Transformer Asset Management-Life Extension, Real Time Status and Enhanced Loading Potential Using State of the Art Monitoring Control and Communications.

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1. Introduction

The paper will explore the benefits of the current state of transformer management systems and condition monitoring, the ability for utilities to extend the life of their transformer assets while obtaining the added value of higher loading capacities through real time monitoring control and communications.

2. Transformer Management Systems – Uprating with Safety

Electrical utilities in general have experienced radical changes over the past few years. Cost and competitiveness have become common business drivers and tight business management is now the norm. Overcapacity is a thing of the past, it is a luxury that can no longer be afforded. Assets must be driven harder to keep costs low, yet without loss of customer service and reliability. Quality of supply measurements quickly show up poor performance. At the same time, networks have become more difficult to operate as they approach their capacity limits and redundancy options dwindle. In order for a utility to operate successfully in this environment, better tools are needed to permit efficient network management.

Power transformers represent one of the key components in most utility networks. They are the single most costly items in a substation and can become strategic bottlenecks in a power network system. Significant opportunities for improvement in transformer management as a network component have become possible. This is through new technology that has been developed specifically to address the issues utilities currently face. This paper compares traditional transformer operating practice (which can be equated to “flying blind”) with the approach taken and features available when an effective TMS (Transformer Management System) is employed. Particular emphasis is placed on operating above nameplate and how it is achieved through dynamic rating without compromising safety on either new or existing transformers.

3. Reasons for Investing in Dynamic Rating

Dynamic rating is touted as a transformer management feature of value. Let us examine why.

As stated by Russell [1], "As asset utilisation is increased, the spare capacity once available in the system becomes increasingly scarce. The day-to-day operation of the power system becomes more and more difficult. If the network is going to be run closer to an overload state without damage, we need a better system of monitoring, predicting and acting to prevent damage. It is important that support and decision tools are available to the system operators to ensure effective and efficient management of the power system is achieved and to take automatic action if an operator does not react quickly enough to prevent possible damage”.

"Traditionally, the rating that operators use to run the power transformers has been prepared well in advance and is based on worse case assumptions. Factors such as wind speed and direction, solar radiation, ambient temperature, pre-load can all affect the real-time rating of plant commonly utilised in the electricity industry. For practical reasons, it is necessary to make a number of engineered assumptions about these factors based on the utility’s operating policies when determining the rating of plant. We should also recognise that for any given event when the transformer is running close to its pre-determined rating, the environmental or other conditions may not approximate the assumptions that we have made for these factors very well or at all. In most cases, the utility does not expect the system operators to re-evaluate the ratings on the fly during the system emergency i.e. the system operator should operate the plant within the rating prepared without compensating for current conditions. Therefore, by necessity, for most actual conditions the pre-determined thermal ratings are generally conservative to ensure the transformer is operated safely. This approach invariably yielded very conservative rating figures because of the need to make worst case assumptions. A significant increase in ratings can be assigned, if the actual operating conditions are used to continuously calculate an accurate thermal model for the plant.

"What is needed is a cost-effective technique for maximising the asset utilisation of transformers through real-time monitoring and control while ensuring the transformer is operated within its design parameters. By leveraging the information available through the real-time control and monitoring system, the transformer can be operated to its maximum safe load and its life can be maximised." Another economic gain to be made through the implementation of dynamic ratings is reduction of the following; losses, costs of spinning reserve, running less efficient plant to bypass percieved bottlenecks in the system. Funnel has reported savings by NGC of over $600M per annum largely through the application of dynamic ratings that allowed more efficient operation of the system.

Management of the power network based on ‘fact’, rather than assumption, has become increasingly important as electricity utilities worldwide are faced with ever increasing commercial demands and constraints. Energy utilities must maximise shareholder value through continual improvement and innovation. The techniques described here can have significant impact on the utility’s bottom line."

In order to understand how dynamic rating works we firstly need to review standard transformer rating.

4. Transformer Rating

The rating of a transformer (or maximum allowed loading) is governed by thermal considerations and is based on a simple model. Energizing a transformer results in losses in the core and windings which become hot, causing the oil temperature to rise. Increased loading increases the losses and hence the temperature. The highest temperature in the winding must not exceed the allowable design limit. It is not possible to measure this hot spot temperature directly, so the top oil temperature is measured instead and various methods have been employed to simulate or estimate the WHS (Winding Hot Spot) temperature, with varying degrees of success. See Appendix for more information on these as well as fibre-optic direct WHS measurement systems.

Since factors such as ambient temperature, wind speed and direction, etc. also influence the WHS temperature, the transformer rating is based upon defined values for these factors. Loading guides define limits to loading based on various criteria related to the relevant factors. However, it should be stated that the figures are for transformers in good (“as new”) condition and generally assume a worst case environmental situation.

Under transient conditions the rate of rise of oil and winding temperatures depends on the difference between rate of energy generation and dissipation and on the thermal time constant of the transformer and its components. It therefore becomes more difficult to simulate or estimate the WHS temperature when load and environmental conditions are changing.

5. Static Rating

Transformer condition has a bearing on loadability. In an aged transformer for example, if the solid insulation moisture content is high, bubbling could commence at temperatures well below the design limits. Thus the actual transformer condition must be assessed and taken into account before setting realistic limits to loading for that transformer.

Traditionally the loading guides have been used to prepare static thermal ratings for transformers for various ambient and operating conditions. Some SCADA and substation control systems include transformer thermal models with continuously monitored load currents, and sometimes, ambient temperatures.

Typically this static thermal rating makes it possible to load a transformer 10-20% above nameplate rating for extended periods without risk of damage, but this is still not dynamic rating.

6. Dynamic Rating

The Dynamic Rating of a transformer is the maximum load possible without exceeding predefined thermal and current rating limits, based on real time measured ambient and transformer temperatures, condition, cooling status and load. In addition to real-time measurements and calculations for dynamic rating, advanced transformer management systems employ enhanced thermal models which are intrinsically more accurate. A transformer may typically be loaded a further 10-20% higher (above static rating) and with greater confidence with such dynamic rating than with static thermal rating. Instead of "flying blind" when operating close to the limits, dynamic rating provides timely and accurate information as to what the real thermal limit is at any point in time.

The "what-if" dynamic rating information can be presented in two ways [2]:

1) Max Load: Given the present (or pre-defined) conditions such as ambient temperature, transformer temperature, load and LTC position, what is the maximum load that can be carried for a specified time without exceeding the preset load and/or thermal limits?

2) Max Time: Given the present (or pre-defined) conditions as the starting point, how long can the transformer carry the present (or pre-defined) load without exceeding the preset load and/or thermal limits?

Taking advantage of dynamic rating can result in very large savings due to deferred capital expenditure and reduced number of outages.

A 1998 survey, conducted with a representative sample of US utilities for a prior Doble paper, revealed that approximately 30% of utility customers were moving toward some form of increased or dynamic loading policy [3] "In a more recent survey of 63 member utilities of the Edison Electric Institute (EEI), regarding transformer loading practices, revealed that over 75% allowed regular short-term overloading of their transformers. The survey also confirmed that many utilities use dynamic loading methods that accelerate a transformer's aging process in order to obtain additional output during contingency conditions." [4]

Since the uprating is achieved without exceeding predefined thermal and current rating limits it is not only completely safe, but the very fact that such intimate knowledge of winding temperature and condition is continuously available in real time leads directly to several other advantages. Some of the more significant are:

Increased reliability and reduced risk of unplanned outages

Opportunity for reduced maintenance costs by implementing condition-based maintenance

Life consumption tracking.

But these are only some of many benefits of an effective transformer management system.

7. Monitoring

Depending on the system employed and the features implemented, the operational data to be monitored may include: single or three phase amps and volts, watts and vars; frequency; tap position; ambient, oil and winding hot-spot temperatures; tap changer status and cooler status. As a minimum, to implement dynamic ratings, one needs to monitor load current, ambient air temperature in the vicinity of the transformer coolers and transformer top oil temperature. Further improvement in accuracy may be obtained by monitoring tap position since this affects losses and temperature rise.

Where available, additional support for operational decisions is obtained using fibre optic probes to directly measure temperature spots, although this is only possible on new windings since the probes must be fitted during manufacture.

Improved accuracy of temperature measurements on existing transformers can be achieved using electrical sensors compared to traditional capillary tube instruments. With the modern TMS systems this feature is available. This is important because the ageing rate of cellulose insulation increases rapidly with temperature. Oil and winding temperatures can be both measured and calculated (from ambient temperature and load), enabling the thermal model parameters to be calibrated to great accuracy.

Transformer condition assessment parameters are also monitored and can be integrated into the TMS system. These could include any combination of the following:

Moisture in oil
Dissolved gas in oil
Bushing gamma or tan delta
Partial discharge
WHS direct temperature measurement
Oil dielectric withstand

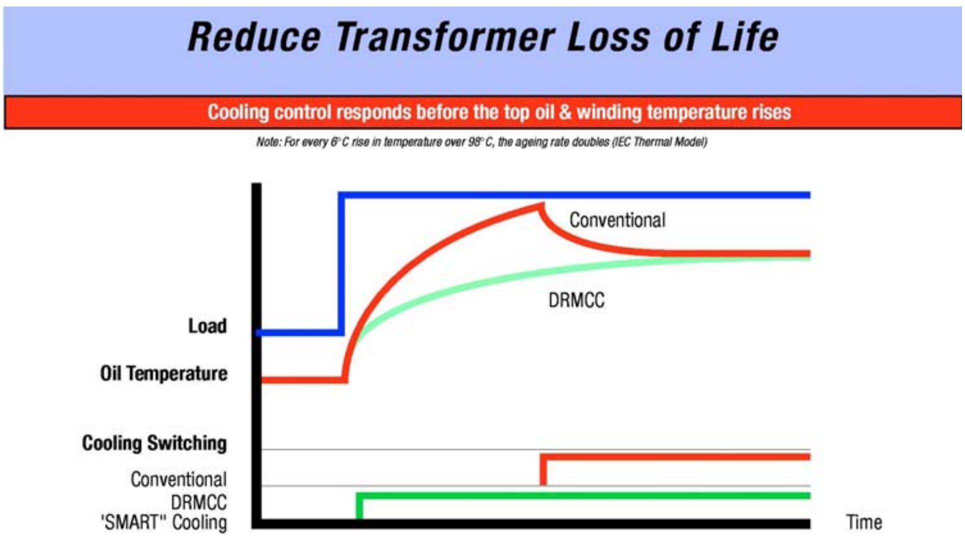
The particular parameters measured depends upon the criticality of the transformer. The existing transformer service history may also have an influence. The recommended philosophy is to monitor just sufficient diagnostic information continuously on-line to give a reliable early warning of potential problems. This can then trigger more thorough diagnostics and site testing as required. This approach leads to savings in monitoring equipment and maintenance costs, improved reliability and reduced down time.

The TMS can also keep track of fan and pump run hours, transformer ageing rates and accumulated age (life consumption) and the number of tap changes for each tap position. Event recording and data logging facilities are also usually included to facilitate incident analysis and fault investigations.

8. Cooler Control

Typically in a conventional TMS the cooling fans and pumps are turned on and off automatically at the respective temperature set points of the top oil and winding hot spot. They may be manually or automatically controlled.

An advanced TMS should have a “Smart Cooling” feature, that on sensing a sudden increase of the load it predicts what the ultimate winding temperature is going to be, and would start the cooling fans and pumps immediately to cool the transformer without having to wait for the temperature to reach the set point. The TMS predicts (based on present temperatures, tap position and load) where the top oil and winding temperatures are headed. If a higher than normal temperature is predicted the cooling is turned on immediately. Thus, the insulation will not be exposed to the high temperature and unnecessary ageing that it may have otherwise experienced.



For some transformers the fans and pumps may not need to run for long periods because of light loads and low ambient temperature. It is vital that when they are required to run, they will run. The fans and pumps can be programmed by the TMS to “exercise” them periodically to detect any faulty equipment. In the event of failure of a temperature transducer or its own communications or power fails, cooling is switched on (“Fail Safe”).

The TMS should also be able to determine when a sensor fails and provide an alarm when such an event occurs and again switch to a fail-safe mode of operation.

9. Voltage & OLTC Control

The TMS should be able to control and monitor the secondary voltage and OLTC. Following are the optional voltage control configurations and modes of operation:

Independent Manual
Independent Auto
Master Manual
Master Auto
Follower
Reverse Reactance
Vars Sharing
Circulating Current
SCADA Control (Direct commands or changes in setpoints or tolerances)

Alarms can be generated if the control voltage is outside tolerance for too long, or if a tap change fails to complete once initiated. Control of two- and three-winding transformers, separately and auto wound is also possible.

The TMS can also monitor and track frequency of use and wear factors of individual tap positions so that maintenance scheduling can be optimized.

10. Communications

Instead of a multiplicity of devices, the Transformer Management System serves as a single point of communication with the outside world, thereby greatly simplifying communications and facilitating access to information about all aspects of the transformer operation and status. All this information is available in real time and is of value to many different groups in the utility through a common web server type interface.

There are 4 primary hardware communication connections that are most common: SCADA, modem, LAN/WAN and Internet.

The TMS system collects a wide variety of information including real time operational information, condition status, maintenance indications and asset life consumption. Each piece of information may be important to one or more groups within the utility. When specifying a TMS system, it is very important to consider how that system can benefit all areas within the utility.

11. Savings

Dynamic rating enables controlled emergency loading beyond nameplate rating and beyond what is possible with conventional static thermal rating based on the loading guides, without undue risk.

When sufficient continuous on-line monitoring is installed to provide early warning of most types of potential problems and faults, further large savings can be achieved by:
• Reducing the risk of failure and improving reliability
• Reducing maintenance costs by using condition-based rather than time based maintenance.

Improved control and communication capabilities facilitate the trend to unmanned substations and reduced frequency for operators and maintenance personnel visits to substations.

The added cost of putting a TMS system on a transformer is typically 2-5% of the total transformer cost. Power transformer users stand to harvest many benefits from the added information and improved control. The relatively small cost can improve the reliability and can facilitate safe higher loading capacity.

Appendix

1. Simulated Winding Hot Spot (Traditional WHS Gauge)

Knowledge of Winding Hot Spot (WHS) temperatures provides critical information regarding safe transformer loading levels. There are three main methods of identifying the winding hot spot of a transformer:

- Simulated WHS temperature (gauge)
- Calculation (electronic temperature monitoring)
- Direct Measurement (fiber optic sensors)

Conventional winding temperature indicators use a capillary thermometer to measure top oil temperature, and have a small heater in them to simulate the temperature rise of the winding hot spot over the top oil temperature ("the gradient"). Current from one of the bushing CTs is passed through the heater, raising the measured temperature. The wattage output of the heater is calibrated using a resistor or other calibrating device.

The capillary thermometer provides a typical accuracy of +/-2 to 3 °C at the one point of calibration and is known to deteriorate with time. Errors of 5 – 10 °C on site are not uncommon. To remain accurate, the system requires regular calibration and servicing, this is difficult to do on site.

Calibration of the WHS heater is based on the temperature rise tests, which measure the average winding and oil temperature rise. The difference is the average gradient, to which is added an allowance for additional rise of hot spot over average in accordance with the IEEE or IEC standards.

The time constant of the simulated value is determined by the sensor, thermal well design and based on the amount of oil circulation near the thermal well (which will dissipate the heat generated by the resistor). The resulting time constant cannot be tuned or adjusted.

Transformer manufacturers are responsible for calibrating the heater to read correctly at full load. If the calculated gradient is accurate, the tuned system will only provide a reasonable reading at full load under steady state conditions. The accuracy of the reading at loads greater and less than this will depend on many factors including the transformer design and the location of the thermometer. The accuracy of the reading during transitions will depend on the WHS system design.

One of the most common complaints with traditional simulated winding hot spot gauge systems is the tendency of the gauge to stick. This problem has been noted on both new and old transformers and is a cause for concern, especially when the gauge is used for cooling control where a stuck gauge can cause excessive transformer aging or transformer failure.

In addition, WHS analog gauges typically do not provide temperature information in an electronic format that can be transmitted back through SCADA. As a result loading capacity as determined from a remote control room is very conservative.

2. Electronic Temperature Monitors (ETM)

The use of Electronic Temperature Monitors (ETMs) has become the standard for many utilities, providing the needed temperature information to their SCADA systems.

The most basic ETM systems operate exactly the same as a simulated WHS gauge, except that the additional temperature rise of winding hot spot over top oil is added digitally in the built-in computer, instead of thermally using a heater. Hence, they calculate the WHS instead of simulating it. More advanced systems incorporate more information, providing more precise hot spot calculations and providing many other diagnostic and communication functions.

One advantage of using an ETM over a traditional gauge is the accuracy. Most ETMs utilize a Pt100 RTD to measure the top oil temperature. The Pt100 has a typical accuracy of +/- 0.2 °C. Also it is far more precise to enter the hot spot gradient digitally with a precision of 0.1 °C than the trial-and-error mechanical adjustment of a rheostat to probably 2 - 3 °C at best.

A second advantage of using an ETM is the ability to tune the time constant of the

ETM to match the time constant of the transformer. At loads other than full load, or during thermal transients (heating up or cooling down) the advanced ETM is more precise because it is possible to control the thermal model with regard to how temperature varies with load and time. In a capillary instrument this cannot be controlled.

3. Basic ETMs

A Basic ETM is a very cost effective alternative. For approximately the same price as a gauge, an ETM can provide the electronic output to a SCADA system, improved accuracy and equal or better reliability.

Even the basic ETMs can offer some very beneficial features including OLTC Delta T monitoring But they do not have customized thermal models or predictive cooling control or check and adjust their thermal models based on fan or pump status.

4. Advanced ETMs or TMSs

Advanced ETMs are now available that provide utilities with high accuracy and more detailed information. The primary benefit of the advanced ETM over more basic systems is its ability to convert the temperature data into useful information that can more easily guide the safe loading and/or maintenance of the transformer.

Added Accuracy. Following are some of the thermal model enhancements that are available:
WHS per phase: The most basic improvement is achieved through the monitoring or calculation of the load on each of the three phases. Many utilities have applications where the system does not have a balanced load and since most basic ETM systems only monitor one phase, there is a chance that they are not monitoring the hottest phase. Advanced ETM systems can monitor all three phases currents and use either an average load or better yet, a worst-case load in the calculation of the winding hot spot.
WHS per winding: A second improvement is achieved through the calculation of the winding hot spot for each winding. Basic ETM systems are calibrated to only one of either a HV or the LV winding with an assumed tap position. Advanced ETMs calculate the winding hot spot of both the HV and the LV. This may be done by measuring currents in one winding and monitoring the LTC position then adjusting the winding ratio (which affects the thermal model) as the LTC moves. Alternately CTs may be used in both HV and LV. For 3 winding transformers advanced ETMs can calculate the WHS of all three windings using CTs in each, or by calculation measuring LTC position and the magnitude and phase of the currents in two windings.
Adjustments for Cooling System Health: Arguably, the most important improvement in the thermal model is the creation of separate thermal models based on which stages of cooling are on and working. Advanced ETMs are available which select between different thermal models based on ONAN, ODAN, ONAF, ODAF, OFAN and OFAF and with multiple stages and multiple groups within each stage. With such a system, the ETM will be able to recognize the true WHS given the failure of a fan, pump or cooling system contactor/breaker.

Providing More Information. Converting temperature data into useful and actionable information is a key benefit of the more advanced ETMs. Knowing how hot the transformer will eventually become, how long it can safely maintain a load or how much loss of life it has or will incur can enable engineers to make better decisions.

Ultimate Transformer Temperatures. In addition to identifying the present top oil temperature and winding hot spot, it is feasible to utilize the thermal model to interpolate the ultimate steady state top oil temperature and ultimate steady state winding hot spot. These calculations are based on the assumption that the load, ambient and cooling system status remains unchanged.

The advantage of knowing the ultimate top oil and WHS temperature is that it provides an early warning of approaching thermal overload conditions and provides a good sense of “how hot the transformer is going to get”.

5. Dynamic Rating

The dynamic rating of a transformer takes this one step further. Instead of “how hot it is going to get”, dynamic rating tells you “how much load it can carry” or “how long the transformer can continue to carry this load”.

6. Fiber-optic Temperature Measurement

The thermal models available in the advanced ETMs are quite complex and with modern techniques are quite accurate. However, these calculations are only as accurate as the calibration information used to tune the model.

The calibration information is typically based on the thermal heat run tests conducted at the factory. If the transformer thermal information is not available then this can be obtained by measurement of the transformer behavior over a period of time (say 2-3months) and an accurate mathematical extrapolation of a thermal model for the transformer is obtained. Most heat run test reports are designed to meet the calibration needs of the traditional WHS gauges which are calibrated at only one point; full load, all cooling stages on, stead state condition. Newer heat run test procedures provide a time vs. temperature report which is used to program the time constant portion of an ETM system. This added calibration information certainly enhances the accuracy of the ETM. Fiber-optic temperature measurement provides the ability to directly measure a spot temperature of the winding. It is not simulated, not calculated, it is the actual temperature at the spot. This measurement, while dependant on the placement of the probes, certainly complements the calculation method of modern ETM systems and provides additional security. Advanced ETM systems can incorporate this fibre optic measurement and utilize the hottest of its calculated and this measured temperatures for dynamic rating purposes.

References

Russell D. & Stewart P.G: "Cost Effective Method for Maximising Power Transformer Utilisation", Distribution 2000 Conference, Brisbane 1999, Paper No 127

Tony Pink & Peter Stewart “Power Transformer Control System Developments” TechCon® 2004 Asia-Pacific

Woodcock, David J. and Francheck, Michael A., “Life Cycle Considerations of Loading Transformers Above Nameplate Rating,” Sixty-Fifth Annual International Conference of Doble Clients, April 1998.

Woodcock, David J., “Condition-Based Loading of Power Transformers,” Sixty-ninth Annual International Conference of Doble Clients, April 2002.