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Thermal-Network Simulations and Computational Fluid Dynamics for Effective Gas Leakage Detection in SF_6 Switchgear

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SUMMARY

Among the many reasons for the failure of high-voltage apparatus, the knowledge about a possible leakage of SF_6 gas in the switchgear encapsulation is of crucial importance. It is therefore necessary to monitor the SF_6 gas to increase system reliability and to address the concerns of growing environmental awareness.

The measurement of small leakage rates is not trivial. As generally known, gas density measurements in SF_6 switchgear show substantial fluctuations over time. Such fluctuations are originated in non-uniform and time-varying temperature distribution. This complicates the detection of small gas leakages. Therefore a two-level model is suggested in order to filter the density readings. The first level of the model is a thermal-network of the switchgear which calculates the temperature distribution along the surface of the vessel. The second level is a simulation by means of computational fluid dynamics (CFD). It calculates the heat transmission by conduction and gas flow. This leads to the density distribution and therefore to the density fluctuation at a certain position in the gas. By comparing both, model output and measurement, the leakage rate is obtained.

By applying the filtering based on this model there is a significant reduction of fluctuation and therefore an important improvement of detection of small leakages. Furthermore it is also suited to determine accurately the yearly rate of leakage.

KEYWORDS

Switchgear, sulphur hexafluoride, leakage, monitoring, thermal-network, computational fluid dynamics

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1. INTRODUCTION

Modern switchgear often contain sulphur hexafluoride gas (SF_6). This gas is the insulating and arc quenching medium. The arc quenching properties are a function of gas density and become worse with lower density. A minimum gas density must be maintained in order to guarantee a successful switching operation in case of an incident. A survey conducted by CIGRÉ [1] shows that 40 % of minor faults and 7 % of major faults are due to gas leakages in SF_6 circuit breakers. The careful monitoring of the gas density is suggested by the authors to maintain a high reliability and availability of the switchgear.

Another reason to detect gas leakages at a very early state is to reduce the amount of SF_6 release to the atmosphere. SF_6 is a strong greenhouse gas which is ratified in the Kyoto protocol [2]. According to IEC, standardized relative leakage rates for high-voltage circuit breakers are 1% and 3% per year [3]. However, there is only little information available to detect small leakage rates.

In order to be able to detect even very small gas leakages the measured quantity should be well chosen. There are mainly four key features which need to be considered: The correlation with the rate of leakage, the accuracy of available sensors, the insensitivity to disturbances and the independency of the position of the sensor. To the author's knowledge there is no sensor available which fulfils all four requirements. Therefore a compromise needs to be found. Often the measurement of gas density is chosen.

The measurement of small leakage rates is not trivial. Density readings show significant daily and seasonal fluctuations. The reason is the non-uniform and time-varying temperature distribution of the gas, caused by ohmic heating of the current conducting elements of the switchgear and by environmental conditions. Assuming an ideal gas with a uniform pressure distribution p. Furthermore, the gas volume V is assumed to be constant over time [4]. It can be shown that the density distribution ρ is inverse proportional to the temperature distribution T (Eq. 1). M is the molar mass, n the amount of substance and R the universal gas constant.

$$\rho = \frac{\mathrm{d}m}{\mathrm{d}V} = M \cdot \frac{\mathrm{d}n}{\mathrm{d}V} = M \cdot \frac{p}{R \cdot T} \Rightarrow \rho \sim T^{-1}$$

$$\text{with} \quad \mathrm{d}m = M \cdot \mathrm{d}n \quad \text{and} \quad \mathrm{d}n = \frac{p}{R \cdot T} \cdot \mathrm{d}V \qquad \textbf{(Eq. 1)}$$

Generally the density distribution is not constant but a function of external and internal heat sources which are time-varying. Therefore the sensor reading at a certain location in the gas vessel shows significant fluctuations. These fluctuations are in the range of up to several percents of the nominal gas density [5].

2. FILTERING THE SENSOR READINGS

2.1 Statistical Trend Analysis

In order to detect small leakages and to measure the yearly rate of leakage, filter techniques for the sensor signal become a inevitable task. Appropriate algorithms need to consider an instationary behaviour of the time series while still removing daily and seasonal variations. There are mainly two approaches to remove the deterministic fluctuations from the signal. In statistical filter techniques, mathematical models reduce the noise in a way that the moving average of the signal is performed. One possible approach is polynomial regression [6]. In this method the algorithm fits the time series by means of a polynomial function while maintaining a least square condition. This intuitive method is suited to find long-term trends for non-seasonal data. This implies a preconditioning of the density data to remove seasonal variation. As long as there are periodic components in the time series included, forecast of future data is useless.

There is a wide variety of promising, more sophisticated filtering methods like Holt-Winters method [6] or Autoregressive Integrated Moving Average (ARIMA, [6]) to mention only two.

2.2 Model Based Filtering

To the authors' opinion, filter methods which are based on physical knowledge of the distribution and fluctuation of temperature have intrinsic advantage over statistical methods. While the statistical approach only analyses the data, a physical approach considers environmental impacts and the inner state of the situation.

The quintessence of this filtering method is a computational model which calculates the expected density distribution in the gas domain of the switchgear (Fig. 1). The difference between the model prediction and the measured value is the leakage component (plus fluctuations of non-modelled effects) in the measured gas density signal. The input parameters for the model are load current, intensity and direction of solar radiation and ambient temperature. In order to maintain these input parameters some additional sensors are needed. The authors regard this as a task with minor cost impact since they are all external.

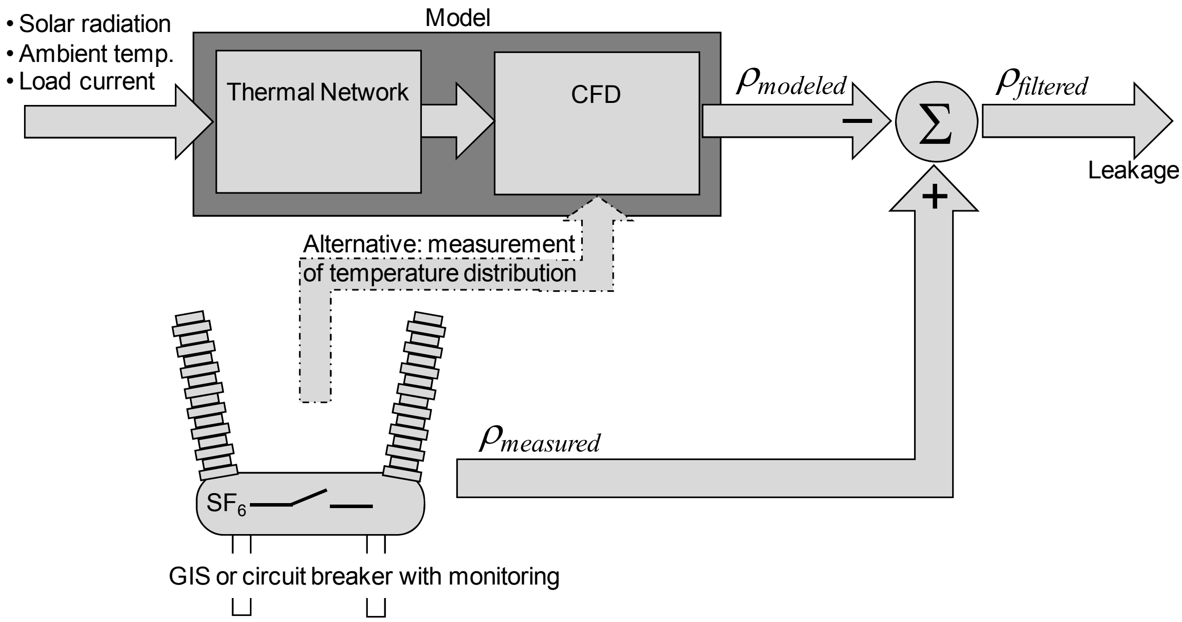

Fig. 1 : Principle of model based filtering

The model consists of two parts. The thermal network model calculates the boundary temperature distribution i.e. the temperature of the solid parts. The calculation of the transient gas temperature distribution is part of the Computational Fluid Dynamics (CFD) model. Instead of the use of a thermal-network model, the temperature distribution on the solid parts could origin from a measurement. They could be fed into the CFD model directly (dashed arrow in Fig. 1). This approach might be suitable for laboratory purposes but in a real substation the addition of several thermocouples to dead and life parts of the switchgear are generally disadvantageous.

3. MODEL OF A GIS BUS-BAR ELEMENT

3.1 Thermal Network Model

The thermal network approach is based on the similarity between the electrical and the thermal field. E.g. all heat transferring processes can be formed as thermal resistances. The network is then built up with heat sources, thermal resistances, thermal capacities (in case of a dynamic model) and thermal potentials. For a high accuracy of the calculated results, the knowledge of the direction and type of the gas flow is required. Also the components which are able to interact with each other have to be known.

The constructed thermal network of the horizontal GIS test object is based on a hierarchical approach and is divided into several layers. The layers are connected to each other to transfer the heat from specific sources to the environment. The highest layer shows the different parts of the test object (modules) and therefore the whole system (Fig. 2). That includes the two main bus-bar elements in the centre of the model, the short circuit on the one side and the input on the other side. The layers below the top layer include the real network of the encapsulation and the conductor.

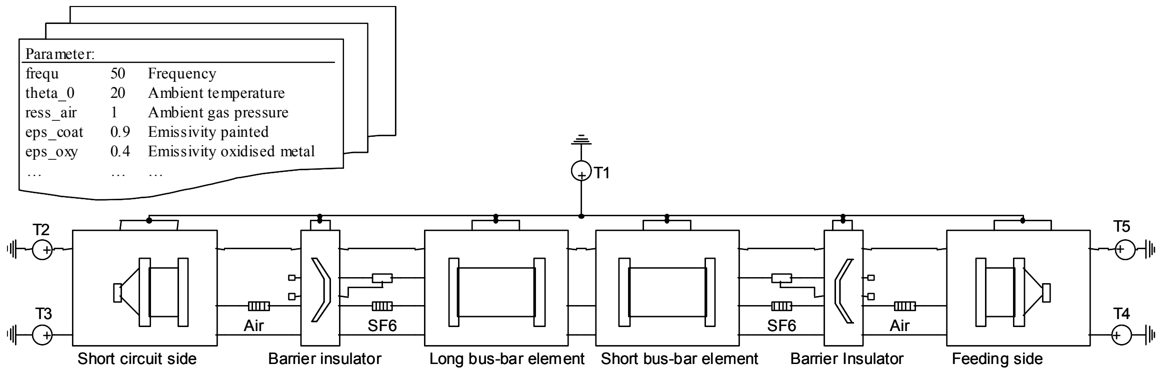

Fig. 2 : Hierarchical thermal network of the GIS test object

The heat sources are mainly sources from electrical current. The electrical current is variable to perform several calculations in short time. In order to maintain the temperature depending character of the heat sources, the material constant for the temperature-dependant electrical resistance is added. The electrical current is forced to flow through the encapsulation and the conductor, so that all sections include two heat sources. The expected high temperature and pressure of the SF_6 lead to a turbulent flow. This means, the gas flow detaches from the hot surfaces very quickly and creates vortices. The transfer of heat becomes more efficient. The gas flow from the outside of the capsule (air) is laminar [8]. The short circuit between the inner conductor and the encapsulation is generated by copper bars. They are directly connected to the GIS-components. A large amount of heat is conducted from the conductor to the encapsulation via these copper bars. The feeding high current transformer is connected to the bus-bar via copper connectors. The temperatures at both ends of the GIS test object in the thermal network were assumed to be constant.

In order to verify thermal networks, the computational results have to be compared with results from measurements. In the past several thermal networks for GIS components were developed and verified by comparison with measurement from appropriate components [9].

3.2 Computational Fluid Dynamics Model

There are basically three principles of heat transportation inside the SF_6 domain: heat transfer, convection and radiation. The radiation can be neglected because of the absorption spectrum of SF_6 in the thermal region. In order to solve the coupled heat transfer and fluid flow problem a Computational Fluid Dynamics (CFD) approach was chosen.

ANSYS CFX 11 was selected among many different commercially available CFD packages because of its wide field of application, the fast and memory-efficient finite volume solver algorithm and the ability to create structured hexahedral meshes of high quality.

The problem has been reduced to one fluid domain in form of a two dimensional disc of SF_6 gas (Fig. 3, left). This was done because of the very little geometric variation of the test object along the long axis. It is expected that for a more complex apparatus like a switching chamber of a circuit-breaker, the whole three dimensional gas domain needs to be modelled. The boundary condition is the temperature distribution along the surface of the fluid domain. This simplifies the model. However, if the power of ohmic heating is assumed to be the boundary condition, the heat transfer from the gas compartment to ambient needs to be properly implemented. This needs to model not only the aluminum parts but also the surrounding air. Such an approach was not tested yet.

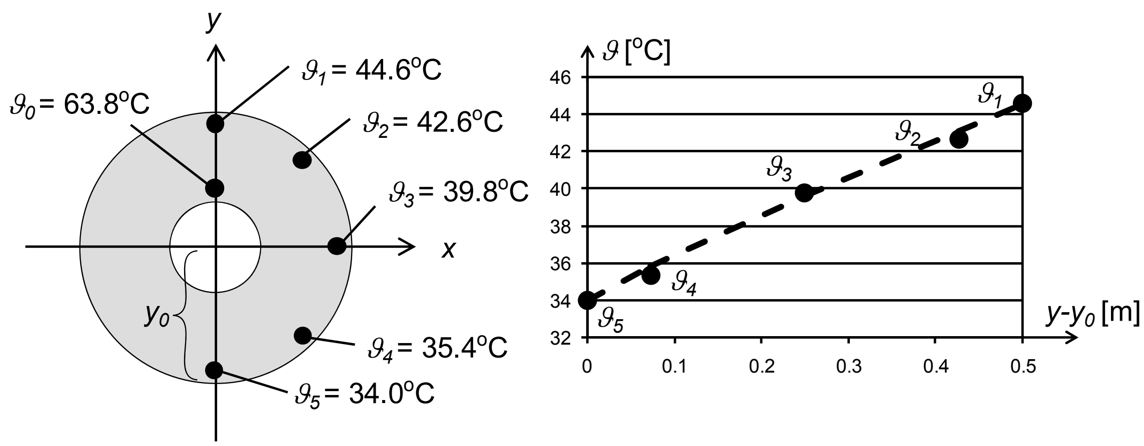

Fig. 3 : Temperature boundary conditions

The boundary temperature distribution needs to be approximated by the calculated or measured temperature potentials. Here, the temperature ϑ is known at five positions ($\vartheta_1 \ldots \vartheta_5$) along the outer circumference of the encapsulation. Since the CFD simulation needs a continuously differentiable mathematical function, the approximation by a third order polynomial was chosen (Eq. 2). The inner conductor has by good approximation a constant temperature along its circumference.

$$\vartheta_{approx}(y) = \sum_{n=0}^{3} \alpha_n \cdot (y - y_0)^n \qquad \text{with} \quad \begin{cases} \alpha_0 = 34.0°\text{C} \\ \alpha_1 = 26.3°\text{C/m} \\ \alpha_2 = -21.0°\text{C/m}^2 \\ \alpha_3 = 21.3°\text{C/m}^3 \end{cases} \qquad \textbf{(Eq. 2)}$$

In order to get accurate results, the gas properties must be well defined. For this purpose it was assumed that the gas is calorically ideal but with temperature dependent parameters which are taken from National Institute of Standards and Technology (NIST) [10]. For the correct calculation of convection, the set of equations must allow the gas to be compressible and the gravity needs to be defined.

For such a problem the existence of a stationary solution is not always guaranteed. In the area above the inner conductor an oscillating gas vane can appear if the temperature distribution is inverse to the direction of gravity. This phenomenon is referred in the literature as the Bénard Problem [11]. Therefore a rough transient simulation for a load current step from 0 kA to 4 kA as shown in Fig. 5 (bottom) was calculated. The computational effort for such a transient calculation should not be underestimated. On a 64 bit desktop computer the simulation time for nine hours of gas flow was around 34 days.

4. TEST SETUP

In our high voltage laboratory a test setup for gas leakage research has been developed. It consists of several commercially available GIS elements of 0.6 m outer diameter. The main part is a 2 m bus-bar segment (Fig. 4). On one side, the inner conductor is short circuited with the encapsulation. On the other side a computer controlled low voltage transformer injects continuous AC current of up to 4 kA. Inside the vessel are several sensors for temperature, pressure and density of which only three density sensors (A, B, C) are shown in the figure. The sensors were used to test the computational model.

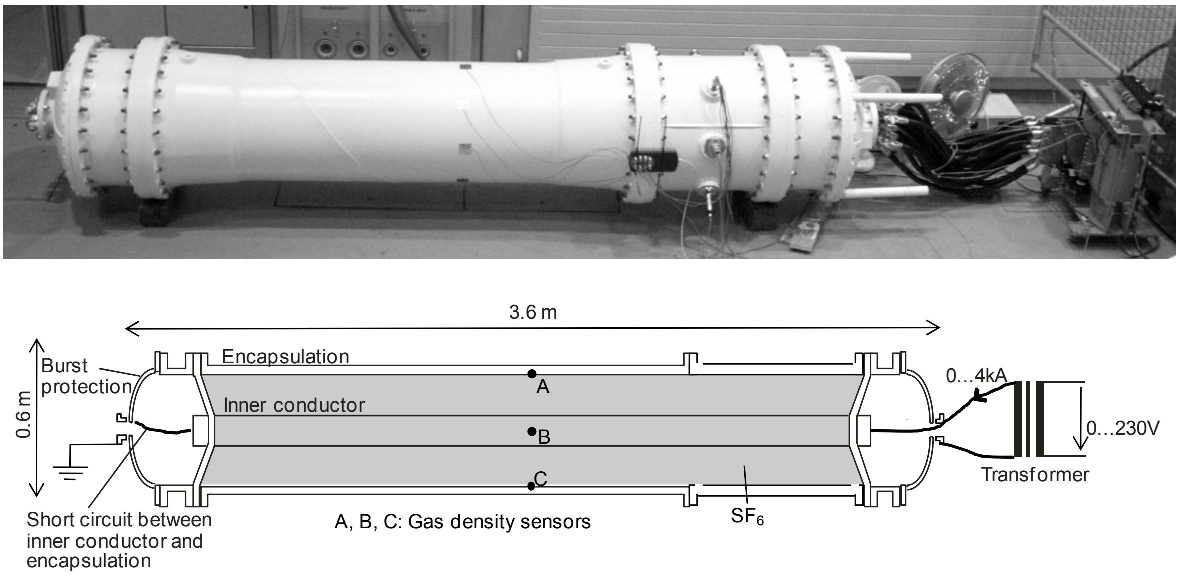

Fig. 4 : GIS test setup (shaded zone: SF_6 gas)

Besides the ohmic heating from load current, solar radiation has a considerable impact on the gas density distribution. Therefore a radiation source is also part of the test setup. This option is not in the scope of this paper. More information in this regard can be found in [7].

In order to have a well reproducible test case, a load current step function was applied to the test setup. At time t = 0 the current changes from 0 A to 4000 A RMS (Fig. 5 below). It is regulated with a tolerance of ± 20 A. At time t = 9 h the current changes back to 0 A for a period of 15 hours. The measurement ends at that time. The behaviour of the density (Fig. 5 top) at the three positions top, side and bottom are plotted during 24 hours. They are normalized to 100 % at t = 0.

After around 4 to 5 hours the density values stabilize at constant values which are significantly different from 100 %. At the bottom position the highest fluctuation of around + 4.4 % appears. Additionally an unexpected behaviour of density readings is clearly visible at the top and side position: These values increase during the first half hour before they fall below the 100 % level. A similar effect but with the other sign is visible after exactly 9 hours when the current suddenly drops to zero.

Such a measurement is not only suitable for testing the performance of the computational model but also delivers directly valuable information, e.g. a recommendation for the best sensor position: The sensor at the side position shows readings with very little fluctuations. Although this might be a good solution for the special case of a horizontal bus-bar, it cannot be generalized to all kind of SF_6 filled gas compartments. In case of a (vertical) bushing it might be difficult to place the sensor somewhere else than at the grounded bottom part to mention just one example.

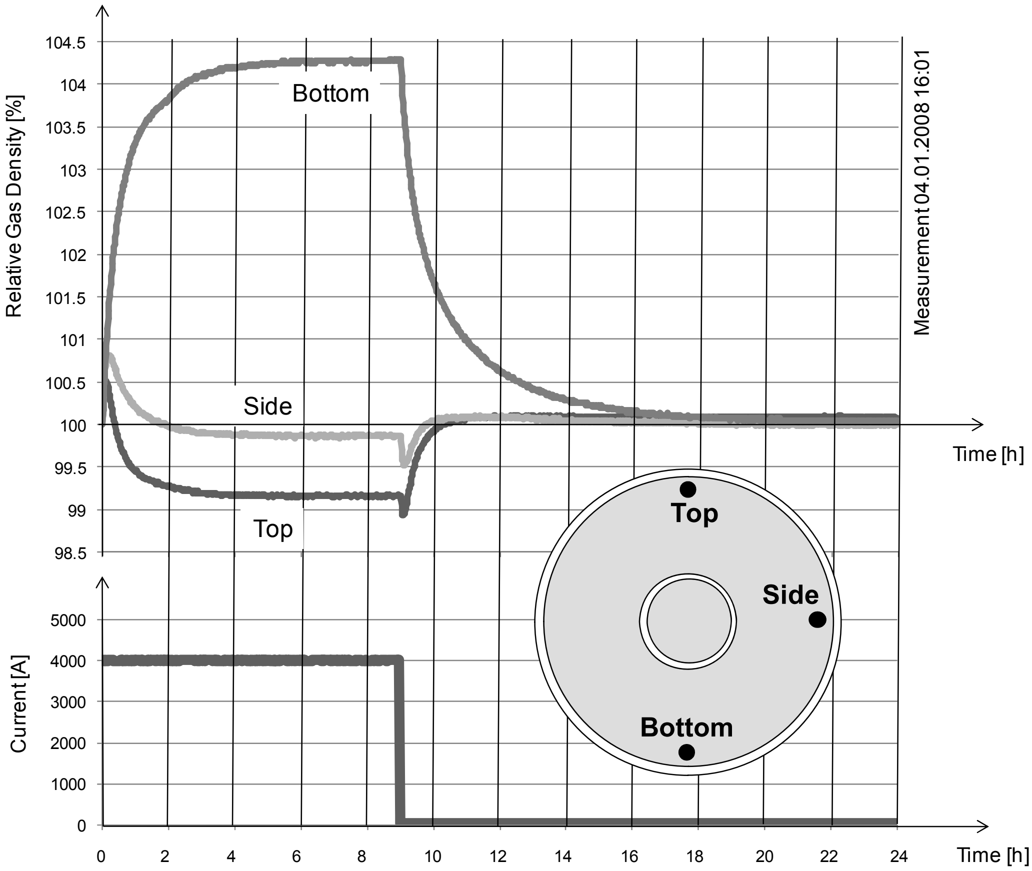

Fig. 5 : Density measurement at three positions (top) and load current (bottom)

5. DISCUSSION OF RESULTS

The results from the stationary model are compared with the density measurements at the three locations at t = 9 h (Table I). The performance of the model based filtering is shown in the last two columns. Without a filtering algorithm at all, density fluctuations of up to 4.4 % could be measured. Such fluctuations are reduced to 0.7 % by application of the model based filtering algorithm. This corresponds to a filter effect of -16 dB.

Table I: Relative density measurement and simulation

Sensor position	Measurement	Simulation	Fluctuation without model	Fluctuation with model
Top	99.1 %	98.9 %	- 0.9 %	+ 0.2 %
Side	99.9 %	99.4 %	- 0.1 %	+ 0.5 %
Bottom	104.4 %	103.7 %	+ 4.4 %	+ 0.7 %

This difference of up to 0.7 % between measurement and simulation is expected to be due to imprecision of the temperature boundary conditions. Little changes of e.g. $\Delta\vartheta$ = 1 °C can have an influence of several ‰ to the simulated density at a certain location. Such imprecision can be caused by errors in conjunction with the measurement of the boundary temperature, errors in the thermal network or its boundary conditions or by a bad polynomial fitting function for the temperature distribution (Eq. 2).

6. CONCLUSION AND OUTLOOK

Early detection of small gas leakages and accurate measurement of a yearly leakage rate is not an easy task. Sensors of necessary precision are available but the signal shows significant noise caused by sensitivity to mean gas temperature and to the exact distribution of temperature. Therefore a two-level model was proposed to filter the signal from such deterministic disturbances.

It was shown, that such a model-based filter can reduce the density fluctuations at the position with highest fluctuation from originally 4.4 % to 0.7 %. This is expected to reduce the time to detect a leakage by around the same factor. A density measurement signal treated in this way also allows to measure more precisely the yearly leakage rate.

A drawback of the proposed method is substantial computational power to perform the necessary CFD calculations. Especially if all gas compartments in a substation need to be monitored the computational effort is exceeding the capabilities of standard personal computers. Having said that, it is merely a question of time until computer power increases to a level that any standard personal computer is able to handle such a calculation in a reasonable time.

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