TRANSFORMER HEALTH ASSESSMENT: THE ETHEKWINI EXPERIENCE

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ABSTRACT
To successfully convert data into valuable business intelligence is the key in managing the life of what is often the most critical and high valued asset to every electrical utility, the Power Transformer. With a fleet comprising over 250 transformers ranging from 275 kV to 11 kV feeding directly key customers as well as a distribution network of customers, eThekwini Electricity's (eTE) HV Substations Branch has employed a system that not only provides realistic risk and consequences of transformer failure at a very early stage but also identifies units that require repairs, refurbishment or replacement. Asset information as per Section 4.3 of PAS55 pinpointing critical assets as well as Section 4.5 of PAS55 where the value of each asset is obtained are additionally features of this system.

INTRODUCTION
In 2011 eTE embarked on an asset management drive in order to ensure compliance with Electricity Regulator's requirement that Electricity Utilities conform to NRS 093 (which requires all licensed Electricity Distributors to have an Asset Management Policy in place) and the strategic decision taken by the organisation to ensure that they comply with PAS55. This led to the development of a long term Asset Management Policy and Strategy to guide all asset management improvement activities in line with the overall business strategy. PAS55 clearly defines hierarchical connectivity between the high-level organisation policy and strategic plan, and the daily activities of managing the assets. With power transformers being the most strategic asset in any power systems network, it is imperative for eTE to have a sound fleet strategy for managing power transformers that delivers directly to organisation's overall Asset Management Strategy.

One component of the transformer fleet strategy is the transformer condition assessement. The condition assessment of assets has a direct influence on a majority of the eTE Asset Management Strategy's key performance area such as information management, risk management, asset care plans, work planning and control, performance measurement and focused improvement. It was for this reason that in 2013 eTE embarked on transformer fleet condition assessment project thereby helping to accelerate eTE's asset management maturity. The project aimed at gathering condition assessment information and performance requirements for each transformer and establishing the planned actions required to meet reliability and performance targets.

ETE has a population of 252 power transformers, with power rating ranging from 315 MVA up to 15 MVA and comprising of fourteen 275/132 kV, thirty-six132/33 kV, one hundred and fifty-six 132/11 kV, forty-two 33/11 kV and four 33/6,6 kV voltage transformations.

Modern asset maintenance philosophies make emphasis on condition based maintenance which deals with understanding the probable condition of strategic equipment, such as power transformers. This approach is fundamental to prioritisation of maintenance spending and in establishing a condition-based reinvestment strategy for optimum system performance.

In order to embark on condition based maintenance, a complete assessment of the entire fleet is needed. Efficient assessments can recommend maintenance actions and strategies to extend transformer life, lower the risk of failure and use advanced diagnostics to augment missing data.

TRANSFORMER CONDITION ASSESSMENT
What we know about transformers is that their life expectancy can vary from a few cycles (ms) to more than fifty years. What we need to know is the life expectancy of a particular transformer in a given network. This fact is interesting and very useful. This is the essence of condition assessment.

Effective condition assessment is not just testing a transformer and reproducing the test results nor is it diagnosing the cause of a failure after the transformer has failed. CIGRE Working Group on Life Management Techniques for Power Transformers has defined condition assessment as *"A comprehensive assessment of the condition of a transformer taking into account all relevant information eg. Design information, service history, operational problems, and results of condition monitoring and other chemical and electrical tests"*. This is an excellent definition that encompasses all aspects of the transformer's life. However, can effective condition assessment be implemented in utilities with little to no information? By using an innovative and proven two phase approach for condition assessment utilities with little documented information can enjoy the benefits of a comprehensive condition assessment on all types of transformers in the network.

THE CONDITION ASSESSMENT PROCESS

The condition assessment technique followed is a two phase approach. Both phases include proprietary risk scoring system and combine analysis of individual units of similar designs with similar operating conditions and age.

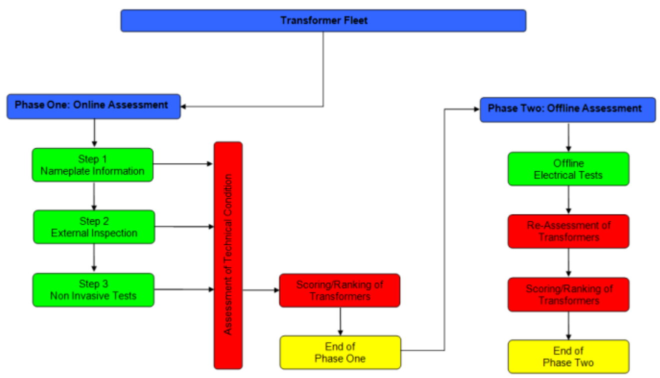

Figure 1: Transformer Fleet Management Process

Phase One

The first phase is an online approach where the transformer is not removed from service for additional testing. Phase one of assessment is a "scanning" approach and is more appropriate as a low cost assessment and step to provide "initial" risk assessment and ranking of transformers in a network. The first phase is essentially a review of available information. These include as much as possible of the following:

Step 1

Basic nameplate information from transformer and tap changer

Step 2

External visual inspection

Step 3

Review of all available documentation, such as:

- Factory test report - Used to compare with current test results and operating ability
- Purchasing specification - Used to compare to current manufacturing standards
- Tests results (electrical and oil) - Current data can be compared to Doble database for industry norms
- Failure reports - Indicates the rate of aging, availability and performance
- Maintenance practices - What are you doing?
- Major modifications or rebuild - Indicates the rate of aging generally expected
- Substation fault level - Changes in fault rating
- Loading - Used to calculate loss of life

Step 4

Consultation with all staff involved in the life management of transformers forms an integral part of this process in that this is a great source of information that has not been documented.

Step 5

Online testing

(i) Oil Quality Indicators

The oil quality indicators such as moisture (from which relative saturation is calculated), acidity, dielectric strength, and interfacial tension are excellent indicators of ageing oil. Poor results normally results in purification and/or regeneration of the transformer oil and it some cases oil replacement.

(ii) Paper Condition

The concentrations of the paper degradation product 2-furfural (2FAL) provide an indication of the condition of the paper. However, there are a number of factors that influence the concentration and stability of furanic compounds such as temperature, type of paper used, oil treatment etc. The use of the rate of change in 2FAL rather than the conversion of 2FAL to Degree of Polymerisation results in an excellent indicator of paper ageing.

(iii) Doble DGA Signature Pattern

Dissolved Gas Analysis (DGA) is the single most important test performed on oils from transformers. As the insulating materials in a transformer break down due to thermal and electrical stresses, gaseous by-products are formed. The by-products are characteristic of the type of incipient-fault condition thereby giving early warning signs of a developing fault that is an excellent trigger for further investigation. The Doble DGA Signature Pattern to analyse DGA results enabling earlier detention of faults, differentiate among thermal, dielectric and overheating faults and as well as stray gassing. The accuracy of the signature pattern increases substantially with DGA history.

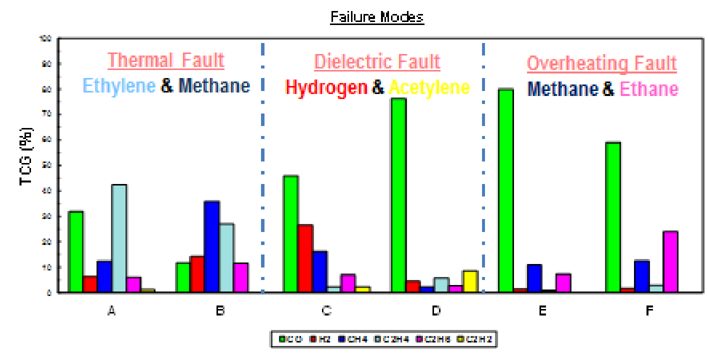

Figure 2: DGA signatures for faulty transformers

(iv) Infra Red (IR) Scan

IR Scanning involves measuring radiated heat, not contact temperature. IR is effective in indicating external joint issues, bushing tap problems, oil levels in bushings and radiators, blockages in radiators, fan function and can also indicate tank heating from stray flux, or frame tank circulating current. See Figure 3.

Figure 3: Typical IR faults

(v) Partial Discharge Scanning
Transformers like other high-voltage substation equipment are exposed to electrical, mechanical, and thermal stresses as well as environmental conditions. All of these stresses can act to accelerate the deterioration of the insulation and hence the electrical integrity of the HV equipment eventually leading to failure. Detection and measurement of partial discharge (PD) phenomena, which are symptoms of insulation deterioration, can provide early warning of insulation failure. PD occurs when the electric field strength exceeds the breakdown strength in a localized portion of the insulating material resulting in a localised breakdown of insulation (oil, paper) that results in a small current flow. Typical PD faults are shown in Figure 4.

Figure 4: Typical PD faults

Step 6: Overall evaluation of Phase One data
Once all the information has been gathered and the online tests performed, the transformers can then be scored based on condition. All units are assessed in terms of design groups with problems, overall condition, thermal and dielectric condition. Each aspect has its own score - a number between 1 and 100. Even with summation any aspect with a 100 score will be carried through and easily recognised. The results are assessed using this sum of the numerical scoring system and it is this sum that determines the position in the "league table" and summarised using a red-green colour traffic light code. It should be emphasised that the scores are not permanent but reviewed as new data is made available.

Phase Two
This phase is a comprehensive analysis of the transformer and requires offline testing. The standard offline tests are as follows:

- Power Factor and Capacitance
- Sweep Frequency Response Analysis
- Leakage reactance
- Insulation resistance
- DC Winding resistance
- Exciting current
- Ratio test

Rescoring the Technical Condition
Once all the offline tests are performed the thermal and dielectric condition of each transformer can be re-scored with greater detail. The re-scoring now includes the mechanical condition of the transformer. With the final scoring for the condition of the transformer now in place, a total risk of each transformer can then be calculated.

Outcomes of Phase Two
Once the rescoring has been completed the following is made evident:

- High risk transformers in terms of the dielectric, thermal and mechanical condition.
- More accurate overall condition as a result of the offline tests.
- An action plan in terms of units that require replacement, repair or monitoring.

The results of Phase Two assessment are merely added to the Phase One assessment.

ETHEKWINI ASSESSMENT

ETE has currently performed the Phase One assessment to all their power transformers. Each of the assessed transformers were scored and ranked in terms of risk of failure. In addition to the risk of failure, recommendations were also formulated either to perform further tests to ascertain the extent of the fault or what immediate action is required to reduce the risk of failure. Figure 5 below is an extract of the summary of the assessment is given below. The condition of transformers was assessed in terms of their thermal and dielectric condition.

Substation	Circuit	Recommendation	Overall	Thermal	Dielectric	Comments
Addington	T1A	Stray gassing test	6	3	3	No PD detected
Alice Street	T1	Drying techniques, oil regeneration, monitor furans and repair of oil leaks	269	3	266	High furans (2.33). High moisture (31ppm). High acidity (0.12)
Alice Street	T2	Drying techniques, oil regeneration, monitor furans and repair of oil leaks	262	3	[illegible]	High furans (4.43). High moisture (34ppm). High acidity (0.21)
Blair Athol	T2A	None	6	3	3	
Chatsworth	T1A	Oil regeneration, electrical testing and repair of oil leaks	185	3	182	Floating potential with high acidity (0.12). Oil leaks. PD detected
Chatsworth	T1B	Drying techniques and repair of oil leaks	86	3	83	High moisture (28ppm) due to oil leaks
Clermont	T2B	None	6	3	3	
Congella	T30/1	Monitor DGA, repair of oil leaks and load readings are required	103	100	3	Overloading/overheating fault
Dalton	T2	Oil regeneration and repair of oil leaks	87	3	84	High acidity (0.15)
Durban North	T2B	Drying techniques, oil regeneration, electrical test and repair of oil leaks	347	100	247	High furan (3.74). High moisture (23ppm). High acidity (0.12). Hot spot of bushing
Durban South	T1A	None	6	3	3	
Durban South	T1B	Electrical testing , monitor DGA and repair of oil leaks	103	100	3	Thermal fault since 2009. Event in 2007 possibly a trigger
Durban South	T2A	Electrical testing , monitor DGA and repair of oil leaks	103	100	3	Thermal fault until 2011. Since regeneration DGA signature has changed to dielectri
Durban South	T2B	None	6	3	3	First 315MVA Powertech transformer
Frametex	T2A	Monitor DGA and PD. Repair of oil leaks	103	3	100	DGA and PD required every 6 months

Figure 5: Phase One Assessment

ANALYSIS OF DATA
Transformer Vintage
The treatment of transformers by age is a matter of owner's internal policy. The age of a transformer can have a number of factors including the effect on the mechanical strength of the transformer's insulation and hence its ability to withstand common short circuit forces that are inherent in a transmission system. A further consideration is the relationship between advanced paper aging and transformer age. The relationship between the age of the transformer and its performance is a subject of great uncertainty. However, coupled with the other factors listed here the transformer's age can play an importance role in risk decision. It is common knowledge that transformers built and designed in the past have proven to be highly reliable with a low failure

rate for many decades. The introduction of advanced computer programming for design purposes have resulted in modern transformers having a low loading capability. However, it is noticed that older transformers may lack adequate provision for leakage flux and have a higher probability of localized thermal problems. Further, industry standards (IEC and IEEE) were revised to ensure greater short circuit duty for modern transformers. Figure 6 below shows the eTE transformer age distribution.

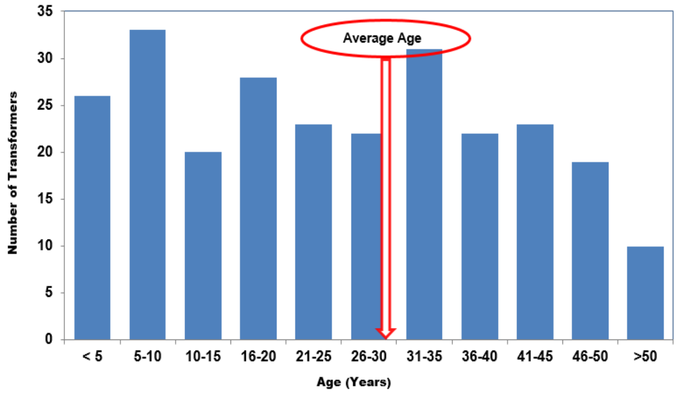

Figure 6: Transformer Age Distribution

Notes:
The date of manufacture was obtained from the transformer nameplate during the visual inspection phase.

This age distribution for the transformers is typical of what is seen in other utilities in South Africa of similar size to that of eTE. The eTE fleet has an average life of 29 years. This average life is also in line with industrial norms (utilities of the similar size in South Africa).

There is large installed base of transformers that are between 20 and 40 years old with a further significant population over 40 years old. This is a clear indication of an aging asset base. Due to the long service life of these aging transformers, maintenance records for these are not accurate as the information management was not advanced decades ago. Maintenance tactics were also of time based or reactive nature and these exposes the network to significant maintenance costs and high probability of failure.

Further, there is an increase in transformers between 0 to 5 years due to the replacement program possibly the result of failures of older transformers. This is a good indicator of transformer failures or an increase in demand of electricity.

Transformer Manufacturer

The place of manufacture or the manufacturer is a key indicator of quality related issues. The identification of dominating deterioration and failure modes for each design group/manufacturer can be used to identify the optimum diagnostic strategy to reveal the onset of failure modes.

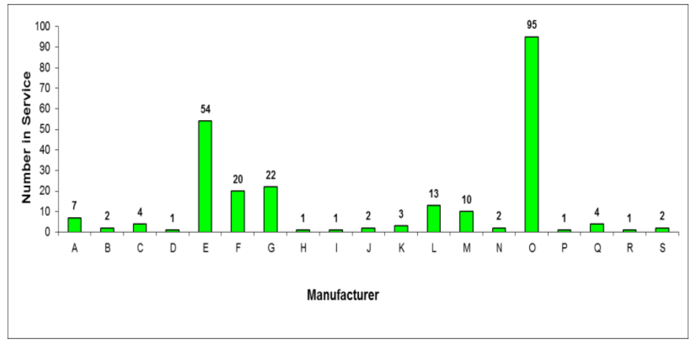

Figure 7: Transformer Manufacturers

Transformers of the same manufacturer and of same design (based on the serial numbers) have shown to have common fault characteristics. The fleet of eTE transformers, as shown in Figure 7 above, comprises units from 19 different original equipment manufacturers (OEMs). This large number of OEMs results in a significant transformer fleet diversity in terms of designs or vintage.

Transformer Faults

Figure 8 below illustrates identified different faults that are considered to increase the risk of a transformer failure.

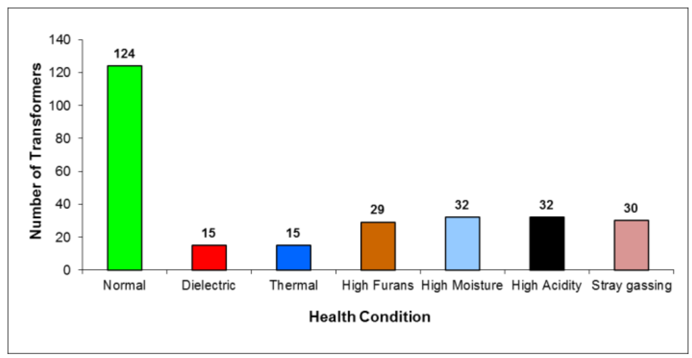

Figure 8: Transformer Condition Classification

All transformers were placed into the following condition classifications

a) Normal

Transformer that are considered to be in normal operation

b) Dielectric Fault

Transformers that are considered to have some form of partial discharge which was detected by DGA and RFI scanning.

c) Thermal Fault

The thermal condition of the transformer is assessed by considering faults that result in excessive temperature rise in the insulation or other parts of the transformer

d) High Furans

The levels of furans and the rate of increase of furans between samples is an excellent indicator of the age of paper insulation

e) High Moisture

Moisture in the insulation influences the life of a transformer in many ways: accelerating aging, increasing losses, reducing insulation strength and introducing the risk of bubble formation during overload

f) High Acidity

Acids in the oil originate from oil decomposition/oxidation products. Acids can also come from external sources such as atmospheric contamination. An increase in the acidity is an indication of the rate of deterioration of the oil, with sludge as the inevitable by-product of an acid situation which is neglected

g) Stray Gassing

The gassing pattern which is generated when the oil is subjected to thermal stress under what is considered to be low temperatures.

ASSET MANAGEMENT TOOL

The data gathered from the transformer condition assessment will further be coupled with an implementation of the platform to integrate the online and offline testing data, online monitoring data and SCADA data into one centralised system that will monitor the risk associated with the asset. See Figure 9.

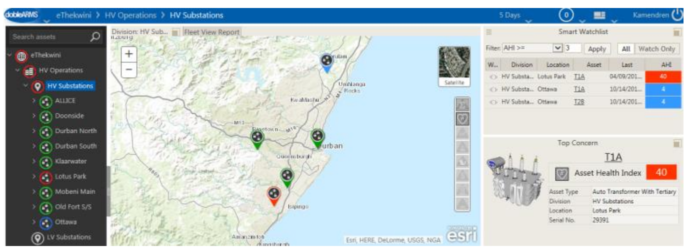

Figure 9: Overview of Assets Risk

This continuous process, will be able to monitor the assets in real time as well as update the asset management and operations management as to changes in the health and risk of an asset.

An asset risk management system is critical to showing an entire fleet's health and risk at-a-glance. The ranked asset health scores allowed for the utility to identify work priority and subsequent critical analysis helps to identify the consequences of failure and aided in scheduling work to mitigate the risk. Bringing data together and making it readily available, is a key to enabling tactical and strategic decision making. In addition this system will accept criticality metrics for safety, environmental impact, business interruption and financial loss, and is calibrated through a common denominator to ensure cohesion of analysis and results. By keeping track of the original risk quantities, eTE will be able to address risks as they develop and manage plans for intervention. See Figure 10.

IM Report

Location	Asset	Serial Number	Manufactu...	AHI	IM Assessment Score	Arcing	Partial Discharge	Thermal Fault Oil	Thermal Fault Paper	Thermal Cellulosic Decomposition	DobleLab TRF	IEC DGA	IEEE DGA	Oil Quality Evaluation
Lotus Park	T1A	29391	ABBPT	40	65	63	67	77	27	44	88	6	35	100
Ottawa	T1A	31084	ABBPT	4	4	2	7	2	2	1	1	2	8	5
Ottawa	T2B	W1161288	ABBPT	4	4	6	2	2	2	1	4	1	1	5
Doonside	T2	80706	EE	2	0	0	0	0	0	0	0	0	0	0
Klaarwater	21 4	30117	ABBPT	2	1	1	1	1	1	1	1	3	1	2
Klaarwater	TX21 5	30881	ABBPT	2	1	1	1	1	6	1	2	1	1	5
ALLICE	T2	29040	A-BB	1	0	0	0	0	0	0	0	0	0	0
Durban North	T1A	28757	ASEA	1	1	1	1	1	1	1	1	1	1	51
Durban North	T2B	28758	ASEA	1	1	1	1	1	1	1	1	1	1	51
Durban South	T1A	K2092	GEC	1	1	1	1	1	1	1	1	1	1	50
Durban South	T1B	28622	ASEA	1	1	1	1	1	1	1	1	1	1	6
Durban South	T2A	28623	ASEA	1	2	1	1	5	2	1	1	8	3	2
Durban South	T2B	31064	ABBPT	1	1	1	1	1	1	1	1	1	1	5
Lotus Park	T1	25965	ANSALDO	1	1	1	1	1	1	1	1	1	1	6
Lotus Park	T2B	29392	ABBPT	1	1	1	1	1	1	1	1	1	1	50

Figure 10: Transformer Health Index

CONCLUSION

Transformer condition assessment program can be effectively introduced by using this two phase approach. This method of condition assessment can be implemented irrespective of the amount of information. ETE has achieved the following benefits from this assessment program:

- Knowledge into the current health of transformers and identified normal, suspect and high risk transformers.
- How to effectively respond during trip or outage
- Plan outages for maintenance or repairs.
- Put procedures in place to replace aged or suspect transformers.
- Identification of design weakness.

A further advantage is the risk assessment and residual life can finally be achieved through sound engineering principles.