XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

SIMULATION SYSTEM WITH CALORIFIC VALUE TRACKING FOR GAS DISTRIBUTION GRIDS WITH AN INCOMPLETE MEASUREMENT INFRASTRUCTURE

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Abstract: State of the art in the use of gas quality tracking systems for billing purposes are systems for transmission grids, where all inlets and rather all offtakes are measured. Such a complete measurement infrastructure is for most gas distribution networks very expensive and not feasible in practice. One promising approach for solving this challenge is the Nodal Point Load Observer, developed at Clausthal University of Technology, which emulates unknown offtakes, based on a mathematical model. This observation problem consists of an accurate determination of the inner state of incompletely instrumented natural gas distribution grids, based on the available measurement information. The knowledge of the inner state of the grid makes it possible to allocate a time series of a specific calorific value, and with that an amount of energy, to each offtake of the grid.

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

1. INTRODUCTION

The increasing number of biogas plants which feed in their biogas in the gas distribution grids leads to an increasing amount of propane and butane fed in the grid for holding the calorific value of the distributed gas. That is necessary for billing and because of the gas burners, which need a defined calorific value. Accordingly the costs for the gas consumers are rising, because they have to pay the propane and butane. Beside this, also the ecological balance of the biogas is affected negatively by the blending with propane and butane.

It should be the aim, also in conjunction with climate protection targets, to avoid the described blending. One approach for this is to track the injected calorific values with a simulation system. The challenge thereby is the simulation of the incompletely measured and highly intermeshed gas distribution grids, where not all offtake quantities are measured, but the most biogas plants feed in their gas. These grids could not be simulated with common simulation systems, because they require completely measured grids. Originally they were developed for completely measured gas transportation grids with in general a low degree of intermeshing. The solution for this challenge is the so called Nodal Point Load Observer (NPLO), developed at Clausthal University of Technology, which emulates the unmeasured offtakes and simulates with them the inner state of the gas grid. Knowing the inner state, that means the pressures at the nodes of the grid and the pipe flows, allows calculating the velocities. With the velocities and the calorific values at the inlets it is possible to track the calorific values in the grid.

The NPLO in its current version is an integrated system, in contrast to the first version described in [1], which was designed as an additional system on top of the classical grid observer. More details about the concept of the NPLO are given in chapter *2. Mathematical Models.* The basics about tracking of calorific values is given in chapter 3, before in chapter 4 different network topologies were described, which are used for testing the NPLO. In chapter 5 a method for identifying the, in conjunction with the simulation task, minimal necessary measurement infrastructure is shown. Following this in chapter 6 several simulation results and validations are presented, before finally in chapter 7 a conclusion and forecast is given.

2. MATHEMATICAL MODELS

First a mathematical model which describes the gas grid in an adequate accuracy and with a manageable complexity is needed. For simulating gas distribution grids the so called “long pipe model” fulfils these requirements, why it is used for the researches described in this article.

The pressures *p* and the pipe flows *q* in gas distribution grids are described by the long pipe model by the following differential equations.

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

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

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

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 found in [2], [3] and [4].

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

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

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

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 inner state of the system and minimises the deviation on this way.

In one of the common gas simulation tools (GANESI) it is done this way. In contrast to that, the NPLO leads the deviation between one highly accurate measured and the simulated pressure at one node back to the unmeasured offtakes in $\underline{u}$. Therefor the pressure difference has to be transformed in an amount of gas, which has to be divided. The transformation is done by the vector g_s, which is calculated in the following way:

$$\underline{g}_S = -\left[g^{TN}\cdot\frac{V_{TN}}{c_T^2(\hat{p}_{TN})} \right] \tag{6}$$

g^{TN}: weighting factor of the measured pressure value
V_{TN}: half of the volume of the connected pipes at node TN
c_T^2: isothermal sound propagation velocity

For dividing the amount of gas to the unmeasured offtakes, criteria are needed which do this correctly. They have to consider the temperatures near the offtake stations, the time of the year, the structure of the consumers, and the size of the offtake station. Additionally to this empirical data, also data from the grid, for example additional pressures, which are measured, should be considered. All this information is combined in matrix $\underline{L}$, which is called the "dividing matrix".

In the actual version of the NPLO the matrix $\underline{L}$ is calculated by load profiles (LP) in each time step in the following way:

$$\underline{L}_n = \frac{LP_{Kn}}{\sum LP} \tag{7}$$

By using the load profiles all the empirical data, as written above, are considered. Nevertheless there are no additional data from the grid included. Because of this it is worked on a method for calculating $\underline{L}$, based on the described method, which will additionally include measured pressures. The main Idea is that the differences between measured and simulated pressures (Δp) nearby the unmeasured offtakes should be used for manipulating the dividing matrix $\underline{L}$ to advance the simulation quality.

$$\Delta p = p_{measured} - \hat{p}_{simulated} \tag{8}$$

For supporting the NPLO an additional predictive control by load profiles at the unmeasured 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 of gas, which makes the simulation faster and in some cases more accurate. In Fig. 1 the complete system of the NPLO is shown as a block diagram.

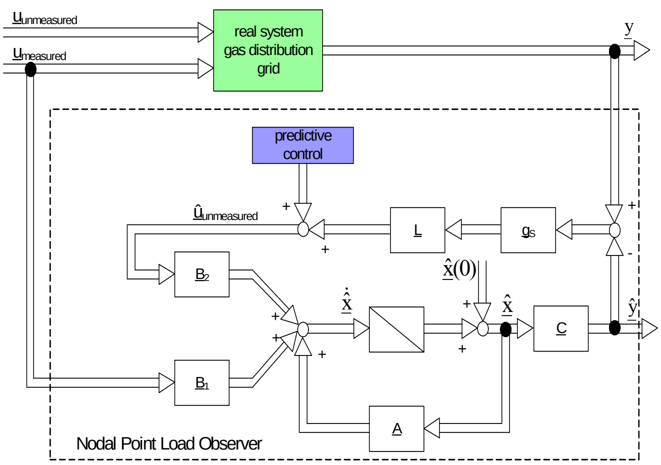

Fig. 1: New model of the Nodal Point Load Observer

3. CALORIFIC VALUE TRACKING

A gas quality, for example the calorific value, is defined as a gas property that is assumed to move at local fluid velocity through the network and mixes at connection points according to a specific rule - either mass mixing or mole mixing.

The mathematical problem which has to be solved is the 1-D transport equation:

$$\frac{\partial GB}{\partial t} + v(z,t)\frac{\partial GB}{\partial z} = 0 \qquad 0 \le z \le L, t \ge 0 \tag{8}$$

where GB is any gas quality and v is the fluid velocity. The quality equation solution is using an upwind finite difference equation which is outlined as follows:

$$\frac{GB_{k,n+1} - GB_{k,n}}{\Delta t_n} + \frac{GB_{k,n+1} - GB_{k-1,n+1}}{\Delta z_k} \cdot v_{k,n+1} = 0. \tag{9}$$

Where

$$GB_{k,n} = GB(z_k, t_n), v_{k,n+1} = v(z_k, t_{n+1}), \\ \Delta t_n = t_{n+1} - t_n \tag{10}$$

and

$$\Delta z_k = z_{k+1} - z_k \quad \text{for } k = 1 \ldots K \text{ pipes.} \tag{11}$$

If

$$\Delta GB_{k,n} = GB_{k,n+1} - GB_{k,n} \tag{12}$$

and

$$e_{k,n} = v_{k,n+1} \cdot \frac{\Delta t_n}{\Delta z_k} \tag{13}$$

the difference equation (9) can be rewritten as:

$$(1 + e_{k,n})\Delta GB_{k,n} - e_{k,n}\Delta GB_{k-1,n} = 0 \\ e_{k,n}(GB_{k-1,n} - GB_{k,n}) = 0 \tag{14}$$

The result is a system of K difference equations with K+1 unknowns ($\Delta GB_{0,n}, \ldots, \Delta GB_{K,n}$). As a boundary condition it can be assumed that the quality of the gas entering the pipe is known. Following $GB(z_k=0,t)$ would be a known function of time. Assuming $\Delta GB_{0,n}$ is known, the previous equation can be solved for the remaining unknowns in the following way:

$$\Delta GB_{k,n} = T_1 + \Delta GB_{0,n} \cdot T_2 \tag{15}$$

where T_1 and T_2 are constants which are calculated from the velocity vector.

The solution for the change in qualities at the nodes by considering a mass mixing is:

$$GB_{mix} = \frac{\sum_i GB_i \cdot q_i}{\sum_i q_i} \tag{16}$$

If the solution of the equations (15) and (16) is complete by means of a Gauss-Seidel iteration, the gas quality values in all pipes of the grid are found, if an affine map is used for each pipe.

4. NETWORK TOPOLOGIES

For testing the simulation system two real gas grids were used. One smaller but completely measured grid (grid 1; Fig. 2) and one large, highly intermeshed gas grid (grid 2; Fig. 3).

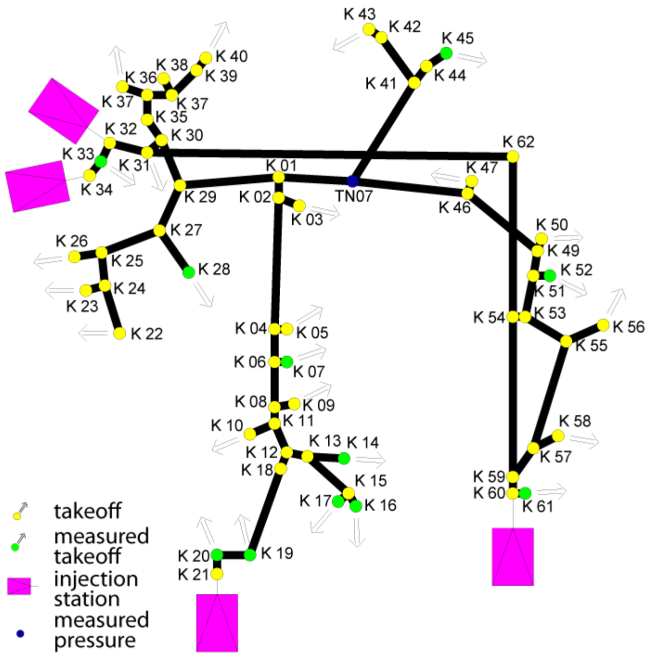

Fig. 2: Completely measured smaller gas distribution grid (grid 1)

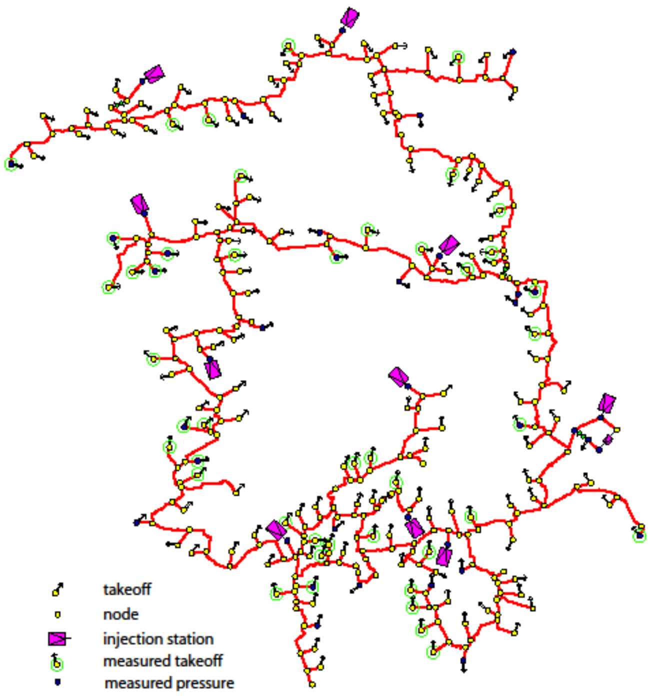

Fig. 3: Incompletely measured large gas distribution grid (grid 2)

The advantage of grid 1 is, because of the measured inlets and offtakes, the knowledge of all boundary conditions. This makes it possible to validate the results of the simulation, by just using a selection of the measured values (green nodes) as inputs for the simulation. All other offtakes are seen as unmeasured. Having the simulation results for these offtakes they could be validated with the measured values.

But this grid is not complex enough to make a general statement about the functionality and the accuracy of the NPLO. Because of that, a second, much more complex grid (grid 2) is needed. In contrast to grid 1 it is not possible in grid 2 to validate the results directly with measured values. For validating the NPLO it is necessary to measure calorific values at some offtakes, what has to be done with mobile systems. This is a proven and accepted method. Because of the high number of inlets and offtakes a lot of data have to be handled, what is the main disadvantage of grid 2.

Because of the described advantages and disadvantages both grids are used for testing and validation of the simulation system. More details about the grids are shown in table 1.

Table 1: Grid parameters

	grid 1	grid 2
Injections	4	11
Offtakes all	26	173
Offtakes measured	26	38
Pipes	64	371
Nodes	63	372
Volume	2,903 m³	34,925 m³

5. METROLOGICAL INFRASTRUCTURE

The quality of the simulations with the NPLO is mainly affected by the measured values. A precondition for the NPLO is, that all injections and one pressure are measured. Beside this a minimum number of offtakes have to be measured. To keep this number small it is important to know, which offtakes have a large influence to the inner state of the grid and which have not. Therefor a method, combining empirical and mathematical parameters, was developed.

The result of the empirical methods is that the following offtakes have necessarily to be measured

- via subsidiary gas grids connected offtakes (n-1)

and that the following offtakes are recommended to be measured

- more than 25 % unmeasured industrial customers
- homogeneous allocation of the measurements in the grid.

Additionally an empirical weighting coefficient is calculated, considering the amount of gas at each offtake and the structure of the customers. Together with mathematical researches, in detail with the Benninger criterion for a representative inner state of the grid, and with a maximum number of additional offtakes (regulated by a financial budget), a minimal measurement infrastructure could be found. In Fig. 4 the complete process is shown in a flow diagram.

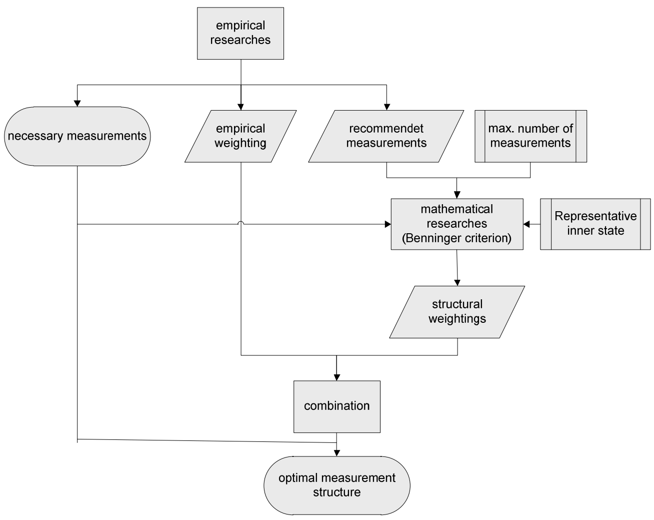

Fig. 4: Flow diagram of the finding process of an optimal measurement infrastructure

For proving this method it was adopted at grid 1 with a test configuration. The details about the installed measurements and the recommended measurements are shown in Table 2, together with the 5 most optimal additional measurement configurations, by a maximum number of 4 additional measurements. The result is, that the offtakes K03, K31, K37 and K56 should be measured additionally to the already measured offtakes. For checking the results, several simulations at different times were done. The results (Relative Mean Fault over all offtakes) are shown in Table 3. The mean faults are all close together, but measurement infrastructure 1 doesn't have the smallest fault. It shows, that the described method can just give an idea where should be measured, but it is impossible to find an optimal measurement infrastructure for all states in the grid. Especially fluctuations over the year in the injections and offtakes couldn't be considered by such a method.

Table 2: Identified optimal measurement configuration

Installed measurements	K07, K17, K19, K20, K28, K33, K45,K52,K61	Evaluation parameter
Recommended measurements	K03, K09, K14,K16, K22, K26, K31, K37, K43, K47, K56	-
Configuration 1	K03, K31, K37, K56	101,44
Configuration 2	K16, K31, K37, K56	99,66
Configuration 3	K31, K37, K43, K56	98,06
Configuration 4	K09, K31, K37, K56	97,69
Configuration 5	K22, K31, K37, K56	96,42

Table 3: Simulation results for two periods

	06.12.07 – 13.12.07	**31.01.07 – 07.02.07**
Configuration 1	8.81 %	8.35 %
Configuration 2	9.71 %	6.37 %
Configuration 3	8.00 %	7.68 %
Configuration 4	8.96 %	8.48 %
Configuration 5	8.68 %	8.13 %

6. SIMULATION RESULTS AND VALIDATION

For testing and evaluating the NPLO several simulations at the two in chapter 4 described grids were made. In this chapter is just a selection of these shown, which represents the general quality of all simulations.

Fig. 5 compares the measured and the simulated offtake at node K 56 in grid 1. The mean relative fault at this offtake is 3.55 %, what emphasises the high accuracy of the simulation at the small grid 1. Compared to this shows Fig.6 the simulation results at node GT11 in grid 2. This simulation was made with synthetic measurement values, which were generated for all offtakes by falsifying load profiles. As a result simulations could be made without using the synthetic measurements as inputs and finally the simulated offtakes could be compared with them (blue line). In Fig. 6 also the simulation results in the larger grid 2 seem to be relatively good. The relative mean fault at this offtake is 12.1 %. On the first view this seems not to be so good, but in relation to the size of the grid it is a quite good value, which is accurate enough for controlling the grid. For calculating the calorific value for billing mean values over the month are relevant. In this context a mean fault in the dimension of 12 % in the hourly values is absolutely in range.

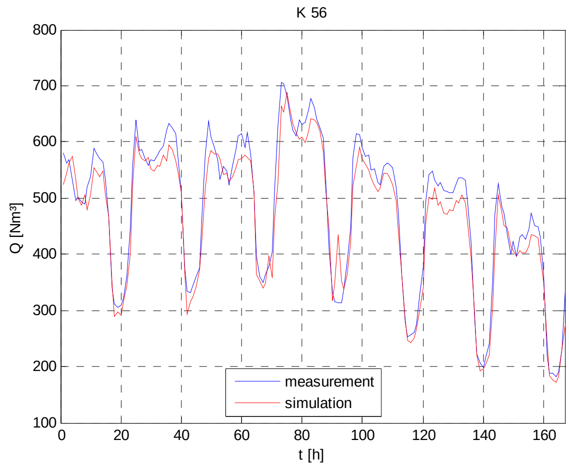

Fig. 5: Comparison measured and simulated offtake at K 56 in grid 1

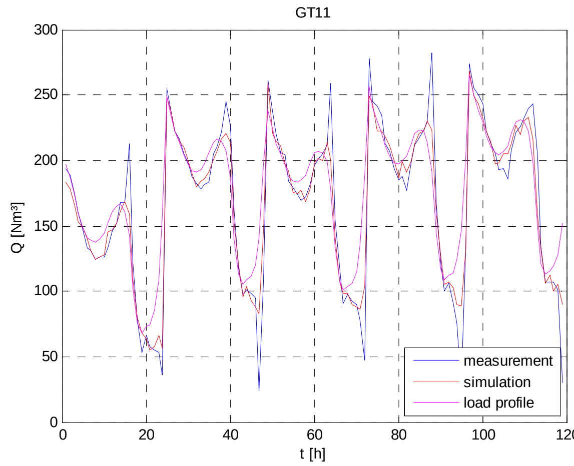

Fig. 6: Comparison measured, simulated offtake and load profile at GT11

7. 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 was presented. In chapter 3 the methods for tracking calorific values were described. By implementing such a simulation system a lot of energy for conditioning biogas could be saved. After presenting two gas distribution grids in chapter 4, a method to identify an optimal measurement infrastructure in the context of gas grid simulation with the NPLO was described in chapter 5. Finally an overview of different simulation results and their quality was given. These results show that the NPLO is on a good way to become a suitable system for simulating gas distribution grids with an incomplete measurement infrastructure. But it is also shown, that in some details still work has to be done. Especially the algorithm for designing the dividing matrix $\underline{L}$ has, as described, to be improved and tested. It is also necessary to evaluate the system with real measurements at grid 2, what is already planned.

After these evaluations, the simulation system has to be implemented in a commercial software tool with the necessary database connections.

8. REFERENCES

[1] C. Schröder, “Process integrated simulation for regional gas distribution grids with incomplete measurement infrastructures by using a Nodal Point Load Observer”, “Prozessbegleitende Simulation von regionalen Gasverteilnetzen mit unvollständiger Messinfrastruktur durch Einsatz eines Knotenlastbeobachters”, dissertation, Clausthal University of Technology, 2009.

[2] A. Weimann, “Modelling and simulation of the dynamic of gas distribution grids regarding gas grid control and monitoring”, “Modellierung und Simulation der Dynamik von Gasverteilnetzen im Hinblick auf Gasnetzführung und Gasnetzüberwachung”, dissertation, Technische Universität München, 1978.

[3] G. Lappus, “Analysis and synthesis of a state observer for gas distribution grids”, ”Analyse und Synthese eines Zustandsbeobachters für große Gasverteilnetze”, dissertation, Technische Universität München, 1984.

[4] D. Vollmer, “A contribution to accompanying state reconstruction in regional gas distribution grids”, “Ein Beitrag zur prozessbegleitenden Zustandsbeobachtung in regionalen Erdgasverteilnetzen”, dissertation, Clausthal University of Technology, 1999.

[5] J Lunze: “Control Theory 1”, “Regelungstechnik 1”, Springer, 2008.