PSIG 0904

Network Simulation of Transmission and Distribution Systems

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ABSTRACT

If you want to know if your network can handle a predicted load, you can perform a steady state simulation. It is not necessary to be an operator to perform such a simulation. Current steady state simulation programs require that prior to a simulation, the user has to define all kinds of pressure and flow settings that may prove to be inconsistent after the simulation. Recognition of the steady state problem in the right way saves you a lot of trouble. The network simulation problem is actually a constrained optimization problem.

There are

- nodal balance equations and pressure drop equations.
- constraints on flows, pressures and pressure differences
- a desire to use the least amount of fuel.

In this paper an approach will be discussed that takes this three points into account. A demonstration will be given that shows the power of this approach.

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1 INTRODUCTION

In the ninetieth of the last century Gasunie changed their way of planning. One used to make plans based on scenarios. However the choice of scenarios is always more or less arbitrarily. Therefore one started to plan based on reliability of the network. So given the reliability figures of the components, the reliability of the whole network had to be calculated. In order to do so thousands of simulations had to be performed where compressors and supplies acted in a degraded fashion. Because of the large amount of simulations, they had to be performed without human intervention. This is how this new approach is born.

Gasunie has a very dense network of 6000 km (4000 mile) with an average diameter of 1 m (40 inch) on an area of 200 x 300 km^2 (125 x 200 $mile^2$) Moreover Gasunie accepts different qualities of gas which are brought to different markets via a more or less integrated network. In most networks in the world a station is a compressor station with one or more compressors in series or parallel. They form one functional compression group. In the Gasunie network a station consist of more functional groups. One of our biggest stations, named Ommen, consist of three functional compression groups and three mixing groups. It is a hell of a job to come up with consistent control modes with setpoints for all these functional groups prior to a simulation. This is why finding a solution within bounds is such a powerful concept in the Gasunie situation.

2 NATURAL FRAMEWORK

Before we go into the simulation problem I want to make some general remarks. As a result of a simulation we want values for pressures and flows. These are the **variables**. They are related to each other by **equations**. Any physical problem exist in a constrained world. So there are **constraints** on variables. In a world with relations and constraints there is a desire. A desire can be expressed as **minimization** of **cost**. A network simulation is a natural problem, so it fits in this natural framework.

3 PIPE AND VALVE

A network consist of elements and nodes. The elements are pipes, supplies, demands, compressors, reducers and valves. Their primary variable is the flow Q.

3.1 Pipe

The pipe is characterized by the pressure drop equation

$$P_b^2 - P_e^2 = c\frac{L}{D^5}|Q|Q$$

3.2 Valve

A valve is characterized by one of two equations

$$\text{open}\ : P_b = P_e$$

$$\text{closed:}\ \ Q = 0$$

4 Demand and Supply

4.1 Demand

A demand is a kind of driving force in a network. It is very much wanted that $Q = Q^*$. However, we don't want the demand pressure to become lower than atmospheric because of this flow. So modeling the demand as an equation is not the right thing to do. The demand should be positive and not larger then Q^*. This can be expressed by the constraints

$$0 \le Q \le Q^*$$

We want the flow to be as high as possible so we impose a cost

$$cQ$$

with $c < 0$ and very large. The effect is that at minimization, Q will become as large as possible. In section 6 constraints on pressure will be treated.

4.2 Supply

A supply is characterized by a maximum flow and a maximum pressure. The flow should be positive

$$0 \le Q \le \bar{Q}$$

In section 6 constraints on pressure will be treated. Suppose that you have a network with more than one supply. Now both supplies can contribute to the demand or only one of them. We can influence that by giving cost to the flow

$$cQ$$

If $c > 0$ then a small supply flow is favorite, while $c < 0$ favors a large supply flow.

We can go one step further and introduce a desired flow Q^*. We do that by introducing a cost function $c(Q)$ with a shape like in figure 1

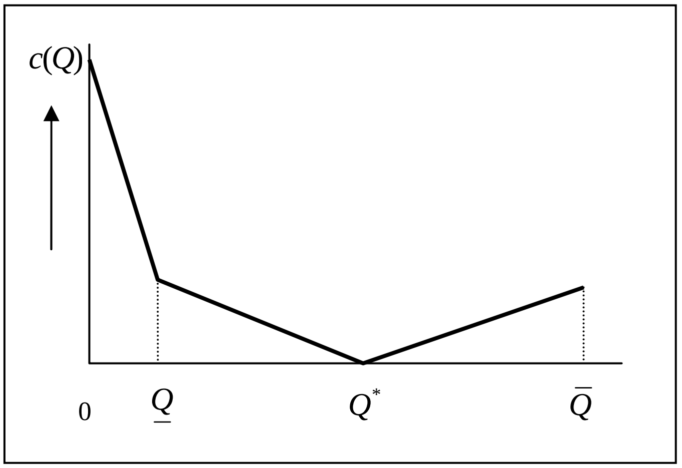

Figure 1 supply cost function

So Q^* is the most desired flow and $\underline{Q}$ is a kind of minimum flow. The real minimum is of course zero but sometimes it is not economical to supply under a certain level. The slope around Q^* is called the priority. If two supplies deliver to a demand, then the one with the highest priority will assume his desired flow Q^*.

5 COMPRESSOR AND REDUCER

For a compressor or a reducer only the characteristics of the device have to be described. It is not necessary to give constraints or settings for the suction an discharge pressure. The devices will act based on pressure constraints placed elsewhere, for instance at supply and demand points.

5.1 Compressor

A compressor is an active device that can bring gas from a lower pressure to a higher pressure. The pressure increase and the flow of a compressor are limited. To increase the pressure at a certain flow rate one needs power. Power is limited and we like to use at least as possible. This all gives constraints and a desire. To facilitate this we bring in extra variables which are a function of the primary variables flow and pressure, and which will be constrained. We start with the pressure increase, which has to be positive

$$\Delta P = P_d - P_s \geq 0$$

The compression ratio is constrained, so

$$C_r = P_d / P_s \leq \overline{C_r}$$

The volumetric flow at pressure conditions is constrained too

$$Q_p = Q / P \leq \overline{Q_p}$$

The power of a compressor is also constrained

$$N = 32\ Q\ \frac{P_d - P_s}{\frac{2}{3} P_s + \frac{1}{3} P_d} \leq \overline{N}$$

The flow must be positive and may be constrained as well

$$0 \leq Q \leq \overline{Q}$$

5.2 Reducer

A reducer is a variable resistive device. It is used to constrain the flow or to keep suction or discharge pressure within limits. In the field one of these variables is measured and based on that measurement the resistance is adjusted. In the model only the typical characteristics of a reducer have to be modeled. The pressure increase has to be negative

$$\Delta P = P_d - P_s \leq 0$$

and the volumetric flow at pressure conditions is constrained

$$Q_p = Q / P \leq \overline{Q_p}$$

The flow must be positive and may be constrained as well

$$0 \leq Q \leq \overline{Q}$$

6 NODAL ISSUES

Elements are coupled at nodes, so at each node there is the balance equation

$$\sum Q_i = \sum Q_u$$

Where i belongs to the elements with a flow toward the node and u belongs to the elements with a flow from the node.

Each node has a pressure P which can be constrained

$$\underline{P} \leq P \leq \overline{P}$$

These restrictions can be placed anywhere in the network.

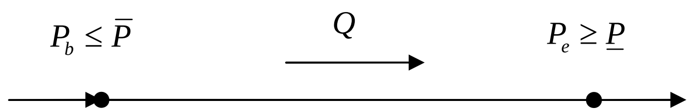

Figure 2 supply, pipe, demand

In figure 2 the supply and demand node are pressure constrained, which implies that the pressure drop is constrained, and so is the pipe flow. As a consequence the demand flow may become smaller then desired.

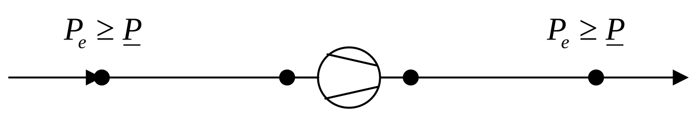

Figure 3 supply, pipe, compressor, pipe, demand

With compression on line, the total of the pressure drops may be higher. So pressure constraints have a remote effect on compressors and reducers.

7 Gas Quality

The approach presented in this paper is especially interesting if supplies have different gas qualities and there are restrictions on quality for different demand nodes. The quality might be the heating value or he CO_2 content or whatever. The quality at a node is the flow weighted average of the qualities of the elements with flow toward the node

$$Y_n = \frac{\sum Q_i Y_i}{\sum Q_i}$$

The quality of the elements with flow from the node is equal to the nodal quality

$$Y_u = Y_n$$

One might put constraints on the qualities as well

$$\underline{Y} \le Y_n \le \overline{Y}$$

8 MATHEMATICAL FRAMEWORK

Here we summarize the variables, relations and cost. After that some remarks on linearity.

8.1 Variables (eventually constrained)

- Nodal pressures P
- Element flows Q
- Extra variables ΔP , Q_p, C_r , N

8.2 Relations

- Nodal balance
- Pressure drop for pipes
- Valve
- Compressor ΔP , Q_p, C_r , N
- Reducer ΔP , Q_p

8.3 Cost

- Demand cQ with $c \le 0$
- Supply $c(Q)$
- Compressor power N

8.4 Non Linear Problem

The problem as stated is a non linear optimization problem and can be solved by a non linear optimization solver. In order to do so one can use Sequential Linear Programming. That is a iterative scheme where at each iteration one linearizes the nonlinear equations and solves the system by means of Linear Programming. Because the cost functions of the supplies are piecewise linear, we use Piecewise Linear Programming. The PLP problem is stated as

$$\begin{aligned} &\text{minimize} \sum f_i(x_i) \\ &Ax = b \\ &\underline{x} \le x \le \overline{x} \end{aligned}$$

where $f_i(x_i)$ are convex piecewise linear functions. Some nonlinear equations can be linearized by a change of variable. For instance the equation

$$Q_p = Q / P \le \overline{Q_p}$$

can be converted to

$$\Delta Q = Q - \overline{Q_p} P \le 0$$

which is equivalent. The pressure drop equation and the power equation have to be replaced by a linear approximation

9 Demo

In the following sections a series of experiments will be described. The following units are used (British units).

Length	L	km	.621	mile
Diameter	D	m	39.37	inch
Flow	Q	$10^6\ m_0^3/h$	37.33	MMSCF/H
Pressure	P	bar	14.50	Psi
Heat. Val.	H	MJ/m_0^3	25.4	BTU/SCF

9.1 Single Pipe with flow constraint

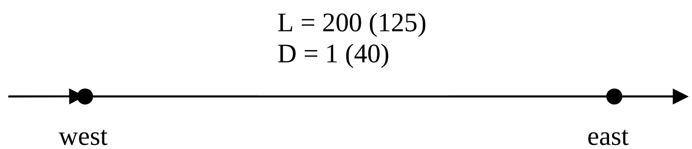

Figure 4 single pipe

Setup: demand: $Q_d = 1.6\,(60)$

supply west: $\overline{Q_w} = 1\,(37)$

Result: $Q = 1\,(37)$

Comment: supply restriction

9.2 Single Pipe with pressure constraint

Setup: supply west: remove flow constraint

apply: $\overline{P_w} = 70\,(1000)$

Result: P_e

Comment: P_e to low, flow to large, pipe to long

9.3 Compressor in the middle

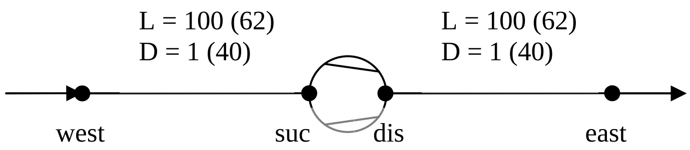

Figure 5 compressor in the middle

Setup: compressor in the middle

Result: P_s, P_d, P_e

Comment: Nothing has changed, why?

9.4 Demand pressure constraint

Setup: demand node $\underline{P_e} = 40\,(580)$

Result: P_s, P_d, P_e, N

Comment: compressor makes $\mathrm{P}_e = \underline{P_e}$

9.5 Power constraint

Setup: compressor: $\overline{N} = 5\,\mathrm{MW}$

Result: N, P_d, Q

Comment: $\mathrm{P}_e < \underline{P_e}$ caused by $\overline{P_w}$ and $\overline{N}$

9.6 Extra supply

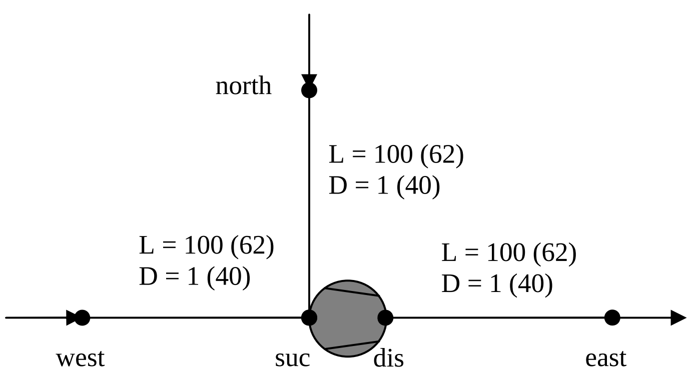

Figure 6 extra pipe and supply

Setup: add pipe and supply north

Result: Q_w, Q_n, P_s

Comment: north does all because no compression needed

9.7 Supply west with desired flow

Setup: supply west $Q_w^* = 0.5\,(19)$ and $prior = 10$

Result: $Q_w = Q_w^*$

Comment: the desire overrules minimum horsepower

9.8 Gas quality with minimum constraint

Setup: $H_w = 30\,(762)$ and $H_n = 40\,(1016)$ and $\underline{H_e} = 35\,(889)$

Result: $H_e = 36.72\,(933)$

Comment: the combination of flows result in this quality

9.9 Gas quality with maximum constraint

Setup: $\overline{H_e} = 35\,(889)$

Result: $H_e = \overline{H_e} = 35\,(889)$

Comment: the combination of flows is fifty-fifty

9.10 Large Network

In the large network of the Netherlands there are minimum pressures at the German boarder. One can remove the minimum pressure at Zevenaar and watch the effect on the compressor group in Ommen. Probably it has no effect, because from Ommen there are two streams to Germany, one via Zevenaar and the other via Winterswijk. If the minimum pressure at Winterswijk is removed as well, we will see that Ommen can compress less.

An other experiment concerns CO_2 content at a node near Amsterdam. We can observe that the CO_2 content is 1.6% We put a maximum of 1.2% on the CO_2 content of that node and perform a simulation. After performing a simulation we will see that the CO_2 content is indeed on 1.2%, but how. After some analysis we can find that a North See supply has a CO_2 content of 16%. Due the maximum CO_2 content we imposed on the node near Amsterdam, the flow of the CO_2 rich supply has decreased dramatically.

10 Math in Gas.. in Alexandria

In august 2008 I gave a copy of my book *Math in Gas and the art of linearization* to the great Library of Alexandria. I am very grateful for their acceptance.

REFERENCES

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