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REQUIREMENTS FOR OPERATION OF TRANSFORMERS BEYOND NAMEPLATE RATING – AUSTRALIAN AND NEW ZEALAND EXPERIENCE

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1. INTRODUCTION

The saving afforded by considering the thermal performance of transformers to assign cyclic ratings higher than nameplate ratings has been recognised for many years. Some Australian utilities have used such capability in system planning at all levels from transmission to distribution for many years (over 34 yrs) obtaining significant savings by deferring augmentation that would have been required earlier based on transformer nameplate ratings. Daily and yearly variations in load and ambient temperatures usually provides an increase in peak loading capability even though highest load is simultaneous with highest ambient temperatures in most parts of Australia. With generation scheduling now market driven, power station owners are finding it economic to make modest increases in generator outputs resulting in overload considerations for generator step-up and auxiliary transformers.

Some organisations responsible for system planning have now moved beyond deterministic planning to probabilistic planning [1] [2] where, based on economic savings and low risk, the load may exceed the N-1 contingency level for a certain number of days of the year. Loss of a transformer or system element during that time requires load shedding. For main system tie transformers whose load current is not dependent purely on load but on system stability requirements and the combination of loads and generation now determined by market arrangements, short time normal and emergency ratings are sought to maximise network loading capability. With the value of transmission being recognised, in Victoria, penalties (paid as rebates) for transformer outages are as high as A$2800/hr.

The above planning arrangement places pressure on asset owners to be confident that when required, transformers will operate satisfactorily at the agreed peak ratings (beyond nameplate rating). Failure of a transformer under these circumstances would result in significant load shedding. Because of the demographics of Australia there are limited ties between substations. Where, as suggested in the IEC loading guide [3] it could be expedient for very low probability events to risk plant in favour of the a system operating condition, the separation of system planning from ownership of the assets now inhibits this consideration. It is proposed in this paper to describe how Australian utilities have approached this aspect of loading transformers beyond nameplate rating for new units, existing transformers and providing examples from experience with using fibre optic temperature probes, field testing, design reviews, factory tests and in-service experience and conclude with recommendations on how to best deal with purchase of new transformers.

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2. CONSIDERATIONS BY UTILITIES TRANSFORMER ENGINEERS

Some utilities are concerned that the requirements of IEC 60076[4] including the standard temperature rise test, does not provide adequate assurance for operation beyond nameplate rating. Those responsible for transformers in utilities have taken a number of steps to reduce the risk and obtain the required confidence that transformers will satisfactorily operate under the highest load conditions.
This includes:

- Specification for new transformers to have a clear statement on the overload requirements.
- Design review, which includes consideration of loading beyond nameplate rating.
- Specification of fibre optic temperature probes to gain more knowledge for better modelling of the thermal performance.
- Factory testing to prove that transformers meet the specified requirement for overloads
- Site tests to confirm calculations and prove capability of existing transformers.
- Installation of monitoring equipment to further refine thermal model and provide dynamic rating assessment.

Experience gained through these processes has provided more confidence, has exposed weaknesses and defects and provided guidance for making future decisions.

2.1 New Transformers

Utilities now tend to specify overload requirements in specific quantitative terms which can be verified during design review, by visual inspections and emergency overload temperature rise tests to satisfy themselves that the specified requirements are met, especially for the medium sized and the large transmission transformers. Requirements in purchasing specifications typically include:

- An overload capability of up to 1.5 per unit (p.u.) for all cooling modes of medium sized transformers and large ONAN or ODAN cooled transformers, but typically, but not in all cases, reduced to 1.3 p.u. for large ODAF cooled transformers due to the high loss density in these designs.
- Current rating of on load tapchangers, bushings are typically specified 1.2 p.u. or higher, than that of the transformer to provide additional safety margin for these higher risk components, which is typically located in the upper part of the transformer and therefore surrounded by hot oil in time of overload. Over-current lockout may also be specified for the tapchanger control to ensure that operation of the tapchanger is blocked at high currents.
- Measurement current transformers are also specified for a higher current rating typically 1.2 p.u. to ensure that saturation of the CT does not occur during overloads up to 1.5 p.u.
- Temperature rise limits for leakage flux shunts, core and coil clamping structures and tank, are typically specified at 75–80 ^{o}C for 1.0 p.u. load and to not exceed the winding hot spot temperature during overload test.
- Some utilities also specify limits on Carbon Oxide and Hydro Carbon gasses generated during normal and overload temperature rise tests, although this requirement is not wide spread yet.

Assurance of overload capability is achieved by:

– Ensuring that the information requested and supplied with the tender is in sufficient detail for the purchaser to verify that the specified overload requirements can be met and are provided for in the contract.
– Using the design review to ensure that the manufacturer has understood the specified overload requirements and has taken appropriate measures.
– Verification of overload capability during factory tests.

2.2 Existing In-service Transformers

With the average age of transformers around 32 years the greatest proportion of transformers in service have not been tested for overload capability. Utilities have approached this by:

- Contacting the original manufacturer for information if such manufacturer exists and if such information is available
- Assessment of design and construction by utility expert
- Factory testing following repairs/up-rating/refurbishment
- On-site loading tests
- Condition assessment.

Overload capability of existing older transformer is commonly based on temperature calculations, where test data is available and if not available, based on assessment by a utility expert. This assessment would normally include an examination of the rating of all the series elements, such as tapchangers, bushings and current transformers and available DGA results. DGA would also be performed whenever a transformer was over-loaded

3. DESIGN REVIEWS

The design review [5] provides the utility with an opportunity to discuss the design of the transformer in detail and to ensure that the designer has understood the utilities requirements in respect to overload conditions and temperature limits including, those components not subject to temperature rise limits by standards and not subjected to measurement during factory tests.

For the purpose of assessing overload capability the following issues are addressed during the design review:

- The winding cooling and location of hottest spot for installation of fibre optic probes
- The current rating of the series elements such as the current transformers, tapchanger, bushings and bushing draw-leads.
- Location of flux shunts and calculated temperature rises of flux shunts, tie rods/flitch plates, frames, tank walls and covers, bushing turrets etc. The knowledge of temperature rises in these components during overloads are of critical importance as the temperature increases exponentially with load and can raise rapidly if saturation point is reached and/or if cooling is inadequate
- The capacity of both the main and the OLTC conservators to ensure sufficient expansion of the oil has been provided up to the maximum overload oil temperature, this being particularly important for transformers with forced oil cooling and transformers which have diaphragm and air cell conservators.
- Temperature rise limits and tests are also important for control cubicles. Many solid state electronic devices are only rated for 55^{o}C, this leaves a cubicle temperature rise of only 15^{o}C for a 40^{o}C ambient and even less when sun radiation is considered or if located in a poorly ventilated sound enclosure.

4. EXPERIENCE WITH FIBRE OPTIC TEMPERATURE MEASUREMENTS

Fibre optic probes have been used for direct measurement of winding temperatures by some Australian utilities since 1985 [6] and are now a common feature on large transmission transformers.
Some utilities require fibre optic probes be fitted for temperature rise tests evaluation purpose only and may provide a multi channel fibre optic thermometer for use during the tests, others require both probes and a permanently fitted fibre optic thermometer. Where probes are required for testing only the probes would still be left in the windings available for in-service use if required at a later date. The main benefit of the fibre optic probes is to be able to determine winding hot spot temperatures during the temperature rise test.

Although there is no universal agreement on the number of probes, it is becoming common practice to use a four channel fibre optic thermometer and either four or a maximum of eight (8) fibre optic probes installed for monitored during the temperature rise test. Eight probes for testing, allows the monitoring of winding hot spot temperature in all three phases of the two main windings (primary and secondary) and provides two additional probes for monitoring of the tapping winding, tertiary winding or other points of interest such as entry/exit leads, top oil, flux shunts, tie rods or flitch plates. Only four of these probes are normally permanently monitoring temperatures in service. The unused probes would be left terminated either at the wall plate or in the control cubicle and thus available for later use if required.

The conventional measurement of winding temperature by resistance provides an average temperature of the winding and the measurement is usually made only on the windings of one phase of a three phase transformer. Under this method the winding hot spot temperature is not determined and differences between phases remain unknown. The fibre optic temperature probes not only provide a measurement of the hotspot temperature of each winding, they provide additional information for transformer designers to verify their calculation methods in a manner not possible from average temperature measurements. The measurement also provides the end user detailed information of the dynamic behaviour of winding temperatures during rapid load changes.

A number of defects and deficiencies, which may not have been found during a conventional temperature rise test, have been detected by use of fibre optic temperature probes. In addition to those cases set out in Table II relating to overload tests, the use of fibre optics has resulted in identification of insufficient oil flow in one phase due to oil leakage around poorly fitted insulation cylinders.

There are also difficulties and issues to consider, when using fibre optic probes for direct temperature measurement in windings. Problems encountered include the following:

- Probe breakage during manufacture was initially a significant problem. This problem has largely been overcome as the suppliers now offers probe of a more rugged construction. However, care still need to be taken to ensure that there is sufficient “slack” for the probe to accommodate shrinkage of the winding during the dryout and the final compression.
- Probe tip not located at winding hot spot. For most transformer designs the winding hot spot is located in the 2nd-4th discs from the top and usually in a location with high radial leakage flux and high thermal resistance. The location of the probe tip should be discussed and agreed between the transformer designer and the customer.
- Oil flow should be excluded from around the probe tips (unless used for measurement of oil temperature). Where a probe is located in the radial spacer between two discs, it is important that the slot where the probe is inserted into to radial spacer is sealed off, so oil flow does not “scour” around the probe tip. This is particularly important with forced directed oil flow, as oil flow around the probe tip will lead to significant temperature errors.

In regard to durability of fibre optic temperature probes, experience to date has been positive. The first Australian utility to use fibre optic temperature probes, now has them installed in some 50 transformers since 1985. Field tests carried out in 2001 on a 200 MVA 275 kV transformer indicated that all its probes were functional after 15 years in service. Spot checks on fibre optic probes fitted to other transformers for test purpose only, have also been found to be functional after having been in service for 10 to 12 years.

5. FACTORY TESTS ON NEW UNITS

The lack of international standards test for verification overload capability of transformers has resulted in utilities to specifying tests to suit their own requirements, which has led to a proliferation of alternative test requirements. However, principally two philosophies/methods that have emerged:

1. A test to verify that the transformer can carry a specified per unit overload or overload profile for a specified duration without exceeding specified temperature rise limits. The test parameters

are typically chosen to match the overload constraints used for planning and operation by the specific utility.

2. A test to verify that the transformer can be overloaded within the limits recommended in the loading guides, without the overloading having a detrimental effect beyond the accelerated ageing normally occurring for overload. One method used, measures winding hot spot temperature rise as a function of time at the specified p.u. overload (1.5 or 1.3 p.u.). A conventional temperature rise shutdown is performed when the temperature rise limit is reached to determine the 1.5 p.u. current winding gradients, which are used in conventional calculations for a comparison with the fibre optic temperature readings. Some utilities continue the overload test with winding hot spot maintained between 135-140 ^{o}C and top oil not exceeding 115 ^{o}C, typically for 12 hours to allow abnormal temperatures to be detected by DGA.

The benefit of Method 1 is that the utility verifies that its transformers can be operated in accordance with the planning criteria and specified operating procedures without it incurring unacceptable or unknown risks. The disadvantage is that the specified overload requirement may be poorly matched to the inherent overload capability for the specified rating of the transformer and may result in a sub optimal design. The benefit of method 2 is that the design remains optimal for the specified nameplate rating.

The criteria generally used for acceptance the overload tests are:

- No gas accumulation in the Buchholz relay during the test or gas accumulation after this test.
- Reasonable correlation between winding average and hot spot temperatures, hot spot temperatures measured in tanks and other structures (frames, flux shields) not exceeding the limits specified. The overload test may include measurement of temperatures in leakage flux shields, clamping structures and infrared scanning of tank and bushings. An overall thermal scan followed by a detailed scan has been found to be the most effective method.
- Temperature rise in control cubicles not exceeding 15 ^{o}C above ambient.
- Increase of gas in oil levels during the overload test during shall not be greater than specified or agreed levels. Table I is an example from one utility.

TABLE I – Acceptable Gas Levels During Heat Runs

Gas generated during overload test (From DGA before & after test)	**CO**	**CO2**	**H2**	**CH_4 + C2H6 + C2H4**	**C2H2**
Equiv rate ppm/hr @ 1 p.u. load *	3	25	4	1	0
Maximum final gas level ppm Total	115	950	150	38	0

*rate normalized to 1.0 p.u.

Based on the experience of another utility the acceptable levels in Table I may still be too high. A rewound generator step up transformer after a 12 hour temperature rise test at 100% rated current, had what was considered good a DGA result, CH4 =3 ppm, C2H4 =1 ppm and C2H6 = 1 ppm. However, after 9 months in service the gas levels increased significantly to CH4= 55 ppm, C2H4 = 7 ppm and C2H6 = 28 ppm suggesting the need for very low values during the short time of a factory heat run.

Two utilities, who have been specifying overload tests for a longtime (as early as 1976), believe quite strongly in the need to perform such test as there have been many instances where these tests have enabled identification of defects which were subsequently rectified prior to leaving the factory. Table II sets out examples of problems found during factory tests. Some of these problems were only identified during the overload test.

For duplicate transformers the results of gradient tests has indicated average winding gradients differences of 3 ^{o}C between units at 1.0 p.u. and a differences of 5 to 10 ^{o}C at 1.5 p.u.

TABLE 1I – Defects Found During Works Overload Tests

TRANSFORMER SIZE	TYPE OF FAULT	HOW FAULT WAS DETECTED
75 MVA	Unintentional loop around magnetic shunt on winding formed by electrostatic shield contacting a bolt.	Gas bubble only during 1.5 p.u. overload test.
150 MVA	Current in tank cover bolts caused overheating.	Serious oil leak at flange due heat damage to gasket at 1.5 p.u.
150 MVA	Tank hot spot due to leakage flux.	Thermal image scans at 1.5 p.u.
375 MVA	Excessive temperature rise in tank due to inadequate size of tank shield.	By thermocouples during full load & overload temperature rise tests.
375 MVA	Various oil inlet ducts blocked on two phases.	During overload test. Fibre optic temperature probes.
150 MVA	Incorrect bushing connection lead caused overheating.	Physical inspection when bushing was removed following 1.5 p.u. Test.
150 MVA	Loop around magnetic shunt.	Gas bubbles during overload test.
150 MVA	Tank hot spot due to contact between core frame and tank.	Thermal image scans during 1.5 p.u. overload test
60 MVA	Overheating in mild steel tie rods.	From DGA results following 1.5 p.u. overload test.
200 MVA	Uneven oil flow between phases.	During overload test –fibre optic temperature probe.

6. EXPERIENCE WITH ON-SITE TESTS - FOR EXISTING TRANSFORMERS

One utility undertook a program to test a number of transformers at site to verify their ability to operate at the assigned overload rating or increased rating after up-rating. On-site tests have been performed by:

(a) switching out other transformers to increase the load on the unit under test.
(b) Using out of step tap positions to circulate current.
(c) Re-connection of a single-phase 230/67.5/22.5 kV transformer with HV taps, to provide the correct ratio to circulate the required test current through a similar single-phase transformer.
(d) Using a synchronous compensator for a supply, similar to the factory short circuit test.

Oil temperatures were measured in the normal way and at the time of shutdown winding resistance measurements used to determine winding temperature similar to factory tests. For some of these tests the average winding temperature was monitored during the test by making resistance measurements using the superposition method. This required insulated platforms for the DC measuring equipment. A circuit diagram is shown in figure 1. Temperatures measured by this method were within 2°C of those obtained by the conventional shutdown. DGA before and after the tests was also used to confirm absence of hot spots.

Results of these tests:

- A transformer up-rated to 44 MVA by addition of pumps to give OFAF cooling, following the test had to be de-rated to 35 MVA
- A shell type auto transformer had tank hotspots at just over rated MVA and could not be up-rated or subjected to the required overloads without some risk. The tank had not been fitted with magnetic shunts and the manufacturer had indicated that there could be a limitation but it was

not anticipated to be at the rated current. Tank temperatures were not considered when this transformer was manufactured. During initial service of these units the electrostatic shields overheated at lower than nameplate rating and were subsequently replaced.

- Generally a number of single-phase transformers found to be suitable for operation at 1.2 to 1.3 p.u. cyclic loads assigned to them and similarly a number of three phase transformers (150 MVA) were found to be suitable for cyclic loading.
- A number of transformers tested developed greater oil leaks due to overheated bolts. Copper shunts were fitted to bushing turret joints where the bolts had overheated.

Based on the success of these tests cyclic ratings of 1.2 to 1.3 p.u. has been assigned to all transformers of similar designs (a total of 90 transformers).

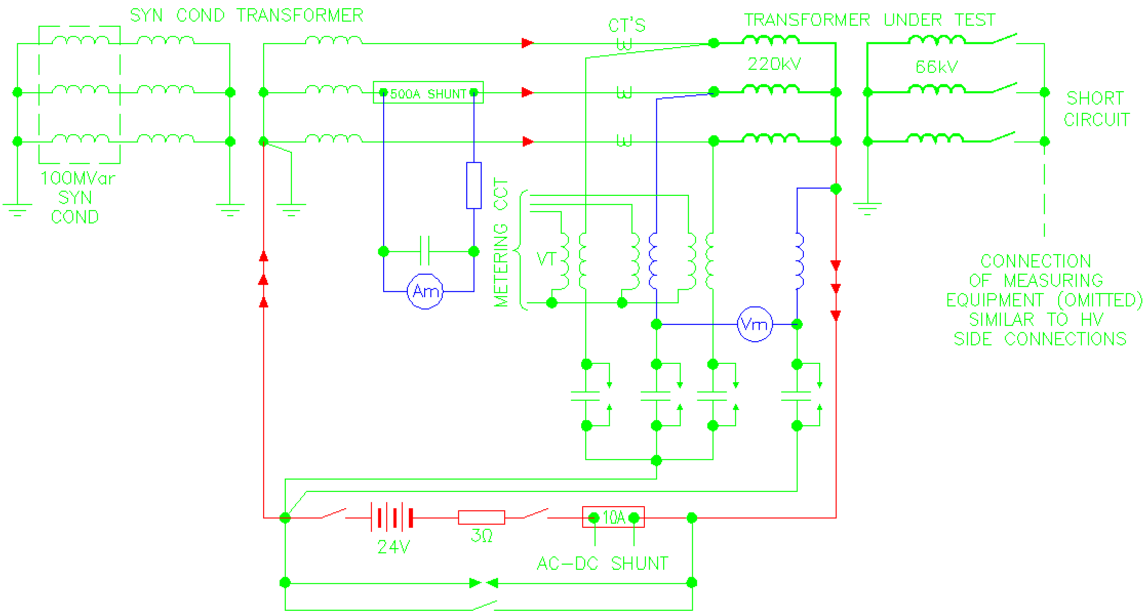

FIGURE 1 – Superpositon Method of Measurement of Winding Resistance

7. IN-SERVICE PERFORMANCE

For one utility, in service cyclic overload of up to 1.3 p.u. is relatively common for transmission and bulk supply transformers. Bulk supply transformers rated up to 100 MVA have on several occasions carried of up to 1.5 p.u. for a short duration. A number of 200 MVA transformers have been subjected to repeated overloads of up to 1.3 p.u. for some weeks in ambient temperatures up to 35 ^{o}C with no significant adverse effect, although increases in the carbon oxide and hydrocarbon gasses were observed following such overloads. The same transformers have also suffered severe oil leaks from the deteriorated gaskets on bushing turrets and the main flanges.

One of the fundamental considerations of overloading transformers, as provided for in the loading guides, is the effect on insulation life or rate of ageing at the higher temperatures. Short time overloads usually have a small effect, however, prolonged operation at milder elevated temperatures can result in significantly higher ageing. Under some conditions, the use of top oil indicators to control cooling or having the switch-on temperature setting too high can result in higher aging rates at intermediate cooling modes without the transformer being considered to have been overloaded. The level of 2-furfural in transformer oil is one of the measurements used to monitor ageing. A case of overloading under ONAN cooling is illustrated by the example shown in table III which compares 4 identical 38 year old transformers, two automatically controlled from top oil and two manually controlled and left running all day during high ambient temperatures and high loads.

TABLE III – Furan Levels Indicate Overloading With ONAN Cooling

	Transformer A	Transformer B	Transformer C	Transformer D
2- Furfural	0.79 ppm	0.80 ppm	2.45 ppm	2.44 ppm
Cooler control	Manual	Manual	Auto – top oil	Auto –top oil

Transformers A &B operate in parallel and C & D operate in parallel at a different station

A similar experience was noted with OFAF cooled single-phase auto transformers where, due to coolers on two units being blocked with dust and grasses, the temperature difference was over 20 ^{o}C and 2 furfural levels 3.0 ppm compared to 0.89 ppm.

Adaptive thermal modelling of transformers is now available in on-line monitoring equipment [7]. In addition to providing cooler control, voltage regulation, other monitoring information such as gas in oil and moisture, various temperatures and status information, the monitoring system models the thermal performance of the transformer. Calculated oil temperatures are compared with measured quantities and corrections fed back into the model to provide more accurate predictive temperatures for dynamic ratings.

8. CONCLUSION

With the division of asset management responsibility from operating and planning responsibilities, it is becoming very important for asset owners to have verified and clearly understandable operating limits for their transformers. According to Australian and New Zealand experience this requires that the loading and overloading requirements are clearly specified and that the compliance with these requirements are verified through design review and factory overload tests. In addition, it is important to obtain more accurate information for on-line dynamic ratings, which are likely to be required in the near future. The use of fibre optic temperature probes and processor based thermal modelling equipment can assist. Standards need to be further developed to include factory testing of specified overload capability, including thermal scans determination of winding hot spot temperatures and acceptance levels for production of gasses in oil during such tests.

9. ACKNOWLEDGEMENTS

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