SF₆ Gas Monitoring and Leakage Detection in Gas Insulated Switchgear

R. Paul Barnett, P.E.
Jeffrey H. Nelson, P.E.
Power System Operations, Substation Projects
Tennessee Valley Authority
Chattanooga, TN USA
rpbarnett@tva.gov, jhnelson@tva.gov

Abstract—For new installations of 500-kV gas insulated switchgear (GIS) at the Pin Hook, TN USA 500-kV Substation and the Maury, TN USA 500-kV Substation, the Tennessee Valley Authority (TVA) chose to install an advanced SF₆ gas monitoring system (GMS). This paper will discuss specifics of the GMS and how its use simplifies identification of leaking sections, facilitates planned outages for repair or replacement, and ultimately increases the availability and reliability of the equipment.

I. INTRODUCTION

Expectations of power system equipment today are high availability, high reliability, and low total life cycle costs. Limited resources require information to make intelligent decisions on operation and maintenance of equipment. Consideration of condition based monitoring has become part of equipment life cycle evaluations for many utilities. The Tennessee Valley Authority (TVA) was no exception when considering new installations of 500-kV GIS for the Pin Hook, TN USA 500-kV Substation and the Maury, TN USA 500-kV Substation.

In general, industry data show that the failure rate of gas insulated switchgear (GIS) components such as the circuit breaker, disconnecting switch, and voltage transformer are less than for air insulated switchgear (AIS), mainly due to the enclosed nature of the GIS equipment and immunity from environmental and other external factors [1].

The report on the second international survey on high voltage GIS confirmed, in general, the increasing reliability of newer GIS [2]. A large portion, 88%, of the total GIS installations reported on had not yet experienced a major failure. Installations with more than 5 failures were only 1% of the total population. About 20% of failures occurred in the first year of GIS service. The failure frequency of the total population, excluding one user who operated very old and unique GIS, was 0.52 failures per 100 circuit breaker bay years. A comparison in [2] shows this was a decrease from the first GIS experience survey which reported an overall frequency of 0.98 failures per 100 circuit breaker bay years.

After many years of service, the data indicates that modern generations of GIS need less maintenance and allow longer service periods before major inspections are required (see Figure 1) [1]. Of course, the ability to extend service periods depends on actual in-service conditions. Based on these expectations, TVA decided not to employ a full condition based monitoring system in the 500-kV GIS for these applications. However, further consideration was given to monitoring of the SF₆ gas system.

In analyzing the total failures, generally, manufacturing (30%) and design (18%) imperfections are identified as the main causes of the problems. Of the total reported major failures in [2], over 21% were associated with the busducts, interconnecting parts, or the SF₆/Air bushing. In identifying the sub-assembly or component responsible for these failures, approximately 26% of busduct/interconnection failures and 50% of SF₆/Air bushing failures were related to gas insulation and sealing issues.

Low gas pressure and density can affect dielectric and fault interrupting capabilities. The loss of SF₆ gas itself was
indicated as a failure symptom in 7.6% of the total failures. The most frequent responsible component of these failures was the SF$_6$ sealing, about 60% of the cases. In general, 50% of the GIS installations reported SF$_6$ leakages less than 0.5%, and almost 89% were less than 1%. Most manufacturers today will guarantee a maximum annual leakage rate of at least 0.5%. Though consider that if all the separate gas zones within an installation had an annual leakage rate of 0.5% per zone, over 50 years it would result in the loss of 25% of the total mass of SF$_6$ in the installation.

In addition to dielectric and circuit breaker interrupting capability concerns with low gas pressure and density there is also the environmental issue of releasing SF$_6$ gas into the atmosphere. The United States Environmental Protection Agency (EPA), and other groups worldwide, has identified SF$_6$ as a greenhouse gas. It has been documented that its presence in the atmosphere would make contribution to the so-called radiative infrared forcing [3], which quantifies the net change in the infrared heat flux and the associated global warming [4]. However, the contribution of SF$_6$ to overall radiative forcing has been estimated to be less than 0.1% of the combined effect of anthropogenic greenhouse gases [3].

In any event, in the 1990’s the EPA initiated a voluntary compliance program with several electric utilities to monitor SF$_6$ gas use and leakage in an effort to control the amount of SF$_6$ released into the environment. Similar adoptions of volunteer actions and environmental regulations have happened worldwide. The EPA requirements became mandatory in 2010 [5].

Ultimately, consideration of the volume of gas in a 500-kV GIS installation, experience with a previous generation of GIS, and the EPA voluntary compliance program for tracking SF$_6$ usage at the time played a significant role in TVA’s decision to employ an advanced GMS.

II. GAS MONITORING SYSTEM (GMS)

A. Gas Monitoring Devices

Independent gas density monitoring is provided for each individual gas zone for each phase. The gas density in each zone is continuously monitored by density sensors which on reaching preset limits trigger the corresponding alarms. The density sensor monitors the true density of the insulating gas in a gas zone by comparing it with density of the same gas in a closed space on the sensor.

The sensors then transmit the values in a continuous stream of distinctive current pulses, the frequency of which depends exclusively on the monitored gas density, to the density sensor interface (DSIF) installed in the local control cabinet (LCC) of the GIS bay (see Figure 2). The DSIF is an electronic device that processes the data and provides the sensors with the necessary supply voltage. Based on the measured frequency the DSIF calculates the associated gas density value for each zone.

The DSIF can be set with two limit values, density warning and density alarm, for each sensor individually. The device continuously compares the actual values against the limit values and transmits a signal if any density value drops below one of the limits.

B. Visualization and Trending

The DSIF sends the gas density data to a central computer workstation that processes and visualizes the data. The purpose of visualization is to represent any important data from the density sensors in a clear form. While the manufacturer can provide a visualization program, TVA utilized software it currently uses for local station control display in the substation. In graphical form it can display the entire station configuration or give an overview of a single circuit breaker bay (see Figure 3). Red bars on the gas single line indicate the barrier insulators separating different gas zones and each zone is labeled (G01, G02...G12, etc.). The gas density and temperature are displayed for each phase and an alert in red appears below the actual values when the warning and/or alarm levels are reached. The gas warning and alarm limit values for each gas zone are displayed above the actual values for reference.

The gas density data is also processed to determine the rate of gas loss for each zone. This leakage rate can then be graphically displayed over different time periods (e.g. 1 week, 1 month, 1 year, etc.) for trending analysis (see Figure 4). This trending will indicate if there is slow leak or if there is a fast leak which needs to be addressed quickly.

Overall the GMS provides valuable information on the gas pressure and density of each gas zone, allows maintenance personnel to pinpoint the specific phase and zone of any gas leakage problem, and calculates the leakage rate to facilitate the optimal scheduling of required maintenance.
III. GMS FIELD EXPERIENCE

A. Pin Hook Indoor Bus Section Leak

During commissioning, a low gas warning was initiated for one of the connecting bus sections in the Pin Hook GIS. Upon investigation, it was determined that SF$_6$ gas had been released from the gas compartment. Further investigation revealed that the point of leakage was an end casting in the bus duct (see Figure 5).

A review of the test reports did not show any irregularity identified during the routine production testing. Visual inspection of the enclosure showed a porosity in the casting structure where the gas was breaking through. The behavior of the leakage and the time of discovery led to the conclusion that it represented a one-off case of void in the casting that revealed itself after transport and normal mechanical stress during installation and static operation.

To assure that the casting was the only leak, the manufacturer applied a cold welding type of filler specifically designed to close such leaks. After re-gassing the bus section the GIS was checked and determined that no additional leaks were present. The manufacturer then proceeded to replace the defective bus duct as indicated in Figure 6. The GMS allowed identification and replacement of the leaking bus section prior to energization of the substation.

B. Pin Hook Outdoor Bus Section Leak

In the summer of 2004, after approximately one year of service, a gas loss was reported at Pin Hook in an outdoor gas zone. The initial investigation determined the cause to be a small defective point in a welded area of an outdoor bus duct (see Figure 7). Trending analysis from the GMS indicated a low leakage rate. Additional gas was added and a two to three day outage was scheduled for late autumn of 2004 to replace the bus duct.

After replacement, testing and analysis was performed on the leaking bus duct to determine the root cause of the leak. To locate the source of leakage an X-ray was done which found aluminum oxide and a small crack of 6 mm length at the surface of the duct. The conclusion was that the crack resulted as a direct consequence of oxide inclusion [6]. Oxide inclusions in steel are foreign substances which disrupt the homogeneity of structure and can lead to cracks and to fatigue failure. The critical crack growth could have been initiated by transportation, static operation or temperature effects over time. It was determined this was an isolated defect.

As a result of the trending analysis available from the GMS, maintenance personnel were able to keep the GIS in service during a critical time of the year for peak system loads.

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### SF$_6$ history chart

<table>
<thead>
<tr>
<th>Year</th>
<th>1 month</th>
<th>2 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>5000</td>
<td>10000</td>
</tr>
<tr>
<td>2006</td>
<td>5500</td>
<td>11000</td>
</tr>
</tbody>
</table>

Figure 4. Example of trending for SF$_6$ leakage in a gas zone.

Figure 5. Point of leakage in casting of GIS indoor bus section.

Figure 6. Removal of defective gas bus duct in Pin Hook GIS.

Figure 7. Location of leak at Pin Hook in an outdoor bus section.

<table>
<thead>
<tr>
<th>Leakage rate: 4.7% per year</th>
<th>Leakage detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to warning limit: 270 days</td>
<td></td>
</tr>
<tr>
<td>Time to alarm limit: 480 days</td>
<td></td>
</tr>
<tr>
<td>Fill level: 600.0 kPa</td>
<td></td>
</tr>
<tr>
<td>Warning pressure: 540.0 kPa</td>
<td></td>
</tr>
<tr>
<td>Alarm pressure: 520.0 kPa</td>
<td></td>
</tr>
</tbody>
</table>

678
and plan an outage in late autumn during low system loading conditions.

C. **Maury SF\textsubscript{6}/Air Bushing Leak**

The Maury GIS was put in service December 2004. In July 2006 a loss of gas was detected in an SF\textsubscript{6}/Air bushing. Trending analysis from the GMS indicated a low leakage rate and an October 2006 outage was scheduled to replace the bushing, which was then returned to the manufacturer for testing and analysis.

The composite hollow bushing is closed and sealed by means of metal flanges. A leakage test, performed using a “Leakmeter 200” (See Figure 8), indicated serious leaking (>1000 ppm) in the transition area between the top metal flange and the fiberglass tube. The leakage was also detectable with leak detection spray (See Figure 9). The top flange was cut off from the tube, sliced to rings 20 mm in width, and laid in a dye bath of 2-3 mm depth. All rings showed a dye penetration after a short time. The penetration channels of all rings were in line with the detected point of leakage, confirming the initial conclusion. Possible reasons for leakage in the tube to flange interface were:

1) Manual contamination of surface after cleaning process
2) Remains of sand blasting (sand grains) created a groove when the metal flange was pressed on to the tube

Possible explanation for a delayed occurrence of leakage is that the silicone housing had suppressed the leak, but then ultimately failed. The insulator manufacturer’s statistics over a ten year period showed that for approximately 100,000 insulators manufactured, only three had been identified with this specific defect.

As was the case at Pin Hook, TVA was able to keep the Maury GIS in service during the critical summer months and schedule an autumn outage to replace the bushing.

**IV. CONCLUSIONS**

1) All three problems found in the two GIS installations were isolated manufacturing defects, which seems to support the data reported in [2] that 48% of the total GIS failures are identified as manufacturing and design imperfections.

2) It was reported in [2] that over 21% of failures were associated with bus ducts, interconnecting parts or the SF\textsubscript{6}/Air bushing, which is where the three defects were found.

3) Two of the three failures were found by approximately the end of the first year in service and [2] reported that about 20% of failures occurred in the first year of service. The defect in the SF\textsubscript{6}/Air bushing, which caused the third failure, existed at the time of energization but took longer to materialize.

4) The previous conclusions and the absence to date of a major failure in the two GIS installations would seem to support TVA’s decision to only install a GMS to monitor SF\textsubscript{6} leakage, rather than install a full condition monitoring system. The GMS has provided the following benefits:

   a) Sensors provide continuous information on gas tightness and insulation integrity of each individual gas zone
   b) Provides early leakage detection which helps to limit the amount of SF\textsubscript{6} released into the environment
   c) Trending analysis allows optimal scheduling of maintenance in case of a leakage
   d) Improved availability and reliability of the GIS

**REFERENCES**


