

IDENTIFICATION OF THE PARAMETERS “PRESSURE, FLOW AND CALORIFIC VALUE” IN UNDER-INSTRUMENTED GAS DISTRIBUTION GRIDS BY USING MODERN RECONSTRUCTION METHODS

T. Hager¹, A. Bentaleb², Dr. E.-A. Wehrmann³, Prof. Dr. H.-P. Beck⁴

¹ Energie-Forschungszentrum Niedersachsen, Goslar, Germany

² Institute of Electrical Power Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

³ Institute of Electrical Power Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

⁴ Energie-Forschungszentrum Niedersachsen, Goslar, Germany

E-mail (corresponding author): torsten.hager@efzn.de

Abstract – The simulation of natural gas networks is only feasible with available simulation tools, if all inlets and rather all offtakes of the grids are measured. At regional gas distribution grids these premises are often not fulfilled. In detail this means, that not enough offtakes are measured and because of that it is not possible to use the common simulation tools. For this reason a method was developed at Clausthal University of Technology which emulates the unmeasured offtakes with a Nodal Point Load Observer. With this emulated offtakes it is possible to simulate the pressures and the pipe flows in gas distribution grids and with them to reconstruct the calorific values. The results of simulations at different gas distribution grids are shown in the article.

A simulation system for gas distribution grids with an incomplete measurement infrastructure would bring a new quality to the controlling and monitoring of gas distribution grids and to the billing. If different gas qualities are in the grid, for example if biogas plants feed in their biogas, it will be necessary to trace the calorific values for billing.

Keywords reconstruction methods, gas distribution grids, Luenberger observer, metrological infrastructure

1. INTRODUCTION

Knowing the inner state of natural gas distribution grids, which includes the pressures at the nodes, the pipe flows and on top of these two the calorific value of the gas, would be helpful for many practical applications. First it would support the dispatching in controlling and monitoring the grid. Secondly it would make the billing easier and in some cases just possible. The knowledge of the inner state of the grid makes it possible to allocate a specific calorific value, and with that an amount of energy, to each offtake of the grid.

For reconstruction and simulation of the inner state of gas grids are several systems available. But these systems were originally designed for gas transportation pipelines. The main difference between gas pipelines and distribution grids is the number of offtakes and the degree of intermeshing. Gas transportation pipelines only have a small number of offtakes and in general a low degree of intermeshing. In contrast to that the number of offtakes in gas distribution grids is much higher and the grids are finely

intermeshed. With the arising number of offtakes the number of necessary measurement instrumentations arises too. But these instrumentations and the infrastructure around them are very expensive, so that they could not be installed at all offtakes. The result of this is that typically only about one-third of the offtakes in gas distribution grids are measured. Typically these are bigger industrial customers, which have to be measured.

Let us come back to the reconstruction and simulation systems from the beginning. These “classical” systems need for their simulations all inlets and offtake quantities of the grid and a few pressure values as time discrete inputs. If not all offtakes are measured, like it is standard in gas distribution grids, these systems do not work correctly. A solution for that problem is shown with the Nodal Point Load Observer (NPLO) in this article.

The NPLO is an additional system on top of the classical grid observer. Its function is to emulate the unmeasured offtakes out of several boundary conditions. These reconstructed offtakes are given as inputs into the classical reconstruction systems, which could then simulate the flows and the pressures in the gas grid.

In the following paragraphs the concept of the NPLO is shown in detail and a forecast of the use of this simulation system is given.

2. MATHEMATICAL MODEL OF GAS DISTRIBUTION GRIDS AND THE NPLO

The pressures and the pipe flows in gas distribution grids are described by the following differential equations.

$$\dot{p}_{no}^{(i)} = \frac{c_T^2 \cdot (p_{no}^{(i)})}{V_{no}^{(i)}} \cdot \left(\sum_{j=1}^{n_{pipe}} k_{i,j} \cdot q_{pipe}^{(j)} - q_R^{(i)} \right) \quad (1)$$

$$\dot{q}_{pipe}^{(j)} = \underline{f}^T \cdot \begin{bmatrix} q_{pipe}^{(j)} \\ p_{no}^{(i)} \\ p_{no}^{(k)} \end{bmatrix} \quad \text{with} \quad (2)$$

$$\underline{f} = \begin{bmatrix} \frac{-2 \cdot \lambda^{(j)} \cdot c_T^2(p_m)}{d^{(j)} \cdot F^{(j)}} \cdot \frac{|q_{pipe}^{(j)}|}{p_{no}^{(i)} + p_{no}^{(k)}} \\ \frac{-k_{i,j} \cdot F^{(j)}}{2 \cdot \Delta z^{(j)}} + \frac{\lambda^{(j)} \cdot c_T^2(p_m)}{d^{(j)} \cdot F^{(j)}} \cdot \frac{q_{pipe}^{(j)} \cdot |q_{pipe}^{(j)}|}{(p_{no}^{(i)} + p_{no}^{(k)})^2} \\ \frac{-k_{k,j} \cdot F^{(j)}}{2 \cdot \Delta z^{(j)}} + \frac{\lambda^{(j)} \cdot c_T^2(p_m)}{d^{(j)} \cdot F^{(j)}} \cdot \frac{q_{pipe}^{(j)} \cdot |q_{pipe}^{(j)}|}{(p_{no}^{(i)} + p_{no}^{(k)})^2} \end{bmatrix} \quad (3)$$

These equations are derived from the continuity equation and the Navier-Stokes equations for a one dimensional pipe flow in a long pipe (“long pipe model”). More detailed information about the derivation could be find in [1], [2] and [3].

Setting up these equations for all nodes and pipes and combining those, results in the state space model (4) [4]. In this model \hat{x} stands for the state variable vector, \hat{y} symbols the measurement vector including the measured pressures and \underline{u} is the input vector with the measured in- and outgoing gas flows (shown in (5)).

To simulate the pressures and flows with these differential equations an observer is necessary. From control theory the Luenberger observer is known for such duties. This observer leads the deviation between the measured values and the simulated back to the entrance of the system and minimises the deviation on this way. The structure of the Luenberger observer is shown in the grey box in Fig. 1.

$$\begin{aligned} \dot{\hat{x}} &= \underline{A} \cdot \hat{x} + \underline{B} \cdot \underline{u} \\ \hat{y} &= \underline{C} \cdot \hat{x} \end{aligned} \quad (4)$$

$$\hat{x} = \begin{bmatrix} p_1 \\ q_2 \\ \vdots \\ q_{n-1} \\ p_n \end{bmatrix}, \quad \hat{y} = \begin{bmatrix} p_1 \\ \vdots \\ p_r \end{bmatrix}, \quad \underline{u} = \begin{bmatrix} q_{ab,1} \\ \vdots \\ q_{ab,m} \end{bmatrix} \quad (5)$$

As written at the beginning, in gas distribution grids are not all offtakes measured. This means, that the input vector \underline{u} is incomplete. For solving this problem, the non-measured offtakes are regarded as disturbances to the systems. In order to calculate these disturbances a so-called Nodal Point Load Observer is used, which is a disturbance observer as known from control theory. For supporting the NPLO an additional predictive control by a predicted time sequence of the non-measured offtakes is implemented. The aim of this predictive control is to reduce the work of the NPLO, because it has just to compensate the deviation between the predicted offtakes and the real offtakes. It must not calculate the complete amount, which makes the simulation faster and in some cases more accurate. In Fig. 1 the complete system is shown as a block diagram, with the NPLO in the yellow box.

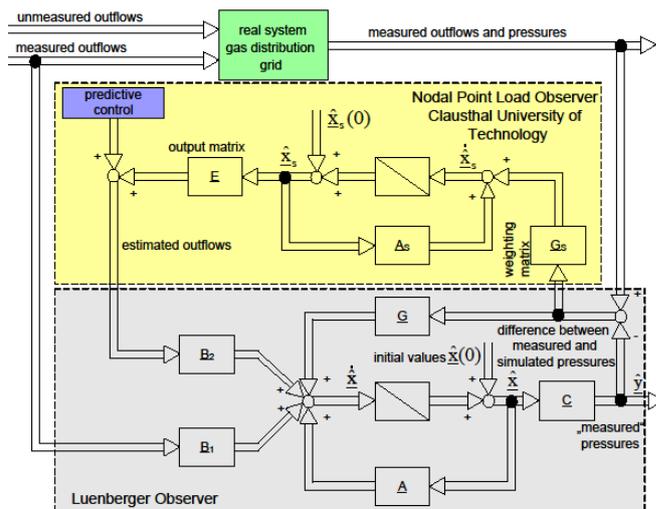


Fig. 1. Nodal Point Load Observer [5]

The accuracy of this system is mainly affected by the matrices of the NPLO. Therefore is one of the main challenges to find a mathematical method for calculating these matrices. More detailed information about these methods is given in chapter 4.

3. METROLOGICAL INFRASTRUCTURE

The presented simulation system works with a reduced metrological infrastructure, but a minimal number of measurement facilities is required. The question is coming up, where these measurement facilities have to be placed for getting an optimal result.

Gas distribution grids and with them their measurement infrastructures are historically grown structures. That means, there are existent facilities, which could not be replaced, respectively it would not make sense to do this. The replacement of a measurement facility would not be cheaper than building a new one and one would lose an additional measurement. At the end the simulation must work with these existing facilities and perhaps with a small number of additional installed.

One of the greatest difficulties for the NPLO are takeoff stations which are connected via subsidiary gas grids. In such cases the annual amount of gas consumption of loads in the subsidiary gas grid, which is necessary for the predictive control, can not be allocated directly to one of the takeoff stations. A result of this is, that all (or all minus one) via subsidiary grids connected takeoff stations have to be measured.

From empirical analyses results, that about one-third of the offtakes should be measured. A consequence of this is, that, if the already measured offtakes together with the connected offtakes do not count one-third of the whole offtakes, additional facilities have to be installed. For that reason additional criteria are required.

One can imagine that a large offtake has a stronger influence on the simulation than a smaller one. Because of that, one should keep the largest offtakes in mind for installing the remaining measurement facilities. But one

more criterion is the structure of the consumers behind the takeoff. If there are big industrial consumers, so that their percentage on the takeoff is high (ca. 75 %) compared with the household consumers, the profiles for the predictive control do not match the reality. And therefore it makes sense to measure these takeoffs, if they are large enough for having a real influence to the simulation.

Additionally the measurements should be distributed all over the network, so that the boundary conditions for the NPLO are not concentrated in a few points.

4 DESIGNING METHODS FOR THE OBSERVER

The observation problem consists of an accurate determination of the inner state of incompletely instrumented natural gas distribution grids, based on the available measurement information. As written in chapter 2 the accuracy is mainly affected by the matrices \underline{G} , \underline{G}_S and \underline{E} of the observers. These could be computed statically or dynamically dependent on what kind of information should be covered.

The first made design in [5] uses a statical method, because of its simplicity, without making any deduction in accuracy. The feedback of the Luenberger observer forces only on the differential equation describing the pressure at one selected node. The feedback factor is given by

$$g = \frac{1}{\Delta t} \quad (6)$$

where Δt is the step size of the simulation. That means a fast settling of the observer can be reached by choosing a small step size.

Compared to that the weighting matrix \underline{G}_S of the NPLO is defined by

$$\underline{G}_S = - \begin{bmatrix} 1 \\ F_R \end{bmatrix} \quad (7)$$

$$F_R = \rho \frac{\Delta p}{Q} \quad (8)$$

Distributing this amount of gas can be done by matrix \underline{E} , which is calculated by

$$\underline{E}_n = \frac{Q_{Kn}}{Q_{Kmin}} \quad (9)$$

where Q_{Kn} is the annual amount of gas at the node Kn and Q_{Kmin} is the lowest annual amount of gas metered in the previous year at the unmeasured takeoff stations.

Another dynamical approach for calculating the matrix \underline{G}_S is introduced in [3] (10). Both methods have their physical justification and the difference of the values between both is pretty small. The results of both methods are close together.

$$\underline{G}_S = - \left[\frac{w_{TN}}{\Delta t} \cdot \frac{V_{nTN}}{c_T^2(\hat{p}_{nTN})} \right] \quad (10)$$

w_{TN} : weighting factor of the measured pressure value

V_{nTN} : half of the volume of the connected pipes at node TN

c_T^2 : isothermal sound propagation velocity

The matrices by dynamical methods are all or a selection of them recalculated in each time step. For doing this there are several methods available. The first tested one is using the values of the predictive control for recalculating the matrix \underline{E} in each time step. With this method the reasonable fluctuations in the offtakes are considered by the observer matrices.

By using the procedure of (6) for calculating \underline{G} many coefficients of the matrix are set to zero to keep the design as simple as possible. But this brings disadvantages in terms of the observer dynamic. An alternative approach to observer design is based on the minimization of the Mean-Square Estimation Error (MSEE). For this purpose a power function, which has to be minimized by a stochastic optimal observer, is defined as follows [4]

$$J = \frac{1}{2} \int_0^{\infty} (\underline{x}^T \underline{Q} \underline{x} + \underline{u}^T \underline{R} \underline{u}) dt \quad (11)$$

with a symmetric positive semi definite weighting matrix \underline{Q} and symmetric positive definite weighting matrix \underline{R} . The disturbance response is approximated with these matrices.

The described approaches are tested in various simulations. A selection of results is presented in the following section.

5. SIMULATION / RESULTS

In chapter 4 different designing methods for the observer were shown. Following that, we want to present a selection of different simulation results with the designing method according to [5]. This model was implemented in MATLAB / Simulink and from PSI AG in a test system. The advantage of MATLAB / Simulink is the possibility to change parameters and parts of the source code quite fast. But the size of the grid which can be simulated is limited. In contrast to that, it is possible to simulate larger grids with the commercial PSI test system. For the simulations two different gas distribution grids will be used. A smaller one of the E.ON Thüringer Energie AG, which is completely instrumented, and a larger one of the E.ON Avacon AG with an incomplete measurement infrastructure.

Implementation and testing of the system started at a small section of the completely measured gas distribution grid, with 10 takeoffs and one injection (Fig. 2). Seven of these takeoffs are assumed as unmeasured and have to be reconstructed by the NPLO. In this configuration the offtakes are reconstructed very well. One of the simulated offtakes, compared with the measured offtake, is shown in Fig. 3.

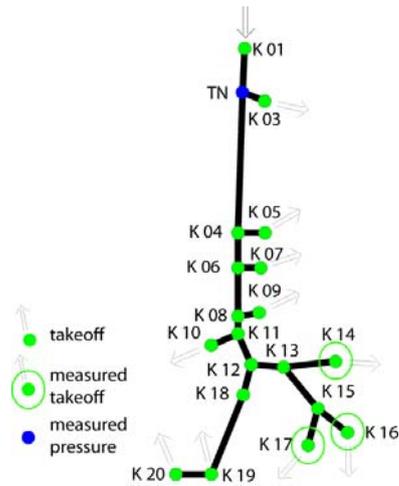


Fig. 2. Testing sector of the gas distribution grid

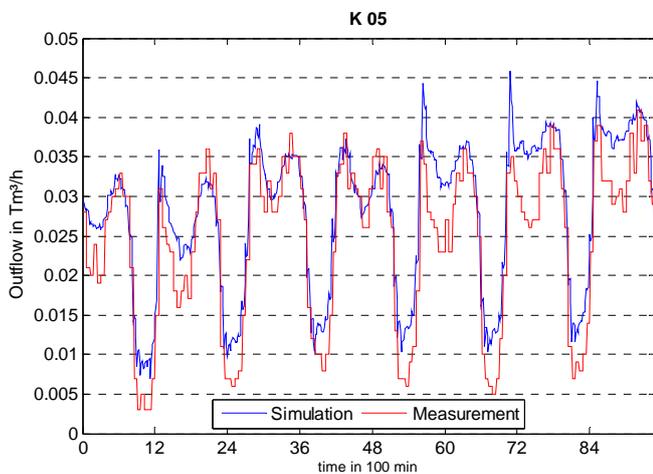


Fig. 3. Simulated and measured offtakes at node K 05

In the second step the completely instrumented distribution grid with 26 offtakes, of which 15 are assumed to be unmeasured, was simulated (Fig. 4). Also for this simulation the measured and the simulated offtake of one node are exemplarily shown in Fig. 5. One can see that the fluctuation is higher, but the developing of the offtake is reconstructed well too. At the beginning one can see a few runaway values in the simulation. That is the result of measuring errors in the pressure values at this time interval.

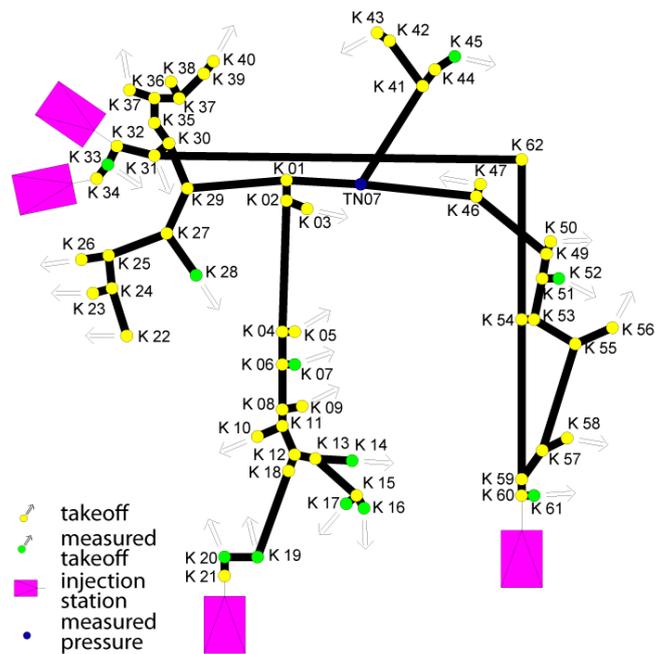


Fig. 4. Completely measured gas distribution grid

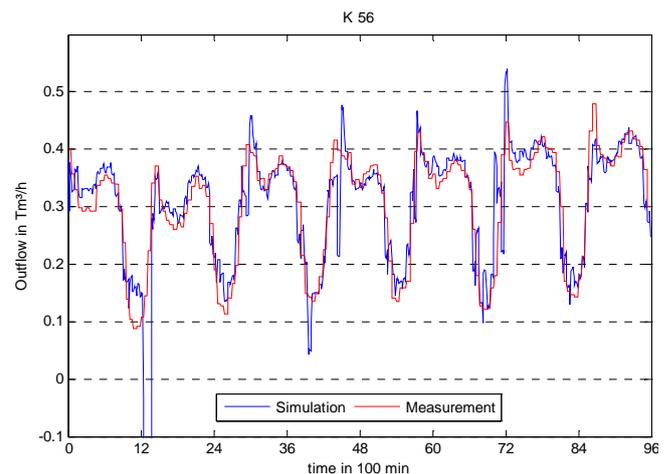


Fig. 5. Simulated and measured offtakes at node K 56

For coming closer to reality the larger grid (Fig. 6) was also simulated with this system. The difference to the previous simulations is that this grid is not completely measured. Because of that there is no direct possibility to control the simulated offtakes with measured values. For this it is necessary to install temporary measurements in the grid. These measurements are planned to be installed in winter 2011 / 2012.

Additionally to that a consistent set of fictive offtakes and pressures were constructed. These values are used instead of measured values. The benefit is that simulations with the large grid and these data can be made without waiting until the measurement infrastructure has been upgraded and the mobile measurements have been finished.

One simulated pressure at node TK07 compared with the “measured” value in a scenario where fifty percent of the offtakes are measured is shown in Fig. 7. One can see larger

differences at the beginning, which are becoming smaller over time. After about 3000 minutes both developing are close together. In contrast to the pressures the offtakes in this scenario are not so well reconstructed with the actual available version of the simulation tool for a grid of this size.

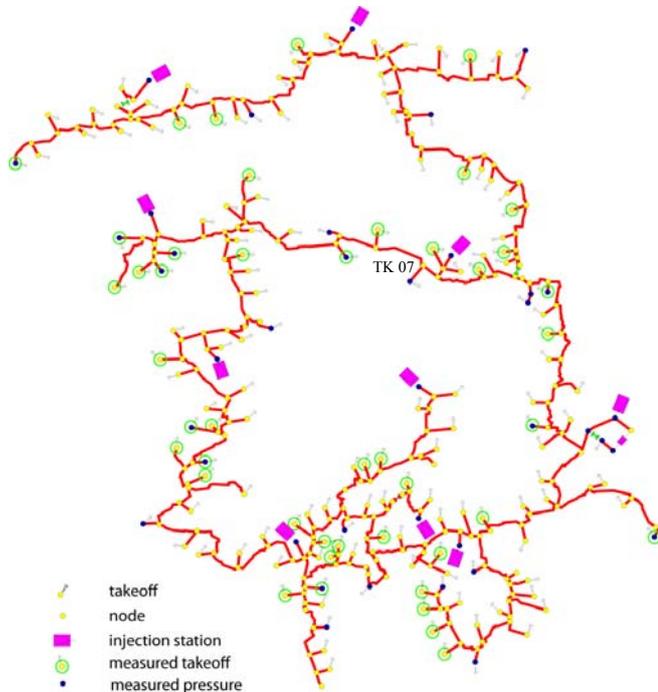


Fig. 6. Large gas distribution grid

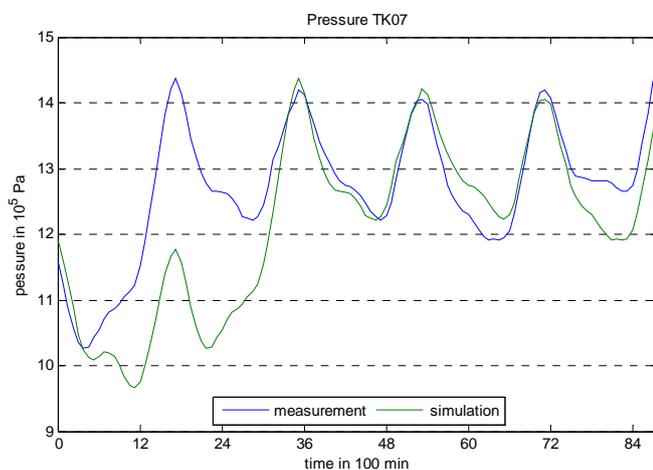


Fig. 7. Simulated and measured pressure at TK07

6. CONCLUSION

It was shown a method for simulating gas distribution grids with an incomplete measurement infrastructure. For replacing the unmeasured offtakes of the grid, the concept of the Nodal Point Load Observer and different methods for designing it were presented. In chapter 5 the evolution over time of the NPLO was shown with different simulation results, on different gas distribution grids with different difficulties for the simulation. The first simulations were made on a small and simple grid. In the second step the size

of the grid and with that the number of offtakes has been increased. And finally in the third step simulation results of a large and complex gas distribution grid were shown and discussed.

The simulations, especially the last one, show that there is still work to be done. In detail, it is necessary to improve the accuracy of the system by finding better methods for designing the matrices of the NPLO for large grids. The challenge at large grids are the differences of the pressures over the grid and with them the need of more than one pressure value for observer balancing, which brings various difficulties with it. Several methods for solving these difficulties have already been developed as in parts shown in chapter 4. It is now necessary to implement these in the software and to test them. For testing them the in chapter 5 contemplated fictive measurement values are available and in future values from temporary measurements should be available, too.

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Authors:

Dipl.-Ing. Torsten Hager, Energie-Forschungszentrum Niedersachsen, Am Stollen 19, 38640 Goslar, Germany, phone: +49 5323 72-3736, fax: +49 5323 72-2104, torsten.hager@efzn.de.

Dipl.-Ing. Abdelhamid Bentaleb, Institute of Electrical Power Engineering, Clausthal University of Technology, Leibnizstraße 28, 38678 Clausthal-Zellerfeld, Germany, phone: +49 5323 72-2593, fax: +49 5323 72-2104, abdelhamid.bentaleb@tu-clausthal.de.

Dr.-Ing. Ernst-August Wehrmann, Institute of Electrical Power Engineering, Clausthal University of Technology, Leibnizstraße 28, 38678 Clausthal-Zellerfeld, Germany, phone: +49 5323 72-2595, fax: +49 5323 72-2104, wehrmann@iee.tu-clausthal.de.

Prof. Dr.-Ing. Hans-Peter Beck, Energie-Forschungszentrum Niedersachsen, Am Stollen 19, 38640 Goslar, Germany, phone: +49 5321 3816 8001, vorsitzender@efzn.de.