GE
Digital Energy

New Era Transformer Fleet Management

Part 2 of a 2 Part Series:
Solutions Using New Era Asset Fleet Management Software

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imagination at work

Executive Summary

Power transformers, regarded as critical grid assets, are presenting an increasing challenge to asset fleet managers due to their large numbers, advancing age and increasing risk. Condition Based Maintenance (CBM) of these assets, based on dissolved gas analysis monitoring, has long been considered the panacea of transformer fleet management. However, while online transformer monitoring systems provide part of the solution, organizations have been struggling to achieve the benefits of their CBM vision.

Increasingly, organizations are in search of software to perform data interpretation and automatic transformer evaluation. Compared to expensive custom built systems which take years to roll out, the new era of "out of the box" intelligent software, using algorithms combining best practices and recognized industry standards, allows for faster return of their monitoring investment dollars. By adopting new era data analytics software which also facilitates easy customization, organizations can instantly benefit from data validation, amalgamation and cross-correlation. They can oversee their whole fleet and replace data overload with actionable intelligent information, the key to unlocking true condition monitoring value.

Part 1

Challenges in Realizing the Condition Monitoring Vision

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Part 2

Solutions Using New Era Asset Fleet Management Software

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Abundance of data

As described in Part 1, online monitors deliver a constant flow of data, providing customers with a regular insight into the transformers condition. The information provided by this data is essential to establishing and understanding the condition of the power transformers within a fleet.

Utilizing the information

Unfortunately it has been noticed in the industry that this valuable information is consistently being under-utilised. This is due to a number of factors ranging from a lack of understanding on how to interpret the information, missing or overstretched transformer expert resource, unwanted accountability that comes with the analysis and a fundamental misunderstanding of the purpose and power of online monitoring.

Many organizations are faced with the challenge of not benefiting from the information provided by online monitors. Often they rely heavily on the built in features of the online monitors, namely the alarm/warning information and data from 4-20ma signal outputs. The alarm/warning system built into online monitors can alert operators should a measured value breach a defined alarm limit. By connecting 4-20ma signal outputs from the online monitor to a SCADA system in the control room, the operator can also see the latest values from the online monitor.

Figure 1: GE's PowerOn ADMS software

For example:

> *If Hydrogen gas reaches 110ppm and the caution (or high) alarm is set to 100ppm an alarm signal and audio siren can be triggered in a control room using a dry contact relay. On the SCADA system the operator is able to see the 110 ppm measurement for Hydrogen that the online monitor has reported: through the 4-20mA output.*

Both of these methods provide valuable notifications when a specific event occurs. However, focusing solely on alarm breaches and current values can result in faults being caught and reported too late.

By continually evaluating the data provided by the online monitor, faults can be detected and actions can be taken at a much earlier stage, pre-empting failures, preventing unplanned outages and halting premature aging caused by untreated defects.

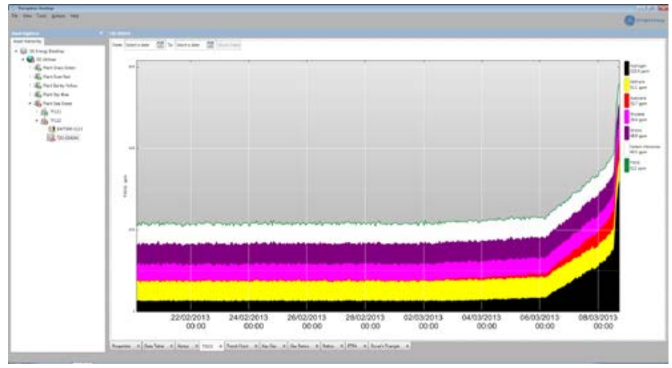

Figure 2: Trend of transformer key gases as displayed in GE's Perception Fleet Software

For example:

> *By trending Hydrogen gas levels over time the situation is easier to grasp: how long has Hydrogen been rising and is the rate of change increasing. This would indicate if the transformer is entering or has entered a fault spiral, enabling action to be taken early.*

Asset management applications

More and more organizations are turning to software in the form of asset management applications, to help them make crucial asset life cycle decisions based on the information derived from the monitor data.

The information presented in asset management applications is consumed in different ways depending on the end user. It is vital that the data can be easily accessed and delivers coherent information tailored to the audience. Along with that, ensuring that the data is centrally located and accessible remotely via thick clients (desktop applications) and thin client (web browser interface), is essential for ensuring the integrity of the information shared.

Data consumption

For transformer experts, asset management applications help them with their constant juggling of priorities:

- focusing on recommending and executing maintenance programs,
- evaluating the possibility of extending an asset mid-life,
- recommending asset replacement where required,
- reducing the risk of unplanned outages,
- minimizing the risk of catastrophic failure.

Providing guidance without getting bogged down in data analysis.

Asset management applications perform data analysis automatically and can be tailored to take into consideration the expert's best practices and individual asset knowledge thus greatly reducing the burden of data analysis and building confidence in the automated analysis.

Figure 3: Evaluation of transformer bushing data using GE's Perception Fleet Software

For transformer maintenance engineers, asset management applications provide the information on maintenance and repair requirements for the transformers. Data trending and diagnostics tools along with expert advice help the engineer determine the maintenance or repair tasks and subsequently evaluate if the maintenance work was successful in improving the transformer's condition.

For asset managers, asset management applications help bridge the gap between the experts and those responsible for budgets. It does this by constantly providing clear and concise data driven information, allowing them to reduce and focus operating maintenance costs, calculate and plan capital expenditure and better plan emergency action budgets for ill-health vital assets.

Figure 4: Asset manager tracking asset condition changes using GE's Perception Fleet Software

For example:

A substation responsible for delivering power to a highly populated suburb has 2 transformers (referred to as a 2 bank substation). It is vital that the asset manager and maintenance engineer knows the condition of both transformers to ensure successful redundancy should one of the transformers fail unexpectedly and the load has to be transferred to the 2nd transformer to maintain an uninterrupted service. If it's the transformer experts opinion that both of these vital assets are 'at risk' there is the potential that the 2nd asset may also fail when the additional load is shifted from the already failed transformer circuit. This would result in a loss of service for utility customers, increased repair bill and engineering time to fix both transformers. Ideally at least 1 of the transformer in a 2 bank substation should be considered in healthy condition to prevent such an event occurring.

Application expectations

In order to deliver on this expectation, asset management applications need the ability to automatically amalgamate, cross-correlate, analyse and interpret data converting it into easy to understand, meaningful and actionable information.

To perform such tasks, the software industry uses algorithms and workflow engines for processing and evaluating data. In order to be effective and accurate, the algorithms must be architected using a combination of industrial expertise and knowledge, combined with well-regarded and evaluated, globally recognized standards and best practices.

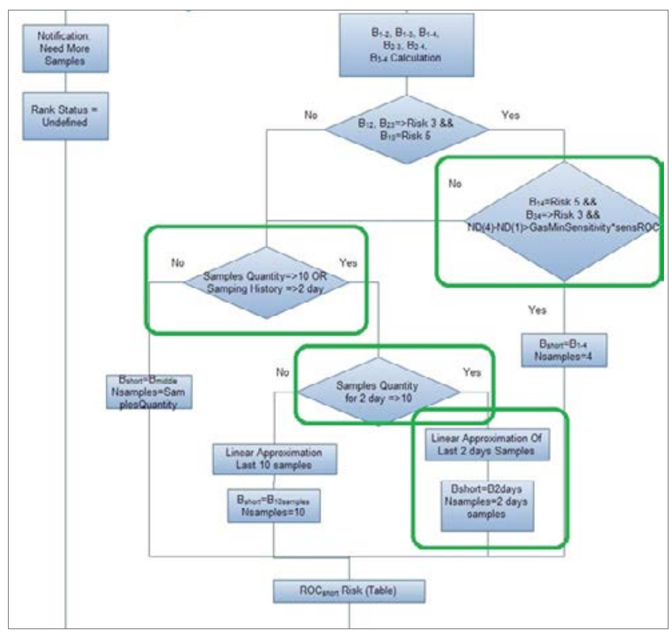

Figure 5: Algorithm example from GE's Perception Fleet Software.

When rolling out analytics applications, organizations feel they have to choose between applications that can perform 'out of the box' analytics or investing in a fully customised application developed and tailored to the organization's needs.

A fully customised application is developed and tailored by taking into consideration your assets characteristics and organizational best practices. Although these applications can deliver powerful data analytics, the majority of such applications require extensive customisation and user input, which can be extremely expensive and take a considerable amount of time to develop. It has even been said that such large scale applications are never really completed as they require not only a huge effort to get up and running, but also continuous development in order to consider and maintain the unique characteristics of the assets they are evaluating and the specific end users requirements.

The ideal asset management application is one that can provide 'out of the box' intelligent analytics based on best practices and standards, with the ability to not only adjust the built in analytics but create new ones using the end users' best practices and asset knowledge. The underlying intelligence should be based on published standards, well regarded transformer diagnostics techniques and user configured alarms, enabling the software to deliver transformer evaluations from day one without lengthy bedding in process.

Identifying & utilizing the important data

As described in Part 1 section 2, the analysis of dissolved gases (DGA) and moisture in insulation oil along with bushing insulation characteristics can be used to identify transformer failure modes before a fault or failure occurs. By studying transformer failure modes, failure case studies and establishing fault patterns within trending information, it is possible to identify the nature of a fault that is occurring within the transformer without the need for an expensive and intrusive forensic examination.

Dissolved gas and moisture analysis experts focus on three specific aspects: the absolute concentration (AC) of gases and moisture, gas ratio analysis and the gases rate of change (ROC) within the insulation oil. Priority is given to gas ROC because gas ROC is an indicator of potential fault severity and impending failure. Gas AC and ratio analysis provides diagnostic information relating to the type and cause of the fault.

For Example:

Hydrogen gas is ever present in transformer insulation oil. If the levels of Hydrogen suddenly increases and trace amounts of Acetylene also appear, this can point to arcing occurring in the transformer tank. If the levels of these gases increase rapidly over a short period of time, this can help the experts determine the force and energy of the arc. By analysing the CO2/CO ratio the expert can also determine if the cellulose insulation has been affected. Backed up by this evidence, the transformer expert can make a confident decision as to the necessity to bring the transformer offline in order to prevent an unplanned outage or serious damage to the transformer.

Transformer bushing analysis is also vital as bushing failure can, and often does lead to catastrophic transformer failures. These can have huge environmental and safety repercussions as the mixture of high energy and flammable oil combines to create an intense explosion and fire. By looking at the variations in power factor (or dissipation factor or tan delta) and capacitance of a bushing, it is possible to determine its health and pre-empt a failure.

For Example:

When an insulation layer in a bushing degrades there will be slight change in capacitance and a noticeable fluctuation in power factor\tan delta and traces of partial discharge. If action is not taken, an increasing difference in capacitance becomes apparent in a very short space of time as further degradation in the insulation layers occur leading to a catastrophic failure of the bushing.

Along with these measured data inputs, the transformers criticality information is also vital in understanding the business, economical and environment health and safety risks of a transformer failure. By taking into consideration information such as process/delivery loss, access for repairs, spare parts availability, physical location etc... the criticality of individual assets failing can be gauged. The more criticality information that can be entered into the asset management application regarding the transformers, the more accurate the risk evaluation of the transformer will be.

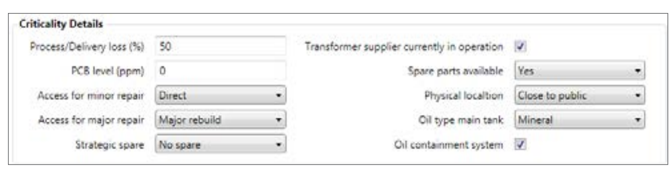

Figure 6: Transformer criticallity details as captured depected in GE's Perception Fleet Software

For Example:

If there are two transformers with similar poor health data readings but one is located very close to the public. Its criticality would be higher than the other transformer as its failure could cause a health and safety issue or in worst case fatality.

Data analysis methodology

We have looked how asset management applications can play a key role in the day to day tasks of utility personnel and the important data provided by monitors and sensor. Now we will look at how the data is evaluated and how the results are conveyed to the user as actionable information.

Transformer risk is a term often used in the industry to articulate the health of a transformer, the potential and impact of an unplanned failure and its criticality to the daily business operations of the organization. By analysing the afore mentioned key data, it is possible to determine a transformer's risk and apply a categorization and priority to the transformer based on its risk evaluation.

Industry standards and best practices

Associations and research institutes such as Cigré and EPRI have founded committees and working groups made up of industry experts who specialise in analysing key transformer data. Standards organizations such as IEEE & IEC provide a forum for industry experts to converge, discuss and publish recommendations for transformer analysis which are well regarded and recognised throughout the world. Although there are numerous publications and papers written on transformer analysis, there are some which a regularly referred to by industry experts and are considered to provide best practice information.

IEEE C57.104 - Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers, is an IEEE standard that looks at key gas patterns as well as moisture information, and provides indication of malfunctions that may eventual lead to transformer failures.

Within this standard there is a table which offers condition levels based on the concentrations of key fault as can be seen in Figure 7:

IEC 60955 provides guidance on the dissolved gas rates of change expected from normally operating transformers. Coefficients can also be considered to create a more accurate evaluation of the gas increase.

Typical rates of gas increase for power transformers in millilitres per day.

Hydrogen	<5
Methane	<2
Ethane	<2
Ethylene	<2
Acetylene	<0,1
Carbon monoxide	<50
Carbon dioxide	<200
NOTE – The values listed in this table were obtained from individual networks. Values on other networks may differ. Values on other types of transformers, for instance sealed transformers, may also differ.	

Figure 8: Table showing expected gas rate of change as detailed in IEC 60599-1999

In order to create a more accurate evaluation of gas rate of change, a piece-wise linear approach can be adopted. Piece-wise linear analysis of rate of change uses multiple time spans, each providing an individual line of best fits. By using this approach and looking at a long, mid and short time period when analysing the dissolved gas rate of change, experts can determine if the rise or fall in gas is due to the natural decay of the transformer insulating oil and paper, seasonal variation and power consumption hikes or an indication of a defect causing high energy discharge or overheating.

For Example:

Figure 9 depicts no change in concentrations of Acetylene over long & mid time span, and then a rapid rise over a short period of time. This rate of change pattern indicates that there was high energy discharge occurring within this transformer resulting in the production of Acetylene.

Status	Dissolved key gas concentration limits [µL/L (ppm)a]						
	Hydrogen (H2)	Methane (CH4)	Acetylene (C2H2)	Ethylene (C2H4)	Ethane (C2H6)	Carbon monoxide (CO)	Carbon dioxide (CO2)
Condition 1	100	120	1	50	65	350	2500
Condition 2	101 – 700	121 – 400	2 – 9	51 – 100	66 – 100	351 – 570	2500 - 4000
Condition 3	701 - 1800	401 – 1000	10 – 35	101 – 200	101 – 150	571 – 1400	
Condition 4	>1800	>1000	>35	>200	>150	>1400	

NOTE 1—Table 1 assumes that no previous tests on the transformer for dissolved gas analysis have been made or that no recent history exists. If a previous analysis exists, it should be reviewed to determine if the situation is stable or unstable. Refer to 6.5.2 for appropriate action(s) to be taken.

NOTE 2—An ASTM round-robin indicated variability in gas analysis between labs. This should be considered when having gas analysis made by different labs. a The numbers shown in Table 1 are in parts of gas per million parts of oil [µL/L (ppm)] volumetrically and are based on a large power transformer with several thousand gallons of oil. With a smaller oil volume, the same volume of gas will give a higher gas concentration. Small distribution transformers and voltage regulators may contain combustible gases because of the operation of internal expulsion fuses or load break switches. The status codes in Table 1 are also not applicable to other apparatus in which load break switches operate under oil.

b The TDCG value does not include CO2, which is not a combustible gas.

Figure 7: Table showing absolute gas concentration levels taken from IEEE C57.104

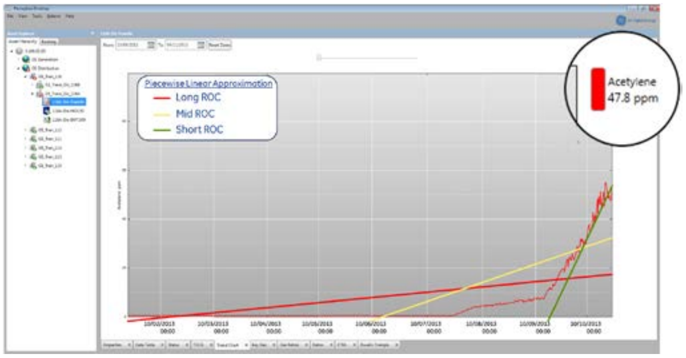

Figure 9: Gas rate of change in trend chart

IEC 60422 provides guidance on the analysis of moisture (H2O) in oil and like the IEEE C57.104 for DGA, it provides condition levels based on the concentrations of moisture. The rated voltage of a transformer is heavily dependent on the moisture content as described in IEC 60422. The higher the rated voltage of the transformer is, the lower the tolerance for moisture within the transformer oil becomes.

Water has long been challenging to manage simply because there are many avenues by which it finds its way into the transformer. A leaking transformer will eventually become a wet transformer, and an ageing transformer will also see an increase in moisture content. A by-product of ageing cellulose material is water production, therefore as the transformer ages, the water content will rise, and will be a problem if left untreated.

CIGRE TB227 Written by the late Dr. V. Sokolov, TB227 provides five transformer conditions in terms of its reliable operation. Dr V. Sokolov took the information outlined in transformer DGA standards and expanded upon them, using his own expert knowledge and many years of service within the industry.

EPRI have created guidance for DGA within transformer resistor type on load tap changer insulation oil, by analysing certain key gas ratios. One of the ratio's developed by EPRI called the 'R3' formula, analyses Ethylene over Acetylene. R3 is used to determine a transformers "at risk" condition from good condition and operating as expected through to an impending failure.

Automating evaluations

The premise of automatic transformer condition and risk evaluation is based on the ability to take the available measured data along with the organizations information on a transformer & their best practice criteria, and produce concise, coherent and actionable information without expert intervention or evaluation in early stages.

By building algorithms based on the diagnostics rules outlined in standards, technical papers, industry best practice guideline, transformer name plate and criticality data; intelligent asset management applications can automatically determine the transformer's risk. The methodology takes all available data gathered using the online monitors as well as key transformer information and using a workflow engine passes it through a sequence of intelligent statements whilst also taking into consideration the criticality data for the transformer.

An integral aspect of fleet management and automatic transformer evaluation is ensuring that the application does not generate or raise false alarms, introducing concern where it shouldn't.

It is well known and regarded that each transformer is unique and can produce uncommon amounts of gases depending on their unique characteristics, design and operating conditions. In these cases, the variation in gas production is not a fault with the transformer but is a natural generation of gas under normal operating conditions. In order to compensate for this, the algorithms need the ability to be easily adjusted to recognise these uncommon gas levels.

The analytics engine must also be able to identify and ignore inconsistent data which falls outside of the normal data set and is often the result of external factors. Such data can skew the analytics and the evaluation performed on the transformer.

By making sure that they take these factors into consideration, fleet asset management applications can be trusted to provide a reliable evaluation of a transformers condition with which experts who have a deep knowledge of the individual transformers would agree with.

Dissolved gas analysis evaluation

Here is an example of how a dissolved gas and moisture analysis algorithm works.

When evaluating a transformer's condition based on DGA and moisture content in its insulation oil, the intelligence built into the algorithms is derived from information published in standards along with best practice and expert knowledge.

Before the main data analysis is performed, the algorithm must remove any DGA and moisture measurement that appears to be an inconsistent result. The algorithms must then consider the importance of the various gases when performing an evaluation. Each gas has its own importance depending on the diagnostic conclusion it represents and the determination presented in the industry standards and best practice guides. Figure 10 shows 7 key gases, CO2/CO ratio and moisture measured within transformer insulating oil and their importance in a risk scale.

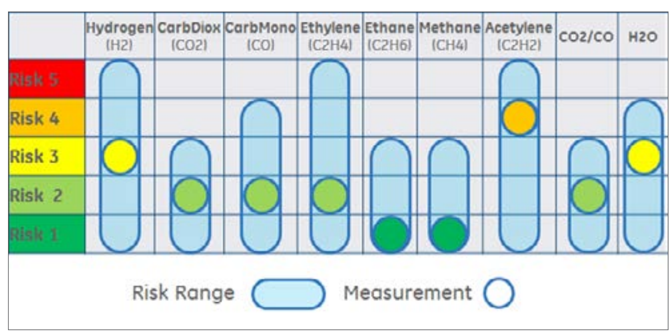

Figure 10: Absolute gas concentration analysis to determine risk index, as used in GE's Perception Fleet Software.

As you can see in figure 10, Hydrogen, Ethylene and Acetylene are key gases that can raise a Risk Index to 5 for a transformer, whereas Carbon Dioxide for example will only raise a Risk Index up to 3 because its presence and concentration is not seen as being an indicator of a serious fault or impending failure. The CO2/CO ratio can raise a Risk Index of 3 and moisture content can raise a Risk Index of 4. Although Risk Index 3 and 4 may not point to an impending failure of the asset. It will alert and prompt operators to perform further investigations, preventing premature aging of the asset due to life eroding faults.

The same consideration must be taken for the individual gases rate of change. Figure 11 shows that the potential for affecting the risk of a transformer differs between the rate of change time periods for each gas.

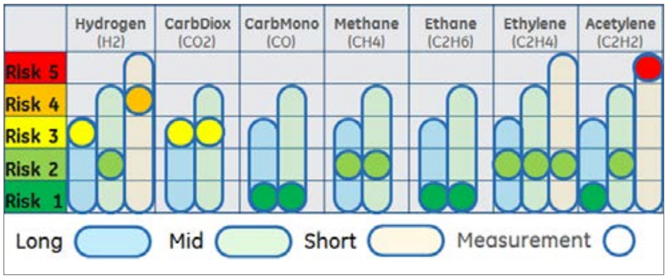

Figure 11: Gas rate of change analysis to determine risk index, as used in GE's Perception Fleet Software.

When the Risk Index is established for the dissolved gas and moisture concentrations, gas ratio and gas rate of change, the workflow engine then produces a single Risk Index for the combined DGA and moisture evaluation. The risk matrix in Figure 12 visualises the decision statement used to establish the Risk Index

		Risk Index for Absolute gas concentration (AGC) & Moisture				
		1	2	3	4	5
Risk Index for ROC	1	1	1	2	2	3
	2	2	2	2	3	3
	3	2	3	3	3	4
	4	4	4	4	4	5
	5	5	5	5	5	5

Figure 12: Risk matrix for absolute gas concentration and gas rate of change as used in GE's Perception Fleet Software.

The same procedure and intelligence is applied to all the measured data evaluated by the workflow engine and a Risk Index is established for each data set and algorithm. As well as outputting a Risk Index value, a condition statement is also generated as a result of the evaluation. The condition statement provides a description of the results of the algorithm, outlining why the Risk Index was designated.

The Risk Index evaluation is also influenced by name plate information entered into the system. An example of this is the impact on moisture analysis, which varies depending on the transformers rated voltage.

Once the Risk Index for each data set has been established the resulting Risk Indexes are cross-correlated. The final stage of the analysis looks at the transformer criticality information. The criticality details enable the workflow engine to perform a more in-depth analysis of the transformers risk and consequence of failure. This can be very important as the business, financial or environmental impact of a transformer failure is unique for each asset.

For Example:

An organization has a transformer with DGA monitor and an online bushing monitor. The DGA data is evaluated using the DGA and moisture concentration and rate of change algorithm. The transformer has a rated voltage of 400kV meaning the moisture content in the oil should be low. The bushing capacitance, power factor and partial discharge data is then evaluated using the bushing algorithm to check for drift from the expected norm. Each algorithm calculation results in a separate Risk Index, the Risk Indexes are then cross correlated. The criticality of the transformer is determined based on the details entered into the system such as availability of spares, proximity of the transformer to the public, ease of access for repair, oil containment system around the transformer, etc... A final Risk Index value is then established and output for the transformer.

Customizing the analytics

By customizing the analytics the evaluations of the assets and results become are more accurate. In turn this provides greater confidence in the evaluations putting experts, maintenance engineers and asset managers minds at ease. At a basic level applying a weighting factor on the algorithms enables the organization to define what they consider to be the most important measured evaluation result.

For example:

As in our example above, If bushing evaluation is seen as being more important than DGA evaluation the organization can set a positive weighting influence for the bushing algorithm. When the Risk Index results are calculated for the algorithms with the bushing algorithm result a Risk Index of 3 and the DGA evaluation result a Risk Index of 4, then the final overall Risk Index for the measured data algorithms returns a value of 3.

Providing an algorithm development tool along with the asset management software is key to allowing organizations to easily develop and deploy custom algorithms specifically designed around organizations best practices and unique asset characteristics. It may also allow organizations to utilise and cross correlate data held in the asset management software which is not currently considered as part of the 'out of the box' transformer evaluation.

Final result of the evaluation

Once all the evaluations are performed for the transformer a final overall Risk Index is calculated. The overall Risk Index is a single value representation established by the workflow engine evaluating the results of the measured data algorithms, criticality evaluation and name plate information.

A final overall condition statement is also generated for the transformer, along with the single Risk Index value. The condition statement is an amalgamation and summary of the individual evaluation results and explains why the transformer has been given its designated final overall Risk Index.

Visualizing actionable information

Once the Risk Index is established for the transformer, it is vital that this information is delivered effectively and can be easily understood.

'At a glance' identification

By colour coding the Risk Index categories, it makes it easy to identify assets within a particular Risk Index, drawing attention to the transformers considered to be most at risk. This is known as the traffic light system and is as simple as outlined in Figure 13:

5 – Dangerous defects that may cause faults
4 – Serious defects that may have serious consequences
3 - Defects that may affect future reliability
2 – Minor defects not affecting reliability
1 – Good condition

Figure 13: Risk Index colour coding and condition, as used in GE's Perception Fleet Software.

Dashboards are a great way of grouping and delivering important transformer information. Having a dashboard for each individual transformer, as well as a single fleet overview dashboard, provides a simple and concise way of conveying the most important information available.

Figure 14: Transformer dashboard as depected in GE's Perception Fleet Software. showing colour coding and trending of a transformers Risk Index

The ability to trend the transformers Risk Index over time, as depicted in figure 14, allows the end user to see if the transformers condition is improving or degrading and if their maintenance actions are having a direct impact on their risk.

Fleet management

Visualising the transformer risk information at a fleet level provides an overall picture of the entire fleet condition. It shows the risk categories which the transformers align too and which assets in the fleet are at the highest risk and are in need of most attention.

Figure 15: Fleet dashboard as depected in GE's Perception Fleet Software showing the fleet overview.

Capturing the average fleet Risk Index and its fluctuations over time as depicted in figure 15, provides a good indication of how effective the transformer maintenance program is, and if the correct individual actions are being taken. This enables the asset manager to see when assets move from being at a lower risk into a high risk and vice versa following repair or replacement.

This is an effective way of demonstrating progress in terms of reducing risk within a fleet in order to have positive effect on overall fleet reliability.

When it comes to monitoring a large fleet of transformers, a holistic approach is essential as the data and time required for analysis increases exponentially with the number of assets monitored. This has a direct effect on the resources required to analyse the information and make decisions.

Transformer fleet analytics and management software are designed to move organizations from a manual one-on-one transformer assessment process to an automated and online fleet management assessment. By continually evaluating the condition of transformers and establishing their risk of failure, software can automatically prioritize and rank assets within a fleet, focusing the expert's attention and budget expenditure on the crucial assets.

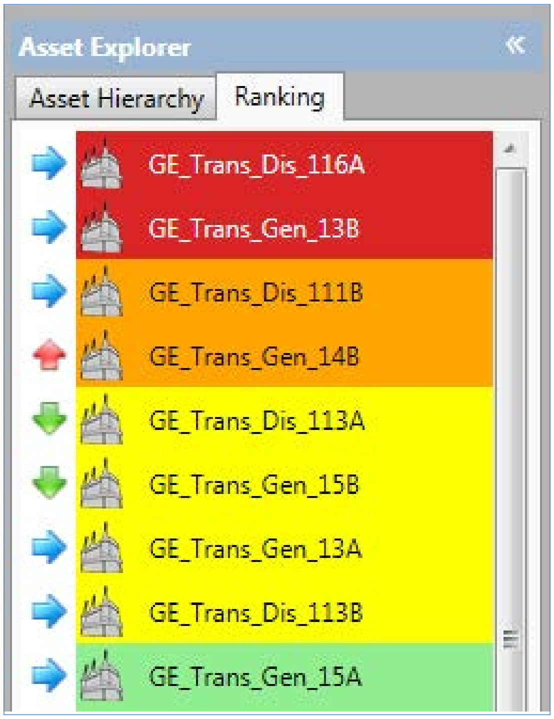

Figure 16: Grouping and ranking of transformers in a fleet based on Risk Index as depected in GE's Perception Fleet Software.

Conclusion

In order to achieve the operational savings expected and avoid unplanned/unnecessary outages or failure, new era asset management applications must provide analytics which can be trusted, have the ability to perform evaluations 'out of the box' and at the same time be flexible enough to be customised to the specific characteristics of the and organizations best practices after transformers.

New era asset fleet management software can perform a decisive role in transformer evaluation and fleet management. It can focus transformer experts and help free up their time for other critical tasks. It opens a bridge between transformer experts and higher level management, providing the information required to develop budgets, plan expenditures and make important business decisions based on the health of the entire fleet and individual transformers.

GE's Perception Fleet Advanced Asset Management Software incorporates all of the asset management application features described in this paper. It provides 'out of the box' transformer analytics with the ability to customise the analytics to the unique characteristics of transformers as well as organizational best practices. The visualisation within Perception Fleet was designed to provide simple yet powerful information about the entire transformer fleet. It provides high-level easy to follow and understand transformer and fleet condition information. Whilst also providing low-level detailed information that can be used by transformer experts to drill down and further diagnose and investigate transformer's condition.

For more information on GE's Perception Fleet Software, please visit:
http://www.gedigitalenergy.com/md/catalog/perception.htm

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