

TRANSFORMER CONDITION- BASED RANKING ON THE BASIS OF DESIGN REVIEW AND COMPREHENSIVE OIL ANALYSIS

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Abstract

The paper discusses power transformer condition assessment cost effective methodology allowing ranking the transformer population and filter out over 80-90%, which does not require special tests and complex maintenance procedures.. Methodology based on transformer design review, operation condition review and comprehensive oil analysis.

Key words: Power transformer- Design review, Oil analysis.

Introduction

The maintenance policy for HV power apparatus is changing under the pressure of economical considerations. Key utility aspects are long term strategies for system usability and reliability require knowledge of usable service time and serviceability of the transformer. Important factors are budget planning and pressure to postpone the cost not only for replacement of unreliable units but also for major maintenance procedures that require equipment de-energizing and prolong non-availability.

Typical failure rate of power transformer is around 2%. It means that another 5-6% can be in a critical condition in terms of short-term reliability. Among the aged population only 10-15% are typically suffered from excessive deterioration and require special procedures to prevent early end of life.

Condition –based ranking could be a proper solution to select weak components in the transformer population [1]. It was shown that ranking may be performed by means of determination of some critical parameters based on diagnostic testing results (routine and special) and engineering analysis using design tool and historical background of the units [2].

Latest developments of ZTZ-Service have shown that effectiveness of equipment ranking can be significantly enhanced by means of implementation of condition-based functional methodology [3,4].

This paper discusses diagnostic methodology based on transformer design review, operation condition review and comprehensive oil analysis, which allow effective ranking of the transformer population

Life realities

The basic traditional philosophy declares that "the life of the transformer is the mechanical life of aged paper", and typical criterium to represent the end of life of insulation is the "50% retained tensile strength of paper". However both of transformer service experience and transformer models Life Tests have suggested that transformer life is more complex category that just mechanical life of paper.

Technical Life of a transformer maybe thought as of four components:

Thermal Life: Time to critical decomposition of conductor insulation

Dielectric Life: Time span to critical reduction of dielectric safety margin

Mechanical life: Time to critical mechanical weakness and deformation of windings

Life of accessories, especially bushings and LTC

Experiences give grounds to deduce that many failures occur just due to aging phenomena.

However there is still little information available about the units that have failed primarily due to thermal degradation of insulation material. One of the reasons for still a low thermal mode failure rate of aged insulation is that that conductor insulation is subjected basically to compressive but not tensile-mode stresses.

Many failure statistics has not exhibited yet a trend of increasing number of failures with time, showing peak of failures around 19-21 years of service. The failure histogram is not yet a "bathtub curve". Hence time of service is not yet a major weighting factor.

It was shown [4,5] that "Dielectric life" has been shorter than "Thermal life" likely due to effect of aged-mode particles and oil by- products. However specified scope of maintenance tests does not cover properly factors that cause reduction in insulation dielectric margin , particularly oil and insulation surface contamination.

Service aged transformer retains complex moisture and decomposition profiles.

To understand and model moisture behavior in transformers, the insulation structures should be divided by physical categories by temperature zones, and possibly by concentration gradients.

Temperature migration of water across winding conductor insulation and leads terminals has to be considered as well. There is a little information about rate of generation and migration process of aging water. One can expect substantial generation of aging water when polymerization degree (DP) is below 400. Aging water migrates from the hot spot area to coolest zone

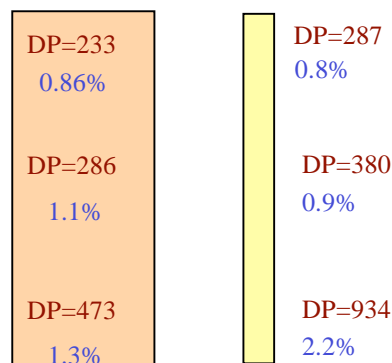


Figure 1
Aging decomposition and aging moisture profile after life test of winding model

The heated mass of conductor insulation that is subjected to accelerate deterioration comprises typically 2-10 % of the total mass of transformer insulation. Accordingly aging profile

of insulation in most instances is strongly non-uniform. While external insulating components have very low reduction of DP, values of DP in hot spot area can exhibit values very close to end of life.

Localized-mode of insulation deterioration and contamination embarrasses effective diagnostics through traditional methods that involve average response of insulation system



Figure 2

Failure mode of 700 MVA GSU transformer due to critical ageing in very limited hot spot area DP interpreted through 2FAL (Chendong curve) has shown 340 units

Functional-based diagnostic methodology

Traditional approach to transformer maintenance (e.g. IEEE Std 62-1995) involves periodically carrying out a series of tests assuming fully check the integrity of the equipment.

The methodology considers the condition of transformer as function of the condition of several components including fluid as a separate component: Accordingly relevant test scope is specified suggesting the limited and critical values for each tested parameter, and looking for change against nameplate/previous test data.

The principal disadvantages of traditional methodology are:

Questionable correlation between tested parameters and transformer defective condition. E.g. Insulation PF > 1% , which is considered as bad” does not mean that dielectric safety margin is really reduced

Uncertain or false diagnosis is possible.

Unnecessary tests are often carried out.

Neglecting defects ,which can not be detected by specified test scope (e.g. contamination of winding conductors insulation)

Practical impossibility to anticipate future state of equipment, particularly remnant life span.

A novel functional-based methodology [3,7] is suggested as an attempt to provide a complete coverage of the key deterioration processes.

Concepts of the methodology include definition of the functional subsystems of a transformer (instead of components), development the functional failure model and utilizing several (not one) diagnostic procedures that relate to the particular fault. Oil is considered as a vital part of the transformer body (not as a separate component), which is responsible for the conditions of insulation integrity, especially for its dielectric and thermal health.

Diagnostic flowchart (Fig 2) that elaborated by ZTZ-Service suggests condition assessment as a test-questionnaire to detect possible defective condition of the functional subsystem, which may lead to equipment malfunctions.

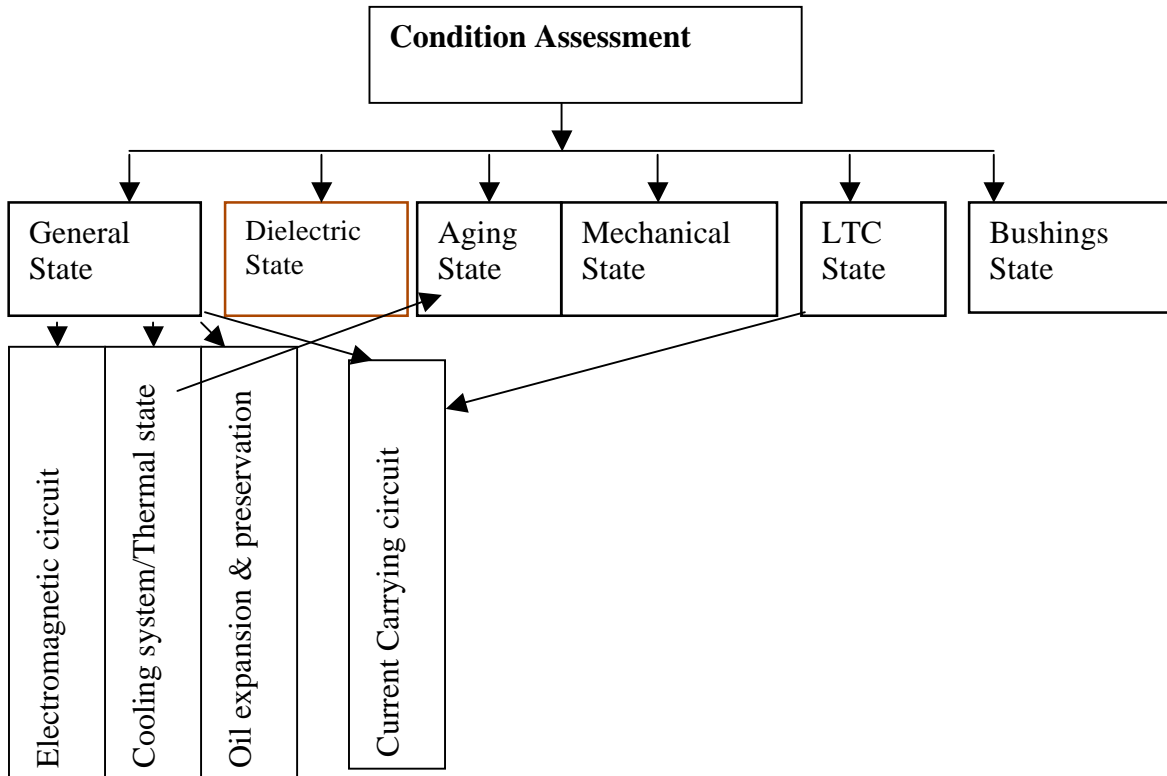


Figure 3
Transformer condition assessment flowchart

Condition-based ranking

Subsequent evolution of functional methodology would be condition –based ranking, which is suggested how to filter out of aged transformer population the units, which may continue service with minimum risk. Relevant flow-chart is presented in Fig 4. Condition based ranking would be likely the most efficient method to select equipment, which really needs in investment.

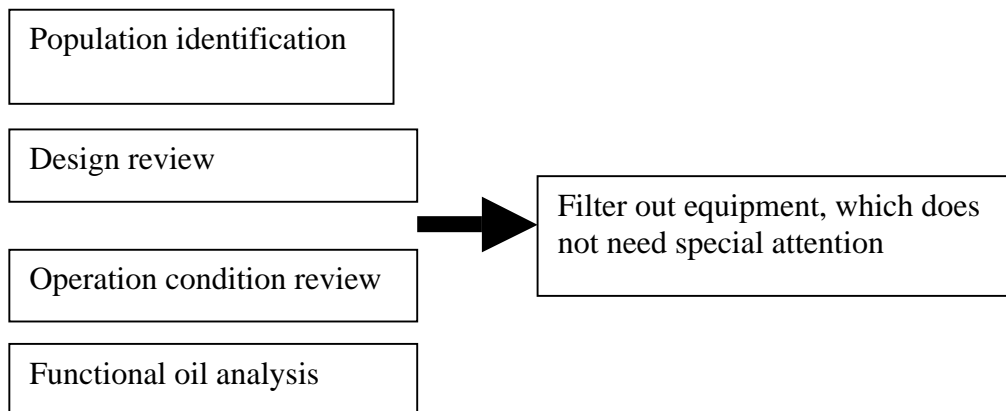


Figure 4
Condition based ranking flowchart

The heart of proper diagnostic system is comprehensive failure model, which to answer the questions:

- What defects and faults can be expected in particular transformer components related to the particular functional subsystem?
- What is the possible path of defect evolution into the malfunction, and then failure?

Relevant Failure model allows minimizing diagnostic program and selection the most economic tools.

The failure model shall consider also the interconnection between a possible defect/fault and real operational stresses on the one hand and the withstand strength on the other.

Transformer failure model is deduced from Historical Review, Design Review, and operation Condition Review

Historical Review includes maintenance issues, particularly preventive tests, failure analysis, comparative condition of sister units.

Design review is a component, which would suggest the weak spots in each transformer subsystem and determine main diagnostic objectives: what to look for?

Engineering analysis and service experience have shown that the functional state of a transformer in many instances can be assessed on-line (Table 1), utilizing advantages of voltage, load and temperature variation.

Table 1 Methods, which successfully experienced for transformer condition assessment

Functional state	Methods
Dielectric state	Fluid tests +temperature and load variation, PD test
Mechanical state	Design review +operation history+vibration test
Thermal and Aging state	Fluid tests + Design review (Temperature profile)+Thermoscanning+coolers efficiency test
LTC state	Fluid tests +Design review + operation history+vibroacoustic
Bushing state	On-line PF tests+design review

Design Review is a powerful Diagnostic Tool[5]

Historically developing transformer population has been accompanied with constantly advancing design techniques. Looking back into 60th and 70th we can find a number of design deficiencies attributed to underestimation of stray losses, inadequate thermal and short-circuit performance, etc. Most units are designed to meet individual utility specifications involving significant difference in design requirements, features, and safety factors. Specification is a living document; which is constantly changing under influence of service experiences, especially failures experiences.

Hence all large transformers are individuals and two units of the same style number can have a totally different “service health and age». Design Review can be the only effective means to identify peculiarities available.

Experience has shown that Life assessment program, namely the scope of tests and their interpretation depend on two design features:

- Sensitive points of the core and coil assembly and transformer components and their likely failure modes
- Variability of the design (diagnostic accessibility)

Design Review is a vital means to gain an insight into transformer structural features, to understand function and structure of transformer components and to determine sensitive parts of components and their expected failure modes. Particular attention should be paid to the following:

- Identification of the transformer composition and functional purpose of the main subsystems.
- Identification of diagnostic related parameters from a fingerprint factory test. Particularly stray loss component, temperature rise of the core, leads and LTC contacts above oil are useful but typically underused diagnostic parameters.
- Estimation of dielectric safety margin and sensitivity of "weak" points to contamination.
- Estimation of mechanical margin of windings in real operating conditions (magnitude of through fault current). Analysis can pinpoint the winding, which can be most likely moved as well as its likely deformation-mode.
- Estimation of thermal –cooling performance, especially winding temperature profile and relevant characteristics of coolers
- Design review and assessing the "sensitive points" and possible failure modes in the bushings and OLTC considering conditions of their operation, service experience and especially failure analysis of particular style number.
- Assessment of design factors influencing diagnostic effectiveness (Design Diagnostic Accessibility). Winding arrangement, insulation structure and construction including share of fluid and pressboard in the insulation space would provide information about sensitivity of dielectric characteristics (PF, PDC, DFR) to pressboard and oil contamination.

Operation Condition Review

Normal, abnormal and unusual conditions should be considered:

Normal operation conditions

- Average load ratio and relevant oil/winding temperature
- Maximum load ratio and relevant oil/winding temperature
- Conditions of activating and workflow of cooling system
- Overloading events
- Daily variation of load
- Conditions of the transformer energizing and de-energizing
- Level of the core excitation, especially autotransformer with OLTC in the neutral part of a winding
- Ratio of maximum operating current and rated current of the OLTC and bushings
- Oil temperature in the bushings (considering heating effect of the transformer) and in the OLTC compartment
- Frequency of tap changing. Operating time in unmoved tap position

Abnormal and unusual operation conditions, including:

- Emergency overloading
- Short-circuit events, especially on the LV side of GSU transformer
- Lightning storms

- System disturbances
- Failure events affecting the transformer
- Frequent switching and energizing
- Energizing the transformer after long storage, especially at low ambient temperature
- Excessive overvoltage caused by fast transients, by capacitance switching operations and by the substation equipment operating characteristics.
- Frequent overloading caused by rotating machinery operation

Fluid as diagnostic media

Experience has shown that fluid can serve as a powerful diagnostic media [6]. The possible benefits from using oil testing are indicated on Table 2, which shows the Transformer Functional Failure Model suggested by the Cigre WG A.18 Transformer Life Management [7]. One may observe that for this collection most of the problems indicated could, in principle, be detected by means of oil analysis.

Table 2
Functional Failure Model
Possible detection of typical defects and faults through oil tests.

SYSTEM, COMPONENTS	DEFECT	Detection Through oil	FAULTS	Detection Through oil
Dielectric Major Insulation Minor Insulation Leads	Excessive water Oil contamination Surface contamination Abnormal aged oil cellulose aging static electrification PD of low energy	Yes Yes No Yes Yes Yes Yes	Destructive PD Localized tracking Creeping discharge Heated cellulose <i>Flashover</i>	Yes No Yes Yes Yes
Magnetic circuit Core insulation Clamping Magnetic shields Grounding circuit	Loosening clamping Short/open-circuit in grounding circuit circulating current Floating potential Aging lamination	No Yes Yes Yes No	Localized hot spot Sparking/ discharges Gassing	Yes Yes Yes
Mechanical Windings Clamping Leads support	Loosening clamping	No	Winding distortion radial axial twisting Insulation Failure	No Yes
<u>Electric circuit</u> Leads Winding conductors	Poor joint Poor contacts Contact deterioration	Yes Yes Yes	Localized hot spot Open-circuit Short-circuit	Yes No Yes

Creating functional test/information groups may assist the diagnostic usability of fluid parameters:

- *Characterization* – which gives parameters that can be used to identify the oil
- *Aging status* – which gives parameters relevant to the aging process
- *Dielectric status* – which gives parameters used to determine the dielectric safety margin and dielectric characteristics of the insulation spaces.
- *Degradation status* – which gives parameters relevant to faults, failure and wear.

Table 3
A Functional Classification of Oil-Based Information

Classification of Oil-Based Information for Transformer Life Management			
Characterization	Aging Status	Dielectric Status	Degradation status
Fluid Composition Carbon Types Specific Gravity Viscosity Refractive Index Permittivity PAH content Inhibitor Content Total sulfur Corrosive Sulfur PCB Content BTA Content	Free Radicals Visible Spectrum Acidity Low molecular acids Saponification number Inhibitor contents IFT IR spectroscopy Dissipation factor Resistivity Polarization Index Turbidity Insoluble sludge Sludge content Residual Life	Water content Percent saturation Bound water Particle profile Breakdown voltage Charging Tendency Resistivity (and temperature response) Power factor (and temperature response) Insoluble sludge Gas tendency PD intention voltage	DGA Extended DGA Furanic compounds Phenols Cresols Dissolved metals Particle profile

Comprehensive fluid test program considering variation of transformer temperature and load while oil sampling and advanced methods for diagnostic interpretation of test results allows ranking the aged transformer population and select the units, which require special off-line tests. For example, temperature response of moisture migration, variation of breakdown voltage, Resistivity and PF, analysis of particles (concentration, size, origin), and in-depth by-products analysis allow effective classification of the equipment condition. New analytical techniques, especially analysis of particles morphology, dissolved sulphur and dissolved metals are recommended as a complementary diagnostic tool.

Weighting of defects and possible failure –modes in ranking determination

It is important to classify the transformer condition (through relevant parameters)

In three groups [8]:

Defective condition, which may results in *catastrophic failures*:

Defective condition, which impact *short-term reliability*

Defective condition, which impact *long-term reliability*

The typical failure modes that may result in catastrophic failure are:

- Puncture of insulating core of HV bushing. Flash over internal porcelain of HV bushing.
- Breakdown of insulation space HV winding-tank, HV bushing-turret.
- Breakdown the phase-to phase insulation of the HV windings.
- Short-circuit in the LTC compartment (selector or diverter).
- Overheating the external terminal contacts resulting in burning-out gasket, oil leak, and failure of some porcelain insulators of the outside tertiary or LV bus.

Apparently, aging deterioration of oil and cellulose is basically issues of long-term reliability, with the exception of oil oxidation state that results in sludge appearance and conductor insulation aging state, which allows short-circuit between wires or intensive generation of water (presumably $DP < 200$).

Defects classification, which allows ranking in terms of reliability, is shown in the Table 4

It's important to emphasize that defects, which in principle allow a long serviceability (e.g. oil overheating due to stray flux or severe oil oxidation) can form a Dormant Incipient Fault by means of deposit conductive particles of bushing and winding surfaces due to trapping effect of electrical field.

Table 4

Typical defects classification in terms of impact on reliability

	Defects that impact on Short-term reliability	Defects that impact on Long-term reliability
Electromagnetic circuit	<p>Localized hot spot-burn-out of metal associated with the main magnetic flux</p> <p>Sparking/discharges associated with the main magnetic flux</p> <p>Short-circuit between parallel strands</p> <p>Sparking/discharges associated with stray magnetic flux</p>	<p>High core temperature-oil/cellulose overheating</p> <p>Loose clamping/ laminations</p> <p>Short-circuit (open-circuit) in grounding circuit</p> <p>Floating potential</p> <p>Aging lamination</p> <p>Core and core structure Insulation degradation</p> <p>Overheating of external components (tank, joints),</p> <p>Localized hot spot-burn-out of metal associated with stray magnetic flux</p>
Dielectric system	<p>Bubbles in Oil</p> <p>Voids within insulation</p> <p>Free water</p> <p>Excessive dissolved water</p> <p>Conductive-mode particles in oil (e.g. metals, carbon)</p> <p>Surface contamination with conductive particles</p> <p>Static electrification</p> <p>PD of a high energy</p> <p>Surface discharges</p> <p>Localized tracking</p> <p>Creeping discharge</p>	<p>High moisture in barriers allowing build up moisture in oil with temperature</p> <p>High moisture in conductor insulation allowing bubbles evolution with temperature</p> <p>High concentration of non-conductive particles capable to adsorb moisture</p> <p>Sludge particles</p> <p>PD of low energy</p>
Current-carrying circuit	<p><i>Wire/leads connection:</i></p> <p>Pyrolytic carbon growth, gas generation, coking, melting the copper</p> <p>severe oil contamination</p> <p><i>Movable LTC connection</i></p> <p>A progressive rise of contact resistance and temperature, gas generation, , coking, open-circuit or short-circuit occurrences</p>	<p><i>Wire/leads connection:</i></p> <p>Local heating in places of poor joints, increasing contact resistance, oil overheating, impairment of heat exchange, ,</p> <p><i>Movable LTC connection</i></p> <p>formation of film coating, increasing the contact resistance and temperature</p>
Mechanical system	<p>Axial distortion</p> <p>Wire bending</p> <p>Significant hoop buckling</p>	<p>Loosening clamping-</p> <p>Winding Incipient buckling</p> <p>Winding twisting</p>

Experience with condition –based ranking

Методология функциональной диагностики была применена :

На Запорожской и Южно-Украинской АЭС;

Для шунтирующих реакторов 55 МВАР, 400 кВ в Чешской республике;

На шунтирующих реакторах 750кВ в системе НЭК Украины;
На Ново-Воронежской, Кольской и Билибинской АЭС при определении
возможностей и условий продления срока службы;
На ТЭС Кендал, Южная Африка (трансформаторы 730 МВА);
На АЭС Коеберг , Южная Африка;
На Сургутской ГРЭС 1
На Молдавской ТРП (5-GSU,2 –aux. 9-autotransformers)
В энергокомпании SPFL ,Сан Пауло, Бразилия (61 distribution 69-160 kV)

Результаты показали возможность оценки состояния значительного парка трансформаторов за короткое время (десятки дней)) с выявлением критического оборудования с преимущественным применением методов инженерного анализа и специальных испытаний масла.

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