An Overview of Online Oil Monitoring Technologies

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Abstract — Several new and exciting oil monitoring technologies have become commercially available over the past several years. This paper examines the mechanisms and capabilities of new and existing oil monitors. It discusses the motivations for oil monitoring and considerations for selecting a monitor.

The increasing demands on the time and talent of today’s utility engineer have continued to drive development of new tools to help automate the condition assessment of power transformers. The various maintenance philosophies, software tools, instruments and databases that have been developed over the past 20 years are centered around the notion that transformers should in some way be monitored. Transformer monitoring can mean any number of things, from hundreds of thousands of dollars of on-line instrumentation, to routine oil sampling and analysis, to merely periodically recording temperatures. An informal survey of several utilities found that most were willing to spend up to 5% of the cost of a transformer on monitoring equipment. On the purchase of a new multimillion dollar GSU or transmission unit, this can amount to an overwhelmingly complete set of instrumentation. In most cases however, and especially in retrofits, many utilities can’t afford the time or expense of monitoring everything and are faced with the difficult decision of what to monitor where, when to start, and why.

MONITORING DECISIONS

Statistics have shown that the old adage “if the transformer lasts through the first 6 months, it’ll last 30 years” is generally true [1]. Unfortunately, the average transformer age in most fleets today is over 30 years. Thus, it is important to have timely and accurate information on the condition of older transformers to help manage their end of life.

With the “average” transformer in the twilight of its life and without enough funding to monitor everything, monitors are most commonly justified where they are either easy to buy, install and operate, or are critically needed. Most monitors are purchased either on new or rebuilt units when the capital is more easily available or on the oldest and most critical transformers where the risks are highest. There are a number of risk and investment optimization tools and methodologies for determining which transformers warrant an investment in monitoring [2, 3]. While it would be prudent to have some level of monitoring attached to every transformer, these tools usually do not prescribe unlimited monitoring investment.

Most large transformers already have some form of monitoring of the fundamentals: voltage, load, temperature, cooling status, etc. These are parameters critical to the healthy operation of the transformer. Moving beyond this “operational data” there is a myriad of monitors available for the online condition assessment of the transformer or “condition data”. Examples of these sensors include dissolved gas, moisture, oil quality, partial discharge, bushing power factor, and vibration. Given the number of choices and the inevitable limit on funding, careful consideration must be given to the type of monitor to buy. While newer online measurements such as partial discharge promise to bring another level of fault detection and accuracy, no diagnostic can outweigh the cost-effectiveness and power of oil analysis.

ONLINE OIL MONITORING

Experience has shown that most internal transformer condition problems can be detected through oil analysis [4, 5]. Over the past 20 years, a large testing and diagnostic industry has evolved to perform ever more accurate and sophisticated oil analyses. There are a number of diagnostics that are commonly applied to in-service transformer oil
samples (Table 1). Of these, only a handful have been developed such that they can be performed online and in service, namely, dissolved gas analysis (DGA), moisture, and dielectric strength.

<table>
<thead>
<tr>
<th>Test</th>
<th>ASTM Designation</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Color</td>
<td>D1500</td>
<td>Increase in color indicates deterioration or contamination</td>
</tr>
<tr>
<td>Visual Examination</td>
<td>D1524</td>
<td>Clouldiness or sludge should be investigated</td>
</tr>
<tr>
<td>Dielectric Breakdown Strength</td>
<td>D877 D1816</td>
<td>Measures oil's ability to insulate. Sensitive to contaminants, moisture</td>
</tr>
<tr>
<td>Power Factor</td>
<td>D924</td>
<td>Detects polar contaminants</td>
</tr>
<tr>
<td>Dissolved Gas Analysis</td>
<td>D3612</td>
<td>Detects and identifies incipient faults</td>
</tr>
<tr>
<td>Interfacial Tension</td>
<td>D971</td>
<td>Detects polar contaminants and oxidation</td>
</tr>
<tr>
<td>Neutralization Number</td>
<td>D974</td>
<td>Measures acidity of oil. Indicator of deterioration</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>D1298</td>
<td>Can detect contamination</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>D1533</td>
<td>Moisture can damage insulation</td>
</tr>
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</table>

Table 1. Common In-Service Oil Diagnostics [5]

The online oil monitors that are available today can be roughly grouped into three categories: 1. Combustible Gas Monitors, 2. Complete Multi-Gas Monitors, and 3. Oil Quality Monitors, (Table 2).

**COMBUSTIBLE GAS MONITORS**

During the late 70’s and early 80’s there was an effort by several vendors to develop an online dissolved gas monitor for transformer oil. Some of these efforts materialized into what is available today as combustible gas monitors. These devices have a long service history and the largest base of users. Examples are the GE Hydran and the Morgan Schaffer Calisto.

The GE Hydran uses a rather ingenious approach to measuring dissolved combustible gas [6]. Transformer oil passes over a special membrane that hydrogen and other combustible gasses can permeate. The gasses then pass into a cell where they are chemically “burned” in what is essentially a fuel cell to create an electric current. This current is then measured and is proportional to the gas content of the oil.

Unfortunately, the elegance of the Hydran creates one of its biggest complaints: it is only broadly sensitive to combustible gas. A high content of acetylene and low hydrogen content can give the same reading as a low acetylene and high hydrogen. These are distinctly different conditions that cannot be easily resolved with the Hydran alone. However, this shortcoming is less severe than it appears. Typically when a reading changes on any oil monitor, regardless of the monitor’s sophistication, the natural response is to send an oil sample off to the lab for immediate analysis. While today there are more advanced Hydran models available with multi-gas and moisture capability, the basic Hydran 201R has enjoyed a large deployment and acceptance because of its reasonable cost and ability to simply detect and annunciate change.

Like the Hydran, the Morgan Schaffer Calisto, evolved out of research work performed in Canada in the late 70’s and early 80’s. The Calisto also uses diffusion through a polymer barrier to extract hydrogen gas from the oil [7], but that’s where the similarity ends. The capillary tube probe of the Calisto extracts only hydrogen from the oil and has the advantage (or disadvantage) of being insensitive to other combustible gasses. The concentration of extracted hydrogen is measured in a thermal conductivity detector which relies on the exceptional thermal conductivity of hydrogen gas.

A worthwhile feature built into the Calisto is the measurement of moisture. As will be discussed later, moisture can be an invaluable indicator of the health of the paper insulation in a transformer and can be difficult to ascertain without an online reading. In the Calisto, moisture is measured by a specialized integrated circuit which is in contact with the oil [8]. The Calisto’s moisture measurements have the advantage that the oil sample is always heated to a constant and known temperature. This is necessitated by the thermal conductivity measurement for hydrogen, but allows a percentage of relative saturation of moisture to be easily calculated.
The use of integrated circuits to measure dissolved gasses and moisture has not been limited to the Morgan Schaffer Calisto. Various integrated circuits (ICs) have been developed for other industries, and in particular blood gas measurements. A predecessor to the Serveron Online Transformer Monitor was developed with one of these multi-gas ICs around the same time as the Hydran and Calisto were developed [15]. Unfortunately, there were problems with a purely IC based multi-gas monitor, but out of that work, and with EPRI’s help, the present Serveron Online Transformer Monitor multi-gas monitor evolved.

The Serveron Online Transformer Monitor has a number of years of field experience behind it and is truly a sophisticated measurement instrument. Essentially recreating the laboratory gas chromatograph [16], the Serveron monitor is able to measure eight gasses, and recently, has an added option for measuring moisture as well. The Serveron monitor is designed to replace manual sampling and off-site laboratory analysis, and has the accuracy to meet or beat a laboratory DGA [17]. Unfortunately, few if any utilities can afford such a sophisticated monitor on all their transformers and the Serveron unit is most commonly found on only the most critical transformers. With limited deployment, it is difficult for the Serveron monitor to significantly reduce laboratory sampling and expenses. Its primary value comes from its ability to annunciate and detail sudden change.

The newest entry into the multi-gas online monitor arena is the Kelman Transfix. The Transfix is based on the same technology that has been used for several years in the Kelman Transport X portable gas analyzer. This technology can measure eight gasses and moisture. The principle behind the Kelman analyzer is photo acoustic spectroscopy (PAS) [18].

<table>
<thead>
<tr>
<th>Product</th>
<th>Measures</th>
<th>Type</th>
</tr>
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<tbody>
<tr>
<td>GE Hydran 201R [9]</td>
<td>Composite Combustible Gas (H₂, CO, C₂H₂, C₂H₄)</td>
<td>Combustible Gas</td>
</tr>
<tr>
<td>GE Hydran Multi 2010 [10]</td>
<td>Composite Combustible Gas (H₂, CO, C₂H₂, C₂H₄) Acetylene (C₂H₂)</td>
<td>Combustible Gas</td>
</tr>
<tr>
<td>Weidmann Centurion [14]</td>
<td>Oil Dielectric Strength</td>
<td>Oil Quality</td>
</tr>
</tbody>
</table>

Table 2 On-line Oil Monitoring Instruments Available from Various Vendors
When a gas absorbs electromagnetic radiation, such as infrared light, it is heated and it expands. When gas is heated suddenly, it expands suddenly and makes a sound wave (as in thunder). Different gasses absorb different “colors” of electromagnetic radiation in the same way that solids and liquids absorb different radiations to give them what we see as color. In a PAS device specific “colors” or spectra of infrared light (the photo and spectroscopy part or PAS) are shown on a gas sample to heat it and produce a sound (the acoustic part). The intensity of the sound is proportional to the concentration of the gas, so PAS can be a very elegant way to determine a gas concentration.

Photo acoustic spectroscopy has a long history of use in other industries and research. Despite the relatively new appearance of a PAS based transformer gas monitor, the physics behind the technology are sound. Photo acoustic spectroscopy has the further advantage that, unlike gas chromatography, it does not require any carrier gas or calibration. With time, the cost of a PAS monitoring system may be reduced to the point that it makes an attractive alternative to manual testing. In the meantime portable PAS units are available.

**OIL QUALITY MONITORS**

The newest online oil monitoring technology is the Weidmann Centurion. The Centurion began its life as a utility sponsored research project at MIT [19]. The goal of the project was to develop an inexpensive and generalized oil quality monitor that could be cost effectively applied to all types of oil filled equipment, not just the critical transformers. Unlike the aforementioned monitors, the Centurion does not extract gas from the oil. Instead it examines the quality or purity of the oil by measuring its dielectric strength.

Dielectric strength methods such as the ASTM D1816, D877 and IEC 60156 have been used for years to assess the quality of insulating oil, especially in contacting equipment. Unfortunately these existing methods have been limited by their destructive nature. A Dielectric breakdown strength test electrically stresses the oil to the point of failure. This can be the most accurate measure of the oil’s ability to do its job (electrically insulate), but because it is destructive it does not allow for repeated testing of a sample or online analysis. The Centurion method uses special high speed technology to prevent any breakdown energy from damaging the oil. With this new non-destructive breakdown technology, the Centurion opens the door to a whole new level of detailed breakdown analysis.

Dielectric breakdown tests such as those performed by the Centurion are sensitive to moisture, carbon and metallic particulates, fibrous and other impurities, and any burning or degradation of the oil. Thus, many of the same mechanisms that produce dissolved gasses also produce changes in dielectric strength. Given that the first response to a change in condition on any oil monitor is typically to send a sample out for detailed laboratory analysis, the Centurion can serve as an inexpensive annunciator on virtually any oil filled equipment.

**MOISTURE**

All of the oil monitors discussed so far include at least an option to monitor moisture. As any utility engineer will know, maintaining the proper transformer moisture level is critical to maintaining a healthy service life and avoiding damage to the solid insulation of the transformer. Moisture ages the cellulose based solid insulation. Unfortunately there is no easy way to measure the moisture content of the solid insulation directly. Thus, it has to be inferred from the moisture content of the oil. Depending on conditions, typically only 3% of the moisture in a transformer resides in the oil. The remainder is in the solid insulation, and to complicate matters further, moisture migrates back and forth between the two with changes in temperature [20]. With knowledge of the oil temperature, the relative saturation of the moisture can be measured and, in turn, the moisture content of the solid insulation can be calculated.

While the dielectric strength does not measure moisture per se, the dielectric breakdown strength of the oil changes relative to the moisture content of the solid insulation as it varies with temperature [21]. When measured in service, the dielectric strength can be a simple yet accurate way to gauge solid insulation moisture content. Whether by dielectric strength or direct measure, to get a truly accurate idea of the moisture content of the transformer oil, readings must be made on-line, or
at the minimum, samples must be taken at a known operating temperature.

**Dissolved Gas Analysis**

While moisture monitoring is used primarily to monitor ageing and plan maintenance, combustible gas detection is primarily concerned with the detection of incipient faults. There are innumerable publications on the interpretation and diagnosis of dissolved gas analyses, and it is a larger topic than can be discussed here. The same rules hold true whether the DGA was taken online or measured in a laboratory; presently most online DGA readings are still verified with a laboratory test. Because of the continued reliance on laboratory analyses as the final word, perhaps the most important feature of an incipient fault detector is its ability to detect change in the oil condition. All of the monitors discussed here have the ability to detect change to some extent. Thus, the differentiators between the various monitors come down to the speed and ease with which a change can be annunciated, the level of analysis detail that is deemed necessary on-line, and of course, the cost.

**Selecting a Monitor**

Oil monitors can be purchased for several reasons: for maintenance and asset life management, for early fault detection, to monitor or enhance performance, or any combination of the above. As previously discussed there are tools and methodologies that can drive the decision to monitor with one or more of the above reasons. Once the economic and business reasons are justified, the selection of an instrument can begin.

Buying a transformer monitor is much like buying the transformer itself. It is an engineered decision based on the particular needs of a given installation. Initially, many engineers might try one of everything and see what they like best. This can be a great way to ascertain the quality of a particular product and its ease of installation and integration into operating practices. In order for a monitoring plan to be effective, some general parameters should be set. With a few trial experiences it may be easier to select monitors that best suit the goals of a monitoring program. Some of the questions that might be asked when selecting an oil monitor are:

1. What is the purpose of the monitor; maintenance, life management, fault detection, etc.?
2. Is it critical to have a complete analysis available continuously and remotely, or will the monitor serve primarily as an annunciator?
3. What will be the response to annunciation or a change in condition?

Different transformers may warrant different levels of monitoring and a combination of inexpensive monitors may be more appropriate than a single expensive one. For example, it may be feasible to deploy a combustible gas monitor or oil quality monitor on all major transformers and only add a multi-gas monitor to the most critical units. It may also make sense to focus on installing the most sophisticated monitoring on the most important units. Alternatively, an automation focused plan may dictate placing the least costly monitors on the largest number of transformers possible.

Oil monitor users will need to develop a monitor deployment plan that makes sense for their risks, goals, and budget. With the number of oil monitoring technologies available, all transformer owners should be able to select an oil monitor that suits their needs.

**References**


