tricky to compute (real time big data !), and involves basically SCADA and probable state reconstruction issues. These are sensible to sensor failures. And failures are pretty common with 5,000+ flow and pressure sensors on GRTgaz network.

The CRIGEN and GRTgaz have developed a simple and accurate method only based on pressures sensors. It uses a decomposition of the network in areas of influence of sensors, and statistical filters to detect failures and correct them, as well as to reduce sensors noise. In the end, GRTgaz has a robust and accurate map of pressures (hence linepack) within its network, on a real time basis (2 minutes refreshment).

Besides HELP, this has advantages but the thing to keep in mind is that the initial position can be computed with real data, in real time, with minimal error.

B) Destination ?

The question of the destination is also tricky, but not for the same reason. The destination is going to be constrained by the day after and the contractual position of shippers : we want to have a map of pressures and flows by the end of the day so the network is ready for the day after. This topic is a current field of studies. So far, it is based on manual input based on operators expertise and forecasts for the day after.

C) What are the feasible paths ?

Pressures : maximal pressures and minimal pressures. These bounds can vary daily, but for a same day, those bounds are fixed.

Flows : bounds and variation limitations. There are limitations with storage facilities or LNG terminals : on the flows and on the variation of flows coming in or out. Maintenance issues may induce restrictions in flows in parts of the network.

Operational constraints : there has to be enough but not too much either, linepack close to big areas of consumption, so as to be able to handle temporary failures of devices or facilities.

D) What is a “good” solution ?

If it is “easy” for the GPS to give a criterion describing what a good path is, e.g. time of traveling, or cost (fuel + tolls), here we face a multi criteria problem, with costs from contracts and “reasonable solutions costs”. This is a key part to have a solution that is well accepted and usable by operators, because if it does not, then operators might not use it at all.

For instance, completely changing flows within the network at each hour would make the solution unusable in practice : operators will not change everything 24 times a day, if there is “in reality” no need to do so. We will describe later in the paper a few criteria.

Aggregation

One way to get back to the “easy” mono-criterion problem is to have a linear aggregation of those different criteria : giving a price to the different criteria, can sum up to a single “economical” criteria. But as the different criteria are not on the same scale : money vs flow for instance, it might not be that satisfactory in the end: one criterion is going to be “privileged” while operators would prefer a tradeoff. In fact, an interesting result in the Pareto optima theory is that doing aggregation does not lead you to every pareto optimum: the only optima you are going to find, no matter how different you try the multiple prices, will be the extremal points of the convex hull of all Pareto optima.

For instance, with a minimization problem :

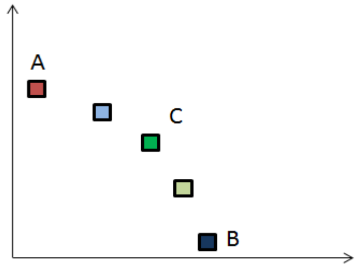

Figure 2: Pareto optima with 2 criteria

On figure 3, you have two criteria and several Pareto optima (minimization problems). No matter what (positive) multipliers you try for aggregation, you will only find points A and B, while point C could be what you were looking for in the first place.

One other (not chosen) option : iterative targets

One other way to find solution C in figure 3, is to iteratively pick one criterion and determine if there are solutions with this criterion below a certain target while all previously studied criterions remain below the target that have been determined earlier. Yet, for computing times reasons, linear aggregation was chosen.

Objective function & modeling options: impact on the optimization problem / on the properties of solutions

In HELP, there are many criteria, for instance :

Distance to the linepack target : given a linepack target for each pipe, making sure the actual linepack is close to the target by the end of the day :
→This can be modeled by the absolute value of the difference between the targeted linepack and the decision variable representing the linepack in the last time step.
→Or also by the square of that difference

Storage contracts : variation from an hour to the other has a cost, deviation to initial plan also

Reasonable solutions : adding penalties to variations of flows and linepack.

The modeling choices between linear and quadratic modify deeply the properties of the "optimal" solution. For instance with the distance to target criterion : if the network is unbalanced and the targets are designed for a balanced network, let's say, shippers being short while targets being the initial state, the unbalance will have to be spread across the different pipes.

Absolute value formulation: any solution such that no pipe is over its target will be optimal for the criterion. In particular, the solution with the unbalance spread evenly across pipes and the solutions in which only a few pipes support the unbalance have the same cost, which might end in unevenly spread optimal solutions.

Quadratic formulation: the only optimum is the evenly spread unbalance, other solutions cost more.

Yet, as linear problems are much easier to solve than quadratic ones, absolute value could be a tradeoff with algorithmic complexity. If constraints are already non linear, it is not much harder to have a quadratic objective function, if constraints are linear, pure linear is way much faster. Depending on the size of the problem quadratic function could also work with current state-of-the-art tools. There are two versions of HELP, one with the linear approach, one with the quadratic penalty.

III. BUILDING HELP

A) MODELING THE NETWORK

The network is modeled by two different concepts :

- meshes, that are set of pipes around cities and areas with large consumptions, interconnection stations and storages facilities.
- large pipelines connecting those meshes

Fig. 4 shows the decomposition of GRTgaz network.

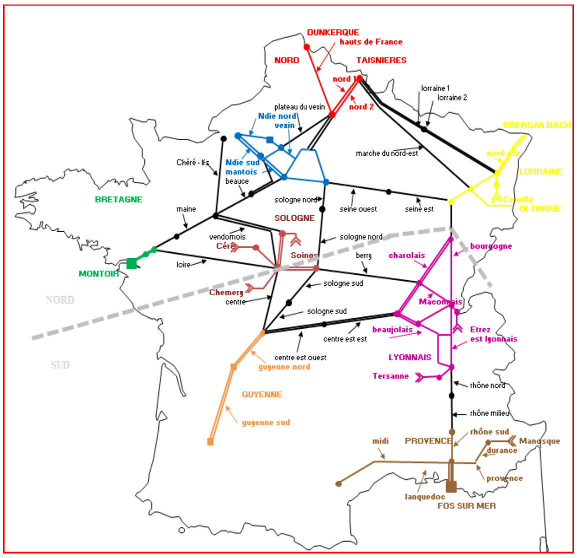

Figure 3: Decomposing GRTgaz network into "meshes" (in color) and transit pipelines (in black)

The idea behind that decomposition is that in the "meshes", because of the interconnections stations, and compressors, the feasible set is rather easy to describe : provided the linepack stays within bounds, there is a way of conducting flows and pressures in that area using interconnections that respects constraints on pressures.

Those bounds include a margin to cover cases of failure in the system. Those bounds are computed taking into account compressor usage.

For transit pipelines, describing the feasible set is a bit more complex than for meshes, two approaches to provide relevant constraints for optimization have been implemented :

- a first steady state approach that will be discussed in this paper (developed in 2010), based on sufficient conditions.
- a transient one (developed in 2013) that enhances the size of the feasible set compared to the steady state approach, that is used for the optimization. This transient version paves the way for other enhancements in the realism of the optimization.

Both approaches yield to optimization problems of different nature and size, but they have a common point : **solved in less than 5 minutes on a standard PC.**

While existing methods for transient optimization of rely on discretization of fluid mechanics equations with decision variables so that pressure and flows for a given space and time node are described by decision variables

B) STEADY STATE APPROACH

We are going to describe the principles of the method used to describe the steady state feasible set for each pipeline. Each pipeline is treated independently from each other for the constraint generation.

The decision variables are the incoming and the outgoing flow in each pipe: for a 24 hour scheduling, there are 24x2 = 48 decision variables for each pipeline.

Through a necessary condition approach, we will be formulating constraints **on linepack instead of pressures**. This has several interests, the most notable one is that we are looking to see the main flow/linepack patterns, which pipeline to pack/unpack, and the trajectory on the whole day.

We will therefore “translate” constraints on pressures on constraints on linepack. For a given pipeline, at a given time step, we want to describe constraints on the decision variables – flows – that ensure that for every point of the pipeline, the pressure stays between bounds (cf II.C) all day long : $\forall x, t\ P(x,t) \in [P_{min}(x), P_{max}(x)]$

We now make the overconstraining assumption that the pressure profile is the one of a steady state, with flow being transmitted in the way of the biggest entering flow in the pipe. Figure 5 shows two pressure profiles within a pipeline: in purple (steady state) and in black (transient state, at a particular point in time, with a packing situation pushing flow into the pipe on the left side and not taking that gas at the right side).

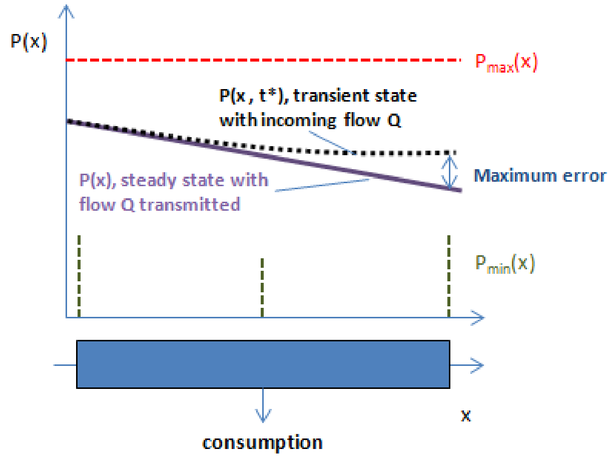

Figure 4: Pressure profiles within a pipeline

Constraints on maximal pressure are shown in dotted red, constraints on minimal pressure in dotted green

In figure 5, both the steady state and the transient (purple and the dotted black) profiles are feasible. We are going to approximate the dotted black transient pressure profile by the purple one. Since pressure drops are overestimated, any solution feasible for the steady state is feasible for the transient state.

That being said, we now consider the problem the other way around : given a flow Q transmitted through the pipeline, what are the minimal and maximal bounds for linepack so that for every point x of the pipeline : $P(x,Q) \in [P_{min}(x), P_{max}(x)]$?

Figure 6 shows the limit pressure profile :

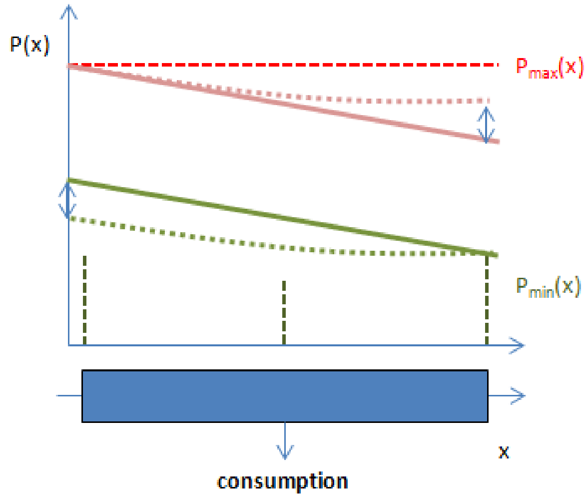

Figure 5: Minimum and maximum pressure profiles within a pipeline : steady state and transient

Computing the minimum and the maximum profile in **steady state** is easy:

1. given the flow Q, compute pressure drops and determine which point is constraining the lower and upper bound for linepack.

2. Starting from this point, compute the steady state such that pressure at the constraining point is equal to the maximum or minimum bound at that point depending on if you are computing minimal or maximal linepack.

3. From the steady state pressure profile, you can easily compute the average pressure and the linepack corresponding to that pressure profile

That computation was made for a given flow Q, let's make Q vary and perform those computations : you get the feasible set of the conservative steady state approach, which you can represent on a 2D graph.

In the example provided for here, you have the following diagram for flows going from left to right :

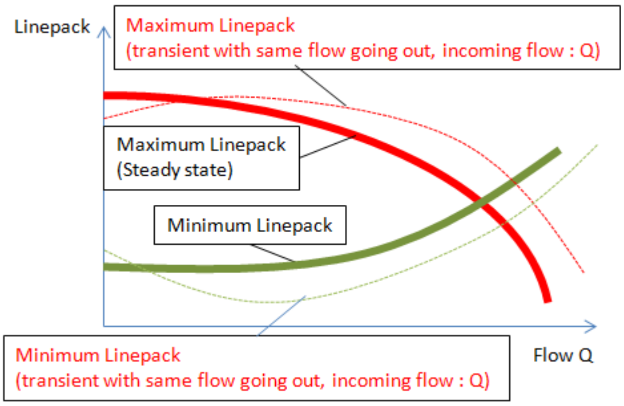

Figure 6: Minimal and maximal linepack in fig. 5,6 configuration

The feasible domain in steady state is bounded by the plain green curve (minimal linepack) and the plain red curve (maximal linepack).

The **curve of maximal linepack** is rather intuitive : maximal pressure is at the leftmost point of the pipeline and hence, as flow increases, pressure drops increase. So average pressure decreases as flow increases. The same causes explain the **curve of minimal linepack**.

Performing the same operation with flows in the opposite direction we can describe the feasible set in terms of linepack and flows

But as we can see on figure 7, the steady state is more constraining compared to the feasible transient.

Mass conservation constraints

As we know the initial state, we know the initial linepack. The linepack of an hour (**t**) is directly linked with the linepack of the previous hour (**t-1**), by a simple mass conservation link:

$$LP_t = LP_{t-1} + Q_{in,t} - Q_{out,t} - \sum consumptions_t$$

Using those 2 sets of constraints, we are able to formulate an optimization problem that can be solved.

This method has advantages and drawbacks :

+ It is simple to implement, and is very fast
+ It is optimal if the scenario of the day is not too tense, if the optimal is an "inner" solution: not activating constraints, for instance, being away from maximal steady state pressure drop
– It is overconstraining, for some cases it can make the optimization problem unfeasible while it is physically feasible. Indeed, points within the dotted line limited domain are feasible and yet, they are declared unfeasible by the steady state approach. More will be said about that in part IV.

C) Transient approach

The transient approach is a completely different approach and treats the problem with decision variables being pressures and flows. Pressure and flows are linked through an linearization of Navier Stokes equations.

Constraints on pressures are much more complex and needed complex optimization techniques and 1 year of developments. A variant of the steady state approach provides interesting results within a few seconds, so it used as a starting point to calibrate parameters in another more complex algorithm.

The combination of steady state and transient provide optimal proven results within 2 minutes.

IV. Current results and perspectives for the future

HELP is currently used at GRTgaz dispatching center:

- Day ahead scheduling : in order to dimension flows and total daily programs with storage facilities, and LNG terminals contracts. (Used as a simulation software to evaluate different scenarios on storage facilities and if the network is being to handle them, because day ahead forecasts use forecasts on consumptions and on shippers behavior that have uncertainty).

- Intraday operations : on an hourly basis in order to build hourly schedules of flows and pressures within the network so as to meet the projected target, having this time real time and more accurate data.

This has helped reduce modulation on storages by using linepack better. Benefits on 2013 were evaluated to around 2.5M€ per year.

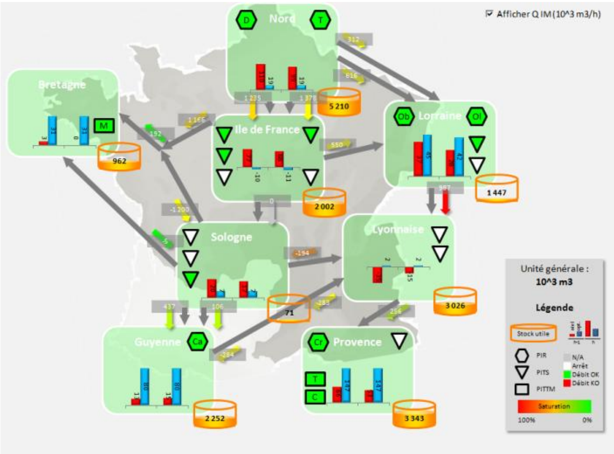

Figure 7: MHI of HELP : showing the limits and the optimized linepack trajectory (red bar in graphs), while printing values of flows at each end of the pipelines (greycolored cells).

TRANSIENT VS STEADY STATE

With all the concerns about multicriteria optimality and about accuracy of data provided to the optimization, the steady state, as well as the transient are solved to optimality for the aggregated criterion.

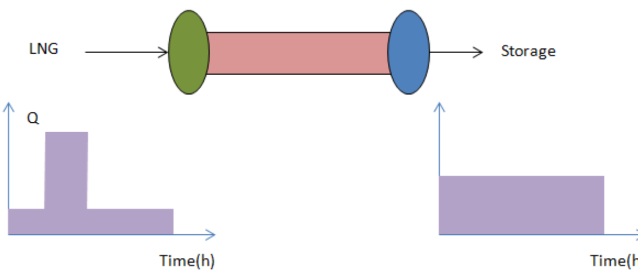

Figure 8: flows from 0 to 15h

To illustrate a situation where using transient might help solve the problem, here is a practical example : the network is very simple : it consists in 2 meshes connected by a pipeline.The left mesh is close to congestion on its upper bound for linepack, and it has one LNG terminal that will emits according to the flow profile on figure 9 : a bumping flow from t=2h to t=10h. The pipeline has a pretty low linepack at t=0, and there is a storage facility on the right mesh that is scheduled to get the gas emitted by the LNG terminal on the whole day, at a very regular rate : ideally at flow totalExtraEmitted/24 at each hour, so that on figure 9, the two purple area represent the same volume of gas.

In a nutshell, transmission from left to right using one pipeline and smoothing the LNG "peak" using the linepack of the network, while respecting constraints on pressures.

When steady state fails and transient succeeds

So, because the left mesh is close to congestion, that extra gas should be evacuated pretty much right away. But the LNG emits so much that the flow injected into the pipeline towards the right mesh has to go over the flow that realizes the maximum pressure drops in steady state for a few hours (the flow for which the red and green curves intersected in figure 7) for a few hours, but that's all we need because the terminal emissions last only five hours and after that flows will decrease. Because what we need to do is to go over the steady state saturation point, there will not be any solutions in steady state, but there are, in real life, and here is what this transient optimization finds (figures 10 and 11) :

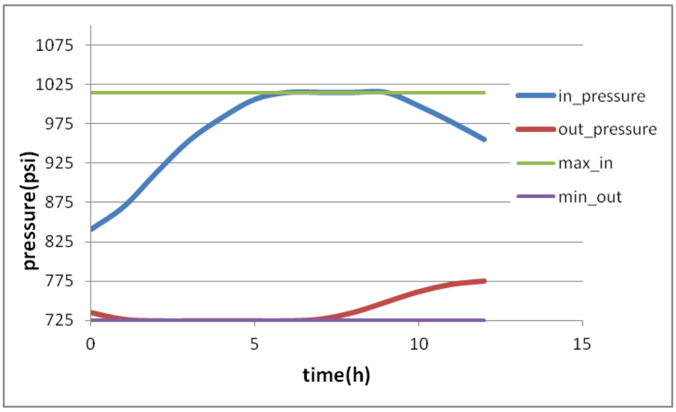

Figure 9: pressures from 0 to 13h at both ends of the pipe

The pressure at the in point of the pipeline (taking gas from the mesh with the LNG terminal) is bounded upperly by maximal pressure (1015 psi). The pressure at the out point (towards the mesh with the storage facility) is bounded inferiorly by the minimal pressure at the exit point by 725 psi (there is a compressor for instance). The initial state is, as we can see on figure 10 close to the minimum linepack possible.

As we can see on pressures, the pipeline reaches saturation (steady state saturation of pressure drops) at t= 6, and is saturated until t=8. But as we can see, the transient optimization anticipates the bump in the LNG terminal by packing in the pipeline before the LNG even starts to emit.

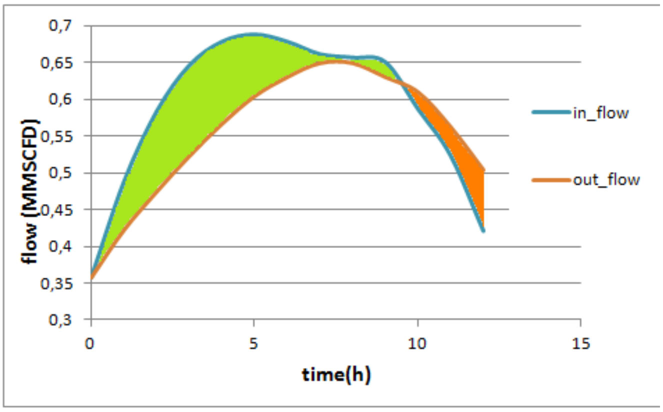

Figure 10: flows from 0 to 13h at both ends : Packing (green areas), unpacking (orange area)

Figure 11 shows that from the initial steady state, incoming flow is soaring quickly as left mesh evacuates gas by anticipating the LNG's start. Starting at t=8, the pipeline packs again by reducing out going flow : pressure at the right node increases a little, this is purely transient. At t=10, the incoming flow drops dramatically (the LNG terminal bump is over) and then the pipe starts unpacking as gas is transmitted "regularly" to the right mesh.

This example also illustrate that for some hours (here t=5h), flow at one end can be greater than the maximum steady state flow (t=8h), that means that transient offers more flexibility and a wider range of possibilities than the steady state.

CONCLUSION

In this paper, we have presented a software, that is used on a daily basis by GRTgaz to optimize its flexibility contracts and help adapt the daily plan to operational hazards and differences between forecasts and real life in terms of consumptions.

This software lies on a two step approach : first performing a steady state approach whose main ideas are detailed in this paper and that gives results making overconstraining assumptions, and a second step using the solution of the first step as a starting point and enhancing it with an accurate transient physical model.

Compression costs are for the time being partially optimized : another software performs an optimization of compression usage on the daily average scenario through a steady state based optimization, the results of this software are used as constraints for the hourly optimization performed by HELP.

Further work will be on a better integration between the two software and eventually having only one software doing a fully combined optimization of both compression and flexibility OPEX. The global problem is big in term of number of variables, of combinatory, and has "bad" non convexity properties that make it really hard.

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