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Criteria for estimation of end of life of power and station transformers in service

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Abstract: Power and Station transformers are among the more expensive and critical elements of a power system, so much so, failure of this component entails unacceptably long interruptions. Further, unscheduled, or, inadvertent failure thereof, has serious consequences on the maintenance of system reliability and revenue accrual. In principle, ensuring the reliability power transformers is a two-step process, involving the detection of an impending failure in its formative stage so as to preclude catastrophic failures and if, for any reason, an outage occurs, evolving an appropriate replacement strategy of the failed units in a minimum possible time. In diagnostic testing, physical parameters used as indices of impending failure shall be sensitive to the amount of ageing and shall possesses a reasonably high degree of correlation with dielectric strength and mechanical strength. Concerted research work is being carried out, the world over, to try and identify such properties of insulation as are sensitive to the amount of degradation. The authors of this paper aim to suggest techniques for acquisition and analysis of ageing data in order to propose a condition-monitoring schedule.

Introduction

The normal operation of a power system is an intimate function of the status of insulation in electrical equipment at a given point of time. An accurate estimation of transformer life, can, to a very large extent, mitigate the problems mentioned above besides satisfying the conflicting requirements of optimum utilization of the equipment and safeguarding the reliability

A large population of power transformers world over approaching an average life of 30 years, it is therefore considered essential to evolve methods for predicting their remaining life. Over the years, different criteria have been prescribed for deciding the end of life (EOL) of equipment from the standpoint of its insulation [1]. But, thus far, no straightforward and unique assertion to this effect is forth coming. Any conformal procedure proposed for a reasonably accurate definition of EOL, has to be based on a technically feasible and economically viable consideration. However, the analysis of insulation life data is complex in itself [2] further vitiated by service related faults. Concepts in life management of transformers was considered by the CIGRE (W.G), [3], [4], prepared a draft proposal for evolving broad guidelines to enable station engineers to make appropriate decision on the replacement schedules.

When a power transformer is considered unsuitable for delivering power, in a certain situation, an EOL is deemed to have reached. As already pointed out, beyond the technical reasons of rejecting a power transformer, viz. due to major failure, there could be non-technical reasons of taking the unit off the service permanently. Accordingly, three types of EOL has been defined [4], which, are as follows;

- Strategic EOL
- Economic EOL
- Technical EOL

In the present work, the technical EOL will be discussed in some detail, the strategic and economic EOL of the equipment are quite outside the purview of the scope of the paper.

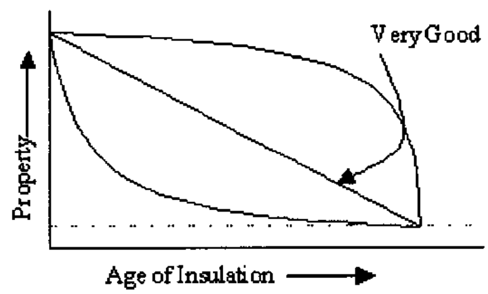

Fig.1 Property vs. Ageing diagram

Parameters, physical and statistical, applied, as indices of impending failure shall meet the requirements of sensitivity and monotonicity. Also, their inter- and- intra correlations need to be high enough as to make further analysis worthwhile. In Fig.1, [1], the temporal changes in the value of three abstract parameters have been shown, the ideal parameter is one which varies linearly with age, however, there seems to be no such parameters of insulation identified so far, exhibits this ideal characteristics. The relation of the changes in the property and the aging is non-linear and complex. The reproducibility of the experimental results is another factor vitiate the situation further. To this end the insulation parameters, such as, degree of polymerization and furan content dissolved in the oil has been seen to bear a sufficient degree of correspondence with the amount of ageing of insulation.

Experimental

The objectives of the current research programme are, to identify the parameters sensitive to and monotonic with, the amount of ageing. To this end, eight nominally identical, scaled- down models of actual power transformers has been designed in the authors' laboratory and fabricated by a local' transformer manufacturer. These prototypes are rated for 5 kVA, 220/5000V, 50 Hz 1-phase and are of core type construction with ON cooling mode. A dry nitrogen gas blanket is provided over the oil surface. Mineral oil impregnated electrical grade Kraft paper and Manila paper have been used for winding insulation and end insulation respectively. Before impregnation with oil, paper was dried under vacuum to have moisture content of less than 0.2 %.

Three sampling ports with septum arrangement (one at the top cover, other two at top and bottom of the front cover) are provided for filling as well as for drawing out the oil for tests. Sampling arrangement has been provided on the top cover for paper insulation also. Provisions have been made to measure the top, middle and bottom oil temperature of the model using thermo-couples

A carefully designed loading schedule was decided depending upon the electrical and thermal stress required for causing a significant degradation in both phases of insulation. The stepped stress loading cycle [5] with three blocks per cycle (representing 3 different temperatures) has been used. The time duration of these blocks are adjusted such that the amount of aging during each blocks remain nearly constant.

In a series of previous works, [6], [7] the authors calculated the magnitude and location of the hottest spot temperature, HST, during each loading cycle. The duration of exposure at each temperature in hours has been selected such a way that 6-10 loading cycles are required to generate an amount of ageing corresponding to end-of-life for a transformers. In addition to the routine tests, insulation resistance (IR), Capacitance between HV-to-LV and HV-to-tank and dissipation factor, performed on all the specimens, partial discharge (PD) measurements, DGA Furan and DP measurements were also carried out.

Condition monitoring transformer prototypes

In a high voltage high power transformer, a careful examination of the two phases, winding insulation (solid part), and the insulating (and cooling) liquid medium are made, treating the two as separate entities. At the end of each load cycle a series of invasive and non-invasive diagnosis tests have been performed on both of the phases.

Monitoring liquid phase

Top oil, middle oil and bottom oil temperature of the specimen have been continuously monitored during load cycle. The most important tests carried out on oil phase after the end of each load cycle, are; its moisture content, capacitance, dissipation factor (tanδ), dielectric breakdown strength, micro-particle infestation, detection, measurement and quantification of the dissolved gases. Monitoring of liquid phase has the potential to assess the condition of solid phase as the by-product of degradation of paper (carbon oxides and furans) are carried to the liquid phase and remain there as dissolved products.

Monitoring solid phase

Hot spot occurs, almost always, in the winding of transformer caused often by transient and/or deliberate over loading. It is generally not possible to directly measure the hot spot temperature. Hot spot temperature is estimated using thermal model with the help of top oil temperature and load current. Except furan analysis there is no non-invasive test to assess the condition of the paper insulation at the end of each cycle paper sample has been taken out to perform both Degree of Polymerization and breakdown strength measurements.

Results

In keeping with the concepts in accelerated thermal stress ageing, a series of experiments have been designed and performed in a planned manner. A number of properties have been identified as being reasonably sensitive indices of degradation and monitored continuously. For the sake of brevity, only a few of the more important of them are included here. In this connection, an abstract degradation, D, is defined as the product of the maximum winding temperature and the duration over which this temperature persists.

The break down strength (BDS) of oil has been measured after every cycle using sphere-sphere geometry (10 mm each), with a separation of 3.3 mm. It can be seen from the Fig.2, that, the BDS of oil is sensitive to the amount of ageing in that it exhibits a nearly monotonically decreasing pattern.

In the course of insulation ageing, free particles are generated and infestation of the particles also serves as a qualitative measure of degradation. The reason for the breakdown strength to be lowered with ageing duration is generally traced to the increase in the size and number density of particles and hence it was decided to obtain information on this aspect. Fig. 3 shows the generation of micro-particle due to degradation in paper, it can be seen that the particle count is sensitive to aging. The quantity shown here is the total count, ranging in particle size from 2.5 μm to 100 μm.

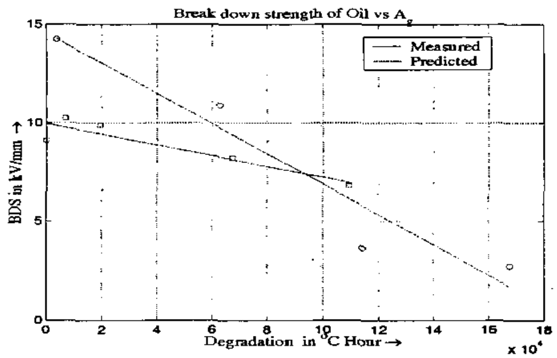

Fig.2 Break down strength of oil vs D

As mentioned earlier, the breakdown strength of oil is related to particle count in oil. The correlation between measured BDS and the quantity predicted based on particle count has been shown in Fig. 2.

On-line gas phase monitoring

On-line analysis of the free gases in the inert gas blanket has been undertaken using a Calmet™ Fourier Transform Infra Red (FTIR) spectroscope. All the hydrocarbons and some of the furans present in gas phase have been analyzed. The typical concentration of furans, in the initial stages of the experimental run has been shown in Table I. It is important to mention here that, at higher temperature beyond 120 °C Furans will be in a gaseous state, so, it was possible to analyze them as gases. It was believed that a systematic study of the quantity of these free gases collected above the surface of the oil helps in assessing the status of cellulose insulation more readily than DGA and hence this investigation.

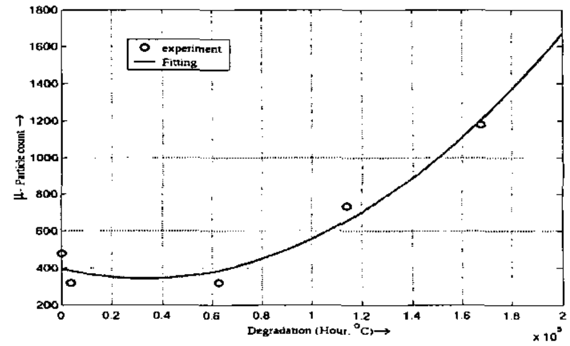

Fig.3 μ-Particle count vs D

Table-I Online gas phase analysis record

Free Gas (blanket)	Case-I (ppm)	Case-II‡(ppm)
2-FD	7.0	5
5HM2F	23.0	26
5M2F	0	0
2AF	1	2
CO	1019	249
CO_2	20,400	19,050
CH_4	76	33
C_2H_6	52	52
C_2H_4	0	9
C_2H_2	7	14
†: 25 hrs at HST=150 °C ‡: 10 hrs at HST=140 °C		

The EOL of power transformers, being a function of several of properties of the insulation system and their temporal changes, a regular sampling and quantification has been made at varying time windows. In Table II, the value of some of these parameters, at a time when the DP reaches a terminal value of around 200, have been given. The projected values of these data obtained from the ageing experiment to actual transformers have also been indicated there in.

Table-II Values of the parameters at the end of life

Parameters	Value at DP <200 (Model)	Projected Value Actual Transformer
Furans	90 ppm	2.25
$CO+CO_2$	120,000 ppm	3000
TCG	5000	4000
BDV (oil)†	7 kV	7 kV
BDV(paper)‡	2.1 kV	2.1 kV
DF	0.44	0.44

†: 3.3 mm spherical gap, ‡: 90 μm thick papers

Discussions

To scientifically justify the time- censoring methodology for the ageing experiments, reported here, IEEE proof test recommendations, need to be followed. It involves application of post ageing thermal and/or electrical 'shocks' to kill the specimens. In the Authors' experiments, however, destructive operations, such as these, are not undertaken, but, certain diagnostic properties and their dynamical behaviour is carefully observed by continuous monitoring.

- Monitoring the temperature such as TOT or HST (by embedded thermocouple).
- Measurement of gas pressure (P) of the inert-gas cushion above the oil surface.

If the properties monitored continuously shows some abnormality in behaviour, a few rigorous diagnostics tests (DT) has to be carried out. Among the other more important DTs are Insulation resistance (IR), PD measurements, Capacitance and DF measurement. Moisture content measurement in both the paper and oil by using Karl-Fischer coulometric Titrator was done to check the reason of less IR. Micro particle counting and sizing, BDV of oil were also performed. The result of single test may not give any decisive information but a trend in change of properties has to be established in order to take any further decision regarding the termination of the tests.

Table III Termination criteria

Properties	Limiting Value
ΔTOT	5 °C (Prediction~ Meas.)
ΔP/Δt	>0.2 kg/cm^2hr
IR	<0.1 GΩ
PD	500 to 1000 pC
DF	0.5 % at 25 °C
Furan	75 ppm
DGA	(see Table below)
Moisture	>100ppm (in oil)
DP	150

If the above measured properties exhibit a positive trend of failure or fault than it was decided to carry out invasive tests (IT) viz. BDV and DP measurement of the paper insulation. These properties are already known to be most informative tests but in the cost of disturbing the transformer insulation to some extent. After the termination of the specimens, a postmortem study is to carry in presence of an expert to see various fingerprints that might help in future investigation and data analysis. In the Table III and Table IV, a brief report on the termination criteria has been included.

In conclusion, it can be pointed out that, accelerated thermal ageing experiments on pro-rated unit of power transformers give a very useful database for condition monitoring power transformers at site. Several parameters have been monitored at regular intervals of time. A reference in DP has been establish-

Table IV Termination criteria (DGA)

Gas	Limit (ppm)	Remarks
H_2	1000	Wide acceptance in industry with some differences R&D for online application
CH_4	1000	
C_2H_2	250	
C_2H_4	1000	
C_2H_6	1000	
$CO+CO_2$	220,000	

-ed as a possible EOL indicator. Diagnostic and confirmatory tests suggested that a value lower than about 200 defines an end -point criterion to take the transformer out of service. Concomitant with this, the diagnostic properties such as furan and CO_2 and CO content as shown in by the results of experiments reported here give a definite indication as to the reference end point. The results of a series of fault-finding experiments, carried out on the scaled down model, has been projected to actual power transformers in service with a reasonable degree of success.

References:

[1] Bal K. Gupta, "End of Life of Power Transformers" Special Technical Session, PES Gen. meeting 2003, Toronto, Jul 13-17.

[2] Pradeep Kumar Shetty, T S Ramu, "Reliability and Interval Estimation of Type-II Censored Electrical Insulation Data", to be appeared in IEEE ISEI-2004, Indianapolis, Indiana, USA 20th -22nd Sept.

[3] Working Group 09, Study Committee 12, "Lifetime Evaluation of Transformers", Electra, No. 150, Oct-1993, pp 39-51

[4] Working Group 12.18, "Life Management of Transformers", Draft interim report, 29- May-1999.

[5] M. K. Pradhan, T. S. Ramu,, "Diagnostic Testing of oil-impregnated paper Insulation in Pro- rated Power Transformers under Accelerated Stress", To be appeared in IEEE ISEI-2004, Indianapolis, Indiana, USA 20th -22nd Sept.

[6] M K Pradhan and T S Ramu, "Prediction of the Hottest Spot Temperature (HST) in Power and Station Transformers", IEEE Trans. on PWRD, Vol-18, No.-4 , Oct. 2003, pp:1275-1283

[7] M K Pradhan and T S Ramu, "Estimation of the Hottest Spot Temperature (HST) in Power Transformers Considering Thermal Inhomogeniety of the Windings", IEEE Trans. Power Delivery (in press).

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