

## Condition Assessment Methodology for Power Transformers

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### SUMMARY

Electrical network operators in developed nations face an important challenge; asset management of rapidly aging networks. Aged power transformer fleets represent significant issues for network reliability. Power transformers are expensive and critical equipment in power systems playing a significant role alongside shunt reactors in the transmission and distribution of electricity. Although transformers are generally reliable pieces of equipment, failures do occur. There are many failure mechanisms in critical components and sub-systems that will ultimately limit the useful operating life. Anticipating the failure mechanisms and taking pre-emptive measures, known as predictive actions, are key for extending the life of electrical utility assets.

Power transformer users and asset managers must be adequately equipped to assess the condition of a fleet of transformers in service as a basis for making critical decisions about operations. Including, classifying candidates and priorities for, repair/rectification of minor failures, refurbishment or replacement. Users and asset managers need to understand all the failure modes of transformers to pinpoint the part of the transformer affected, and to implement appropriate responses. Broadly, there may be failures in active parts of transformers or their accessories due to dielectric, mechanical or thermal breakdown. Some sub-components also have their own unique failure mechanisms.

This article aims to focus on the work completed by the CIGRE WG A2.49, (TB 761) which sets out the failure modes, the tests and diagnostic methods that can be used to detect them, and methods of combining the available data into useful information in the form of assessment indices that can form the basis for decision making and intervention prioritisation in transformer asset management.

### KEYWORDS

Condition Assessment, Building Indices, Classifying Candidates, Risk-based Maintenance, Intervention Optimization

## INTRODUCTION

Identifying the critical components and implementing performance monitoring play a key role in degradation trending and component failure analysis. Utility engineers must distinguish the root causes between random failures, wear-out failures and failures caused by accelerated aging of critical components.

Condition assessment metrics and prioritization of maintenance activities are crucial in order to maintain the grid reliability by anticipating failure patterns. Before putting in place an efficient structure of equipment life cycle management, an electrical network operator must know its profile and adjust its life cycle management strategies accordingly. Prioritization of maintenance activities is the most challenging task of asset management. Best prioritization decisions are made based on reliable health indices, risk management, budgets, human resources considerations and most importantly long-term asset reliability planning.

Asset management engineers must implement proactive risk-based targeted maintenance and replacement programs based on performance metrics. Asset managers must have all the relevant data for accurate remaining life estimation. The data is collected from periodical inspections, online monitoring, failure pattern studies and benchmarking. A mathematical model and the collected data can be used to calculate the optimal periodicity for certain condition assessment activities. Each asset in a power transformer fleet can have a tailored condition assessment profile and an assigned periodicity for those actions based on the condition and the criticality of the asset for the utility.

## CHALLENGES

Rapidly aging electrical utility assets require a more complex life cycle management metrics. The industrial surge and the hike in demand in 60s and 70s resulted big expansion in power networks all over North America. In 2019, more than half of all power transformers in operation in North America are in near the end of their life expectancies. The main challenges remain to be the failure prediction, the prioritization of optimized life cycle management decisions such as targeted conditional maintenance, condition assessment, replacement and planning within specified budgets. Most utilities have yearly pre-set budgets for preventive and reactive maintenance activities. Increase in rate of delay in periodic condition assessment and maintenance activities increases the level of uncertainty in overall condition of the fleet. Planning and execution of field inspections and predictive maintenance activities within the given budgets based on condition assessment scores is another challenge that all electrical utilities are facing.

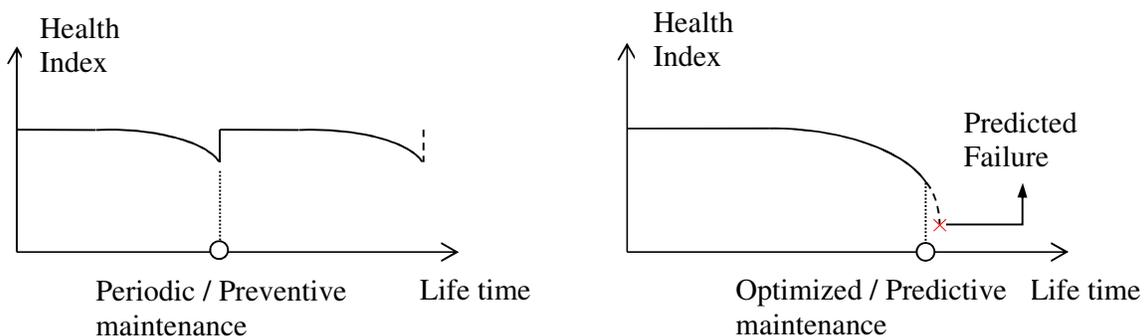


Figure 1 Preventive vs Predictive Maintenance

## **ASSET MANAGEMENT METRICS**

Life cycle management strategies of power transformers are dynamic and depend on many parameters such as the age distribution of transformer fleet, the complexity of equipment and the familiarity to equipment of the electrical utility. Every electrical utility is unique in defining condition assessment and prioritization of maintenance activities. Different approaches are used by utilities when it comes to deciding between risk-based or time-based maintenance centred on the health index of individual equipment or of the transformer fleet. Benchmarking the best practices, an electrical network operator must first recognize its profile. The profile is a combination of the fleet characteristics such as the age distribution and the complexity of assets, company work force profile and the long-term objectives of the operator.

A utility is as efficient as its performance analysis metrics. Investment on performance reporting is one of the key elements that will provide asset managers an important decision-making tool. Asset managers must analyse trends on performance of their transformer fleet and be able to anticipate possible reliability issues.

## **APPROACH TAKEN IN CIGRE WG A2.49 TECHNICAL BROCHURE 761**

An effective predictive maintenance program requires algorithms that would take into account multi-level failure mechanisms and condition assessment interpretations for a reliable model. Transformer Assessment indices (TAIs) are the foundation of an efficient predictive maintenance program. TAIs can be generated by calculating a score for each transformer in the fleet then using the assigned scores to rank the transformers. The five basic steps to develop a TAI are listed below; the complete guide can be found in the WG A2.49 Technical Brochure 761.

### **Step 1: Determine the purpose of the Transformer Assessment Score and Index**

Many asset managers currently use a health index for prioritising asset replacement. However, in many cases the index does not provide any indication of how quickly the worst transformers on the list need to be actioned nor does it provide any indication of the most appropriate action needed i.e. replace, repair or refurbish. This paper shows three examples of different uses of a TAI and some lessons learnt by utilities in creating an assessment score and index.

### **Step 2 and Step 3: Identify the failure modes and determine how each failure mode will be assessed in the TAI**

A clear understanding of the failure modes and interpretation of the results is necessary to ensure reasonable correlation between the asset's condition and the appropriate actions taken. The Technical Brochure includes a comprehensive guide to key transformer components, failure modes and suitable condition assessment techniques that could be included in an assessment index. Examples of some of the diagnostic testing and failure modes that can be included in a TAI are shown in Figure 2.

A deep understanding of a failure mechanism starts with the root cause analysis and determining how to detect the root cause before the failure. Certain phenomena's cannot be explained by a simple or multiple root causes or are not deeply understood. In these cases, it is crucial to determine the chain of events from the failure back to the possible causes. For

each possible cause, a symptom can be determined. For each symptom a condition assessment measurement can then be assigned to detect the symptom efficiently.

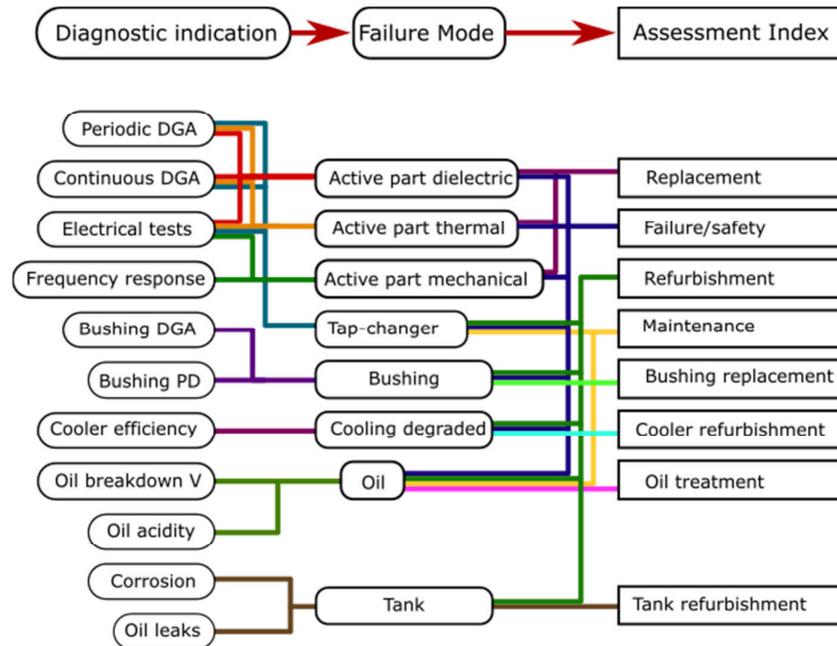


Figure 2 – TAI comprises of diagnostic testing and an understanding of the different types of failure modes.

**Step 4: Design a calibrated system for categorising failure modes (scoring matrix)**

An example of a scoring matrix has been developed by the working group. This matrix effectively has five levels. The 6th level labelled F, is not used when generating a TAI but is noted to consider very short-term failure criteria.

Table 1 – Example of a Scoring Matrix

F	De-energize as soon as possible. Don't return to service until problem is repaired. Component is at end of life.
E	Very Poor Condition. High likelihood of failure. Component is near end of life. Repair or replacement as soon as possible is recommended. De-rating or restricted operation of the transformer may be appropriate and operation under extreme conditions may not be appropriate until replacement is possible.
D	Poor Condition. Repair or replacement should be considered within the short term. Reliable operation may be impaired or compromised. Performance or component may be causing deleterious effects. Consider review of rating and operating condition.
C	Acceptable Condition. With significant signs of aging or deterioration. Reliable operation expected for medium term but consider condition-based maintenance if applicable.
B	Good Condition. Some signs of aging or deterioration are evident. Reliable operation expected for a lengthy period.
A	Minimal Signs of ageing or deterioration. As new condition.

**Step 5: Calculate a TAI Score for each transformer**

There are multiple ways to generate an overall score. The method chosen will depend on the purpose of the TAI (Step 1) and the individual user’s needs.

When designing the scoring system, the following points should be considered:

The scoring system should allow all transformers in a fleet to be ranked, such that those which are the highest priority for action or intervention are easily identified.

The scoring system result should be easily interpretable by any user, with reference to the purpose of the TAI, as well as transparent and reproducible.

Methods of Calculating a TAI Score include:

- Summation of individual failure mode scores;
- Weighted average;
- Non-linear mathematical approach;
- Numerical score using probabilities of failure;
- Worst case approach;
- Hybrid score;
- Count per category;
- Machine learning.

**Erreur ! Source du renvoi introuvable.** below for the advantages and disadvantages for each method of calculating a transformer assessment score (Prepared by WG A2.49).

#	Description	Advantages	Disadvantages
1	<p>Summation of individual failure mode scores:</p> $TAI = \sum_{i=1}^N S_{FM_i}$ <p><math>S_{FM}</math> is the score of an individual failure mode. A simple set of linear or non-linear scores would generally be added to the scoring matrix. Weighting can also be added as per method #2.</p>	<p>Simple algorithm Transparent Weightings can be added if required.</p>	<p>Poor condition assessments may be masked so that score may provide an optimistic indication of transformer’s condition. Using non-linear scoring may help to prevent masking Scores do not generally reflect urgency.</p>
2	<p>(Weighted) average:</p> $TAI = \frac{\sum_{i=1}^N W_{FM_i} \cdot S_{FM_i}}{\sum_{i=1}^N W_{FM_i}}$ <p><math>S_{FM}</math> is the failure individual mode score <math>W_{FM}</math> is the weighting per failure mode N is the total number of failure modes A simple set of linear scores or non-linear scores would generally be added to the scoring matrix. Weighting factors are applied to failure modes that the user wants to highlight.</p>	<p>Transparent Weighting allows some failure modes to be highlighted.</p>	<p>As above Weighting of failure modes, may mask further mask some failure modes.</p>

#	Description	Advantages	Disadvantages
3	<p>Non-linear mathematical approach:</p> $TAI = \sum_{n=0}^{k-1} x_n i^n$ <p>i is the number base / radix, which is equal to or greater than the number of failure modes included in the TAI  <math>x_n</math> is the number of failure modes per category  k is the number of categories included in the failure mode assessment  n is the counter in this formula.</p>	Masking of worse scoring failure modes is prevented.	<p>More complex scoring system</p> <p>The scoring results can be more difficult to interpret</p> <p>If weighting factors are also used, a slight modification of the formula would be needed to prevent masking.</p>
4	<p>Numerical Score using estimated failure probabilities</p> <p>A probability of failure, based on test results data and other assessment information, can be <i>estimated</i> for each of the failure mode. A score can then be calculated</p> $TAI = 1 - ((1 - \text{est. PoF}_{FM1}) \times (1 - \text{est. PoF}_{FM2}) \times (1 - \text{est. PoF}_{FM3}) \times \dots \times (1 - \text{est. PoF}_{FMn}))$	<p>The TAI score can be scaled if required</p> <p>Highlights single advanced failure modes and properly combines several less advanced failure modes for overall comparison</p> <p>Works well provided each failure mode probability, or score is on the same scale even if it is not a true probability.</p>	<p>It is generally only possible to estimate a very approximate probability for each failure mode</p> <p>Method might tend to indicate an unjustified level of precision.</p>
5	<p>Worst case approach</p> $TAI = \text{worst}(S_{FM})$ <p><math>S_{FM}</math> is the score of an individual failure mode</p> <p>It is also possible to indicate the number of failure modes which have been assessed with the worst-case score.</p> <p>Score = <b>Red 3</b> (transformer has 3 failure modes that have been scored as Red).</p>	<p>Simplest algorithm</p> <p>Transparent</p> <p>Worst case failure mode is highlighted.</p>	<p>Weighting of failure modes only possible if the number of failure modes assessed with the worst-case score is included.</p>
5 a	<p>Hybrid Score</p> <p>The worst-case score can be used in conjunction with one of the numerical scoring methods described above.</p> <p>For example, a simple summated score can be combined with a Worst-Case score. Scores would be of the form:</p> <p>TX 1 = <b>64 Red</b></p> <p>TX 2 = <b>64 Orange</b></p> <p>It is clear that TX 1 needs urgent attention, although its numeric score is the same as Tx 2.</p>	<p>Combines two simple scoring methods</p> <p>The simple numeric score gives an indication of the overall condition of the transformer and the worst-case score highlights the worst failure mode of the transformer.</p>	<p>A transformer with a single advanced failure mode, cannot be distinguished from a transformer with multiple advanced failure modes.</p>

#	Description	Advantages	Disadvantages
6	<p>Count per category</p> <p>The TAI is shown as a set of numbers, rather than an individual scalar value. The number of failure modes assessed as being in each category is shown.</p> <p>For example, using the five-colour matrix a score for a transformer with 12 failure modes assessed might be as follows:</p> 	<p>Very good visibility of the total transformer health assessment score</p> <p>Masking of worse scoring failure modes is prevented</p> <p>Weightings are possible if required and will not mask problems.</p>	<p>The TAI is not a single number but a set of numbers. This may make representing the result on a dashboard, or in other simplified forms more difficult.</p>
7	<p>Machine learning:</p> <p>The index does not use a predefined formula to calculate the assessment score, but instead uses modern data analytic techniques, where smart algorithms e.g. neural networks, analyse the condition data and failure data.</p>	<p>These techniques may find new correlations between condition indicators and failure modes, potentially enhancing the index quality.</p>	<p>Complex algorithms are required</p> <p>Large volumes of data are required (including failures)</p> <p>Not transparent. Results would need to be validated to ensure that the machine has 'learnt' correctly.</p>

Table 2 – Scoring advantages and disadvantages.

## DATA QUALITY AND OTHER CONSIDERATIONS

Data quality plays a big role in the calculation of asset condition score. Incorrect or missing information would impact the ranking of a certain asset and therefore the reliability of a predictive maintenance program. Whilst comprehensive asset knowledge is ideal when assessing a transformer, it is not always practical or cost-effective to obtain all possible test results and diagnostic information for all transformers.

A chapter in the TB suggest various techniques that can be used to manage missing information (uncertainty in the index), including subjective and quantitative techniques and includes several examples of the application of these techniques.

Another chapter discusses the role of on-line monitoring systems in the development and maintenance of transformer assessment indices, where significant volumes of data may be available for the assessment of some of the more critical failure modes of a transformer. The chapter notes that an assessment or index based only on on-line data may not cover all failure modes of interest, and that the on-line information can be used in conjunction with other diagnostic information for a more complete assessment.

Each electric utility has different views on design and life cycle management of power transformers based on the company profile and employee experiences. Definitions of maintenance activities may differ but the actual work at all electrical utilities are very similar. Before analysing the best practices, the utilities must first speak a common language. A common terminology is the starting point of any benchmarking study. With a common terminology, electrical utilities will be able to exchange notes with other utilities with similar fleet profiles on best practices, end of life estimations, interruption duration indices and risk matrix calculations.

Benchmarking between large electrical networks based common definitions and practices are essential in order to assess global energy trends. By using a common structure of performance metrics, utilities may compare their approach of asset management to other similar profiled utilities. Mergers and acquisitions between electrical networks would have a technical baseline of electrical equipment fleet assessment. Organisations like North American Electric Reliability Corporation (NERC) would be able to establish more efficient interconnection reliability score metrics.

## PRIORITIZATION OF LIFE CYCLE MANAGEMENT ACTIVITIES

As mentioned, prioritization of maintenance activities is the most challenging task of asset management. Best prioritization decisions are made based on reliable health indices, budget and human resources considerations.

One very efficient approach to prioritization is based on the current value of the equipment and the impact of not realizing the maintenance. Most utilities use risk matrices that rate impact and probability of failure of assets from low to high. Impact is a value calculated based on all the possible consequences in case of failure. Impact index of equipment can be calculated based on its location or its purpose. Transformers in strategic substations such as near hospital or near densely populated areas would have a higher impact index than the rest of the fleet. Probability is the likelihood of a failure. Risk matrix models often exclude the possible damage or replacement costs. Power transformer fleet is usually ranked and prioritized by means of an index that takes into account the risk score of individual assets.

$$Prioritization\ index = 10 * \log \left( 10^{\frac{C_{imp}}{10}} + 10^{\frac{C_{prob}}{10}} + 10^{\frac{C_{del}}{10}} \right)$$

$C_{imp}$  = Impact index: The relative index of the impact of nonfiction of the asset (usually between 1 and 9)

$C_{prob}$  = Probability index : The probability of a failure or normalized TAI (1-9)

$C_{del}$  = Rate of delay index : The uncertainty on health index in case of missing condition assessment information in a given period

## CASE STUDY

### TAI Case - TRANSFORMER SPARES ASSESSMENT INDEX

A distribution utility developed an index to assess the condition of their fleet of spare transformers and to determine which ones that are fit for service and ready for deployment. This index was also useful in helping to identify transformers which have reached their end of life and should be scrapped and those that require some repairs.

1 RED	Scrap - Suggested based on condition
2 ORANGE	Significant issues
3 BLUE	Ready for deployment with very minor work
4 GREEN	Ready for deployment

Table 3 – Scoring matrix for transformer spares

The source of the information was from:

- Visual assessments recording key information and photographs;

- Electrical tests e.g. insulation resistance, dielectric dissipation factor (DDF) or dielectric frequency response (DFR) of any condenser bushings that were fitted in the transformer and had test taps;
- Dissolved Gas Analysis (DGA) from a dielectric fluid sample from the main tank and OLTC taken at the time of visual assessment, but also reviewing any historic results available.

This assessment also evaluated the storage site or substation for bunding, transport access and security. There are many other considerations in making asset management decisions. CIGRE TB 248 “Economics on Transformer Management” describes a methodology that could be used in addition to the TAI, to arrive at a final decision.

“A transformer in perfect condition is of little value if the key parameters does not match the requirement for the system. The more substations that it can match, the more valuable it will become.

A transformer in poor condition, which can be used in a substation for which there are no other suitable spares, could be worth keeping and investing in repairs.”

Identify upfront what is repairable and then consider whether it is economical. Examples of repairable items are;

- Bushing and OLTC maintenance and bushing replacement
- Replacing desiccant in breathers
- Tank repairs and repainting
- Dielectric fluid - oil filtrations

After an assessment there is a lot of information and now the challenge is to combine that to a single number for ranking. If you only considered one aspect of information like only considering the degree of polymerization (shown in Table 4) or the assembly state (shown in 5) the index shows 54 and 59 transformers ready for deployment.

Category	#	Further description
Scrap	1	DP of 221, so close to end-of-life.
Significant issues	11	6 of these have DP above 400, so likely good for a decade or more in service. Ages are 53, 38, 36, 34 34, 33 years. 5 have DP between 300 and 400, so remaining life is fairly limited unless used in a location where they will not be heavily loaded. Ages are 47, 47, 38, 38, 23
Minor work	3	These are 43, 33 and 13 years old. The last one seems a surprise, but with a DP of 626 it still has plenty of insulation life
Ready for deployment	54	Transformers are “as new”

Table 4 – Investigation on the DP (degree of polymerization) as an indication of the active part dielectric condition or remaining life. DP values inferred from Furan results.

Note: Five transformers were not included in the list above because they either had no sample point with valve and/or assumed to be empty of oil and stored under nitrogen.

Category	# and description
Parts Lost	6 transformers had parts removed and could not be found
Parts Found	9 had parts removed, but these were found
Fully Assembled	59 transformers were fully assembled

Table 5 – Investigation on the assembly state of the spare transformers.

Users can utilise a combination of the scores/condition state for a more complete assessment. In the case above, the user had found one spare transformer in an as new condition but was missing bushings and therefore it was not ready for use until the bushing were found.

After completing an advanced condition assessment and combining all available sources of information, using a Hybrid Score (#5a Table 2) it is possible to make the following observations.

A series of score reduction criteria were also applied to help determine the overall index for the purpose highlighting deployment readiness. Some of the scoring reductions believed to be useful in this TAI are shown below;

- If a transformer is fully assembled it gets more points over units that have missing parts (refer to Table 5)
- Core/frame ground was scored very harshly because that could be an indication of transport damage for these transformers which is potentially very severe.
- The score was reduced for transformers in which there was a presence of potentially corrosive sulphur.

No reduction for “new” insulation but a significant scoring reduction for insulation that is at a DP 100 – 200, when it has reached end of life. In this example, the overall scores ranged between 40 and 97%, if a transformer had perfect responses to all questions it would equal to 100%. If this TAI is sorted based on readiness to be deployed the results are shown in Figure 3.

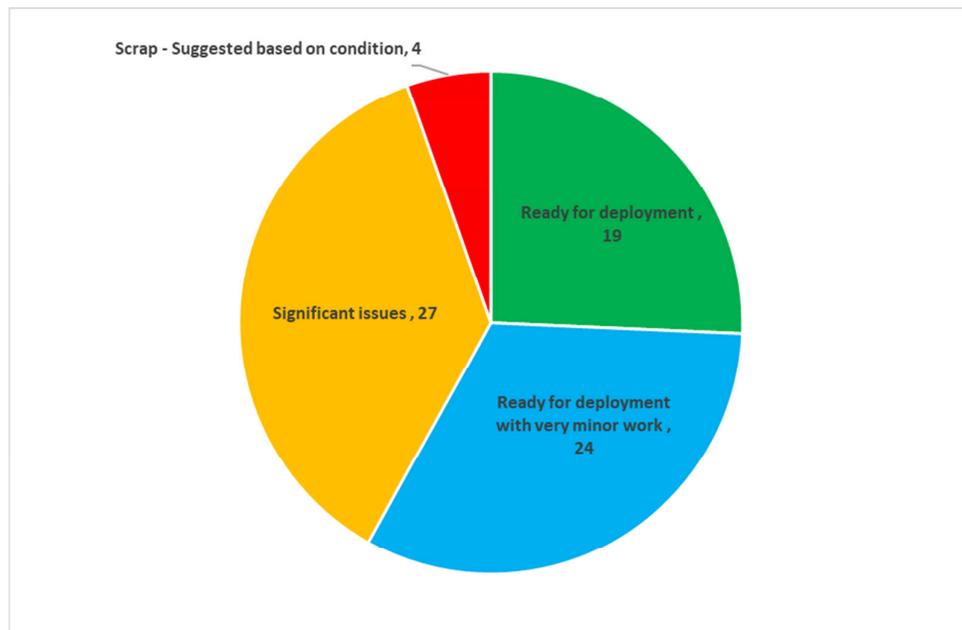


Figure 3 –Transformer spares assessment index

The top 27 transformers were all built this century. **Note:** there was no discrimination/weighting on age or year of manufacture, just physical condition.

Even some of the highest ranked transformers have minor problems.

In the blue category, shown above in Figure 3, some of those transformers had a bad test result regarding the presence of potentially corrosive sulphur resulting in their scores being reduced (by 5%). This is to reflect the increased risk of failure. Recently, numerous failures of transformers have been related to the formation of copper and silver sulphide on metal surfaces and copper sulphide deposits in the insulating paper in the windings (CIGRE TB 625).

Oil could be passivated to correct, but unless these are going to be heavily loaded, the risks of using as-is is manageable. Therefore, it could be argued that the 8 transformers in blue with just those issues could be moved straight to the green category, giving 27 transformers that are okay and ready to go, and 16 needing minor work.

In the significant issues category, also from Figure , 14 out of 27 are on this list for failing bushing testing. However, many of these bushing might pass with maintenance and retesting. As a worst case, the transformers can be fixed by replacing the bushings and can easily move up the list and not down the list. That is to say that this failure mode is repairable and not a recommendation for the transformer to be scrapped.

This example shows how a TAI can be helpful in determining the overall condition of a spares fleet and what repair work is needed on spare transformers before they go into service.

## CONCLUSION

Asset management engineers must implement proactive risk-based targeted maintenance and replacement programs based on reliable performance metrics. The development of a Transformer Assessment Index is an enabling method to help achieve this.

In developing an index, the transformer user or Asset Manager must have a clear understanding from the outset about the intended purpose of the index, as the purpose will determine how the index is constructed to ensure that the appropriate decisions are made. If a condition is detected indicating imminent failure, prompt action should be taken.

Developing a prioritization index requires a well-defined program that would include;

- (1) the transformer assessment index (TAI) based on the condition assessment data and
- (2) the impact index that is a relative score of the criticality of an asset based on its location and its purpose.

The main challenges remain to be the failure prediction, the prioritization of optimized life cycle management decisions such as preventive and predictive maintenance activities.

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### **Acknowledgments**

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