Transformer condition monitoring: making the electrical connection

By S Kuwar-Kanaye, Impact Energy

There is increasing pressure on large power users to engineer value back into the bottom line, particularly in areas of equipment and asset management, capital cost optimisation and life expectancy management. The fault-free operation of power transformers is of major economic and safety importance to power utilities and industrial consumers of electricity. Gas formation in transformers is attributed to two principal causes, ie electrical disturbances and thermal decomposition.

Detecting early signs of deterioration

Modern networks, with their varying complexities of load types, line interconnection requirements and harsh operating environments, place a greater need for key transformers on their systems. The cost of a power transformer is high, but monitoring its performance and its immediate environment is inexpensive compared to the costs of a failure and an interruption in power supply. An holistic approach to condition monitoring is essential for the transformers and the networks in which they operate.

There has been extensive progress in the field of Dissolved Gas Analysis (DGA) of the insulation oil for evaluating transformer health. The breakdown of electrical insulating materials and related components inside a transformer generates gases within the transformer. The identity of the gases being generated can be useful in a preventive maintenance programme. By reviewing the trends in the information provided, maintenance teams and reliability engineers can make a better judgement as to frequency of maintenance and detect early signs of deterioration that, if ignored, would lead to an internal fault.

There are fairly accurate guidelines, tolerances and limits for analysing the data of the chromatogram of oil-dissolved gases to determine the condition of the power transformers and consequently identify faults or problems while still in the incipient phases of development. However, finding linkages, trend analyses and patterns between DGA and the electrical network condition or Power Quality (PQ) monitoring may be useful in establishing the pre-cursors to incipient faults and consequential failure modes. Therefore, building databases of PQ data as well as data of chromatogram of oil-dissolved gases, is a developmental science that allows further advancements in asset life expectancy management.

Where advancements in DGA have been made over several years, now with the increasing accuracy of early fault detection in transformers, the same demands are placed on the reliability and availability of electrical PQ data that are aggravators and contributors to transformer failure.

Failure modes

Transformers age naturally and can deteriorate faster than normal under the influence of agents of deterioration (eg failure occurs when the withstand strength of the transformer with respect to one of its key properties is exceeded by operational stresses).

Operational stresses are usually dominated by events and conditions such as lightning strikes, switching transients, system voltage and frequency, load removals, short-circuits, overloading, harmonics, poor Power Factor (PF), increased losses resonance, inrushes due to large motor starts, and the like.

Harmonic currents increase the core losses, copper losses and stray-flux losses in a transformer. These losses are of no-load losses on load losses. No-load loss is affected by voltage harmonics, although the increase of this loss with harmonics is small, and has two components: hysteresis loss (due to non-linearity of the transformers) and eddy
current loss (which varies in proportion to the square of frequency). Excessive harmonic currents contribute to overloading and additional power losses in the transformer and, in extreme cases, can lead to high thermal stresses and early ageing. A transformer’s theoretical life expectancy of 30 – 40 years can be reduced to as low as 15 – 20 years owing to early ageing caused by increased harmonics pollution in the network. Most of the time, the effects of harmonics are hidden and not immediately visible.

The combination of harmonic currents and high grid impedance aggravates voltage distortions in the network and, in extreme cases, can shift zero-crossing points of the supply voltage waveform. This increases noise and electromagnetic interference in the network transformers, cables and Power Factor Correction (PFC); capacitors are the network components most affected by PQ disturbances.

Another concern is the presence of ‘triple-n’ harmonics. In a network, it is mainly the LV non-linear loads that produce harmonics. With a Medium Voltage (MV)/Low Voltage (LV) transformer of \(\Delta/Y\) configuration, ‘triple-n’ currents circulate in the closed delta winding. Only the ‘non-triple-n’ harmonics pass to the upstream network. When supplying non-linear loads, transformers are vulnerable to overheating. Increased loading can overstress the transformer and risk its premature failure.

It is common understanding that fast transient overvoltages do exist and can cause damage on transformer windings. There is an increasing trend of transformer dielectric failures in the system, some of them with no specific causes. However, a number of unknowns remain regarding this issue with reference to transformer design and testing (particularly its insulation), transformer protection and interactions between transformers and fast transient system ‘sources’ such as circuit breakers, capacitor banks, and power electronics.

Digital simulations show that voltage stresses across transformer terminals are usually restricted to frequencies in the range 40 kHz to 200 kHz. However, when these stresses are compared with the specified standardised waves, they may exceed the transformer withstand design.

PQ conditioning or improvements and maintenance strategies, should be adopted to enhance the lifetime of network components and reduce failure rate. Power quality conditioning is fast becoming a ‘must have’ as a means of increasing PQ performance levels in the network to the desired level. Investment in PQ conditioning has to be approached by carefully analysing PQ issues, establishing baselines and performance targets for engineering value and fulfilling the expectations of business financial investment models.

**Common goals**

The fundamental objective of life management can be defined simply as ‘to get the most out of an asset’ by ensuring that actions are carried out to promote the longest possible service life or minimise the lifetime operating cost, whichever is most appropriate. Key planned actions include the areas of: specification, procurement, design review and manufacture, maintenance, condition monitoring and diagnosis, reha

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*Figures 1 and 2: DGA and harmonics spectrum (sample data only. No correlation exists, used for illustrative purposes only).*
bilitation, refurbishment and remedial work, life extension. To overcome the demands associated with continuous electrical condition monitoring of critical assets and networks, certain analysers empowered by patented PQZIP compression technology, make it possible to store up to 1 000 times more than other typical file formats.

- Continuous waveform recordings: the device is able to record and store all electrical waveforms, all the time, for more than a year (voltage at 1 024 samples per cycle, and current at 256 samples per cycle) with no gaps in data. These innovations provide a clear and comprehensive picture of conditions leading up to, during and after an event.
- Superior accuracy: the measurement uses the dual gain of 2 x 16 Bit to yield a superior accuracy, surpassing IEC 61000-4-30 [1] Class A requirements, thereby capturing the finest details and deviations in PQ and network condition parameters.
- Threshold-free set-up: the set-up is free from any thresholds, triggers and events. If required, during set-up the device may be programmed with individual parameters for event flagging PQZIP takes the guesswork out of PQ and condition monitoring. It allows the analyser to continuously store the waveform of one or more power signals, regardless of whether or not an event of interest has been identified. Applied at different points and locations, the time synchronisation algorithm enables two or more devices to be synchronised with one another and provides a complete and comprehensive picture of the entire grid.

Under the guidance and development of experienced work groups,
PQ data conditioning, including acoustic sensors and piezoelectric transducers, infra-red receivers, special sensitive microphones, radio wave receivers, hermography, etc. It is difficult for individual engineers to build up sufficient first-hand experience of problems and how to deal with them. In addition, failure processes in transformers are often complex and agreement between manufacturers, utilities and academists to share knowledge is necessary if these processes are to be understood, and solved. By co-operating in this way, problems experienced by individuals, their causes and possible remedial actions, likely coloured by local practices, can be combined and converted to general knowledge and theory.

**Factors to consider:**
- Initiation of failure
  - What caused the failure to occur when it did?
- Ageing aspects
  - In what respects did ageing or wear-out contribute to the failure?
- Pre-existing fault
  - What indications were there of any pre-existing faults prior to the failure?
- Initiation of the pre-existing fault
  - What initiated the pre-existing fault?
- Other relevant information
  - Provide other information considered to be relevant to the failure

**Trend analysis**
For many diagnostic tests, the way in which measured results change with time can provide valuable additional information. Some techniques rely heavily on trend analysis, whereas others can provide a diagnosis from the results of one measurement. A rising trend, particularly when the rate of change is increasing, is probably a definite indication of a serious problem or at least something to be investigated further.

**Use the tools in the toolbox**
Condition monitoring is important to guarantee the safe running of power transformers. With condition monitoring, unexpected failures can be avoided by quality information from various sources relating to real-time, continuous and on-line. Moreover, with condition monitoring, maintenance of power transformers can be condition-based rather than periodically-based. The physical processes of failure are not an exact science and the monitors usually set up mappings between the faults and their appearances and then diagnose the faults with pattern recognition techniques.

**Conclusion**
Indication of potential problems within transformers should not be limited to the concentration levels of the key dissolved gases. PQ monitoring opens a new approach to anomalies on a network for further understanding of contributors to asset degradation.

Depending on site-specific conditions, once the initial links are made between PQ data and typical condition monitoring such as DGA, it is important to benchmark alarm levels depending on the tolerance to risk of the maintenance personnel and on the maintenance budget available. This benchmarking could be key to making the electrical connection in condition-based monitoring of critical assets.

**Reference**