
The purpose of this white paper is to provide insight and guidance on the selection of on-line dissolved gas analysis (DGA) monitoring and diagnostic tools for utility transformers. We'll examine transformers as utility asset classes in the context of their impact on revenue, grid stability, and service reliability. We will then consider the appropriate DGA monitoring equipment for each transformer on the basis of its designated asset class.

Transformer Fleet Reliability

We start by considering the issue of reliability and availability in the context of utility transformers.

Reliable energy flow is paramount to a modern economy and power transformers are critical assets in the electrical grid. Transformers are also costly to install or replace. In fact, as an asset class, transformers constitute one of the largest investments in any utility’s electrical system. For this reason transformer management and condition assessment is a high priority for asset manager and utility owners alike. Each electrical utility’s grid is unique and investment in asset condition and assessment tools varies. This variability is inevitably aligned with a risk level and investment return models. While the models are different for each utility, the common element in them is that transformer fleets are stratified according to the criticality of individual transformers. The variability lies in where the prioritization lines are drawn and will be restricted by the investment amounts allocated for asset condition and management.
tools for each level. Typically this approach has the most critical transformers receiving the highest investment of condition assessment and management tools, with a subsequent decreases in investment for each less critical level identified.

An intentionally simplified model below, shows one approach to transformer fleet stratification:

<table>
<thead>
<tr>
<th>Stratification Level</th>
<th>Transformer type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>Those transformers that, if allowed to fail, would have a large or significant negative impact on grid stability, utility revenue, and service reliability. GSU’s and transmission transformers which are part of critical power flows are in this level.</td>
</tr>
<tr>
<td>Important</td>
<td>Those transformers that, if allowed to fail, would have a considerable negative impact on revenue and service reliability and would place extra strain on other parts of the grid. Transmission substation transformers and major distribution substation transformers are generally in this level.</td>
</tr>
<tr>
<td>Significant</td>
<td>Those transformers that, if allowed to fail, would have lower impact on revenue and reliability, although the cost associated with replacing or repairing at short notice may be a concern. These are mainly smaller distribution substation transformers.</td>
</tr>
</tbody>
</table>

Table 1: A simple stratification which considers on the criticality of the electrical function provided by the transformer type

Other significant aspects may move a specific transformer from one stratification level to a higher one. These can include whether failure is likely to have an impact on:

Safety of property or people – E.G. will a failure damage adjoining transformers or risk injuring people

The local environment – E.G. will a transformer fire pollute the air of a nearby urban area or an oil leak pollute the soil and groundwater

The image of the company – E.G. a failure during a significant sporting event can be seen by millions or a failure that makes it into the national media can impact the share price of the utility.
The relevance of transformer fleet stratification is more important today than it has ever been in the past. It is an obvious fact the Transformers don't last forever. However, what may be less immediately obvious is that we are in the midst of a population crisis when it comes to transformer age. Taking the US as an example: US commerce department data shows that new installations peaked in the US in 1973 – 1974. Those transformers are now over 40 years old and today’s capital spending is at its lowest level in decades. While peak installation occurred at different times in different countries around the world, the average age of the entire world fleet continues to rise.

In the US, with a current average age of greater than 40 years, many transformers are now approaching the end of their design life. Higher loads placed on transformers - in a market that demands more electricity - have also taken their toll on transformer longevity. Compound this with the reduction in capital budgets and the need to more closely manage transformer assets becomes essential. Utilities can avoid failures, lower maintenance costs and defer capital expenditures through the appropriate use of transformer condition assessment and management tools. Applying the right tools for each situation is what stratification is all about.

**The Evolution of DGA**

Monitoring the state of health of power transformers, a key component in the path of reliable power, has traditionally been carried out using laboratory testing of the oil, and in particular DGA testing, performed at periodic intervals. It is now almost universally recognized by transformer experts and industry organizations that DGA of transformer oil is the single best indicator of a transformer’s overall condition. It is fair to say that DGA, which started as a discussion about the appearance of flammable gases in oil filled transformers has evolved to be a universal practice today.

The following is a brief summary of the recent evolution of the products and practice of DGA.

Laboratory DGA took off in earnest in the 1960s. The traditional and indeed still current laboratory practice is to collect a sample of oil from the transformer and, without it coming into contact with atmosphere at any time, transport it to a laboratory and analyze it. This remained
the primary method for almost 40 years and is very widely used today. However over the last 20 years, and the last 10 years in particular the use of on-line DGA tools has increased tremendously in popularity. The reason for this is driven by the transformer failure consequences discussed earlier and the associated need for utilities to maintain or improve reliability in the presence of decreased capital expenditures and an aging infrastructure. Something more than periodic laboratory analysis was needed to be successful in the emerging competitive environment and often both approaches (on-line DGA and laboratory DGA) now co-exist at utilities. While laboratory oil analysis is still a routine requirement, on-line DGA provides a level of detail of transformer condition that it helps utilities avoid failures, adopt lower cost condition-based maintenance, and defer capital expenditures by extending the transformer's useful life through careful management.

First generation (1980’s – 1990’s) online monitors were typically used only as a “smoke alarm”. They were sensitive to several gases but could not provide any quantitative detail and so would simply alarm at a chosen set point. These products provided indication of developing problems in the transformer but offered no legitimate diagnostic capability. Today, on-line DGA products in the market have evolved to a high level of sophistication. This has been driven by demand as the power industry became more aware of the value of quantitative and qualitative online DGA. Today’s products are robust and long lasting. They vary in complexity from monitors that are sensitive to a specific fault gas (typically Hydrogen), to systems that accurately analyze all 7 fault gases and the atmospheric gases as well as provide powerful diagnostics described in the IEEE and IEC standards among others.

Modern on-line DGA monitors now have the ability to continuously trend multiple transformer gases and correlate them with other key parameters such as transformer load, oil moisture, oil and ambient temperatures as well as customer specified sensor inputs. This capability enables utilities to relate gassing to both internal and external events, a key to meeting utility reliability goals. Multiple industry studies by organizations such as CIGRE have also shown that some of the current on-line DGA monitors offer better accuracy and repeatability than laboratory DGA. This is probably the result of the fact that sampling and analysis are done in a closed environment without any delay from one step to the next. Indeed this improved
accuracy form on-line monitoring can improve the transformer asset manager’s decision
timeliness and confidence when incipient faults are detected.

With the advent of on-line DGA monitoring there has also been new learning about the nature
of developing faults in transformers. On-line DGA monitoring has produced multiple case
studies that document the development of critical faults, which could cause catastrophic
transformer failure if left undetected, in timeframes from a few days to a few weeks. There is a
low probability of capturing these rapidly developing fault conditions with a laboratory DGA
testing program. However with on-line monitors operating at 6 samples per day typically, a
significant increase in resolution of the data allows for a lot of these rapid progression faults to
be detected. Indeed in some cases the nature of a fault’s evolution in observed gases only
became obvious with the use of online monitoring. Thus the technique of online DGA has in
fact furthered the science of DGA diagnostics in general.

One aspect of this DGA capabilities evolution has been the recent emergence of neural
networks for analysis of the DGA data, providing for even greater powers of diagnosis. Large
scale deployment of online DGA monitors at a utility, for example, 50+ individual 8 gas
monitors, can result in a lot of data for asset managers to contend with. This can be
bothersome if it results in alarms that, while legitimate may not be necessary for a particular
transformer. An artificial intelligence systems has the capability of looking at the DGA data,
not in the isolation of a single measurement, as most diagnostic techniques do, but rather
considering historical DGA data, current data and even the future, predicting what gas will be
produced in the medium term future, based on current trends. It can rank a fleet of transformer
with a value which indicates severity of fault on a sliding scale to allow for better management
of resources through condition based maintenance. They systems can even go so far as to be
trained on particular utilities transformers, thus resulting in greater accuracy. While neural
networks for DGA is a relatively new approach and has been borne out the emergence of 8
gas online monitors, it has nonetheless been successfully deployed and implemented by
several major utilities around the globe.

For smaller scale monitor deployment, the ability to automatically populate traditional DGA
diagnostic tools with on-line DGA data is now commonplace. Instrument manufacturers give a
high level of significance to the ability of their customers to get useful information out of the
data. After all, a utility manager does not care about ppm levels of gas in his transformer; he cares about transformer faults. Today’s sophisticated software makes it easy to convert from one to the other. This new development offers users of on-line DGA monitors unprecedented insight into the nature and identification of developing faults. The tools are typically ratio-based and the on-line data set enables trending of fault gas ratios over time rather than the traditional static snapshots. Diagnostic outcomes can now be determined quickly and with more certainty than in the past. Neural network diagnostic approaches utilizing DGA data are also new to the market, offered by only Serveron at present but they can be used to provide even more accurate diagnoses.

The next section will cover some of the decision criteria for employing on-line DGA tools.

**Selecting On-line DGA Monitors**

The last few years have seen a new array of DGA monitors available in the market, and this poses challenges for utilities to understand and choose an approach that best meets their needs. Transformer asset managers have important decisions to make based on DGA information, including whether or not to take a transformer off-line in order to avoid a catastrophic failure. These decisions can significantly affect utility service reliability and revenue and so must be based on sound data. The aging infrastructure and increasing electricity demand placed on existing transformer assets is exacerbating the problem. Higher loading on older transformers is causing faults that can lead to catastrophic failure to develop faster and more often. The transformer reliability bathtub curve shows that new transformers are not immune to failure either. This puts pressure on transformer asset managers to make critical reliability and revenue decisions more quickly and more often than in the past. Each transformer asset manager must choose the amount and type of transformer condition data they require for each level in their stratification model to make these big decisions. In response to this need the vendor community has brought out products that better support the asset manager’s decision integrity by supplying timelier, accurate and certain transformer DGA data together with modern diagnostic tools.

The increasing variety of on-line DGA monitors, while helpful to the industry overall by expanding options, presents transformer asset managers with the problem of matching the
right product to their needs. A framework for decision making is required. The first step is the determination of a transformer fleet stratification model. For purposes of this paper, the stratification model discussed on page 1 will be used. To recap, the model has 3 levels of transformer assets identified; critical, important, and significant. In Table 1 below there is a list of attributes for various on-line DGA product categories relevant to on-line DGA tool selection. This list of attributes should be considered when applying on-line DGA to the various levels of a stratification model.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>1 Gas</th>
<th>2 Gas</th>
<th>3 Gas</th>
<th>8 Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases</td>
<td>H₂</td>
<td>CO, H₂</td>
<td>CH₄, C₂H₂, C₂H₄</td>
<td>All IEC and IEEE fault gases + O₂</td>
</tr>
<tr>
<td>Fault Coverage</td>
<td>Limited</td>
<td>Minimal</td>
<td>Better</td>
<td>Best</td>
</tr>
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<td></td>
<td>Undetermined faults</td>
<td>Cellulose aging. All other faults undetermined</td>
<td>Critical Faults: Partial Discharge, Arching, Thermal Faults</td>
<td>All fault types detectable with DGA</td>
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<td>Diagnostics</td>
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<td>Cost</td>
<td>Low</td>
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**Table 2:** On-line DGA monitors can be categorized by the number of gases they measure. The other attributes in the table are a direct result of the number of gases measured. Most modern on-line DGA tools offer the ability to measure other parameters such as moisture-in-oil. These other parameters are not included in the table as they are common for most offerings in the market today. Table 2 shows that the number of gases measured enables better fault coverage and diagnostic capability. These two attributes are critical decision
criteria for the transformer asset manager. They define the extent of asset condition information available from the on-line DGA tool.

Fault coverage: is the number of detectable incipient fault conditions that the on-line DGA tool can support from its gas data. The fewer gases measured, the more fault conditions go undetected by the on-line DGA tool and vice versa.

Diagnostics: is the capability of the DGA results to support the various diagnostic tools available in the IEEE and IEC guides. Once again, fewer gases measured mean fewer diagnostic tools available to identify fault modes.

Fault coverage and diagnostics are the critical attributes that transformer asset managers should consider when choosing on-line DGA monitors for the various levels in their stratification models. Price is also a consideration but the relative value of the solution, as defined by the fault coverage and diagnostic capabilities, is the more important measure. In other words, some solutions may have a higher price but the value provided (through superior transformer condition knowledge) in terms of improved utility service reliability and revenue may far outweigh the initial higher purchase price.

Cross referencing the stratification model levels identified in Table 1 to the fault coverage attributes in Table 2 creates Table 3 below. This table indicates the potential application of on-line DGA tools to our stratification model. This selection of on-line DGA tools for each level reflects the approach of making the highest investment in on-line DGA tools for the most critical transformers and inversely the lowest investment in tools for lower levels in the stratification model. This approach utilizes the on-line DGA tools with the most fault coverage and diagnostics for the critical and important transformers in the fleet. Utilities will find more appropriate returns on investment for their critical and important transformers with 8 gas on-line DGA tools that offer full fault coverage and diagnostics capability. Conversely they would be advised to consider the application of 1, 2 or 3 gas monitors as been more appropriate for transformers lower in criticality in the stratification model.
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</tr>
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<td>Stratification Model Level</td>
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<td>Significant</td>
<td>Important</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Smaller Substation Distribution Transformer</td>
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<td>Transmission and Major Distribution Transformers</td>
<td>GSU and Major Transmission Transformers</td>
</tr>
</tbody>
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**Table 3.** Cross referencing Table 1 and Table 2 results in a model for selection of online monitors based on the criticality of the individual transformer.

The current environment of higher loading on aging transformers, deferred capital expenditures as well as increased service reliability requirements suggests that utilities should take advantage of the improved on-line DGA offerings (i.e. better fault coverage and diagnostics) in the market to get the best protection for its biggest asset class – at all levels. Appropriate on-line DGA monitoring and diagnostic tools will help utilities avoid failures, lower maintenance costs and extend transformer useful life.