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CONSIDERATIONS ON POWER TRANSFORMER CONDITION- BASED MAINTENANCE

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Abstract

The paper discusses concepts of the transformer condition based monitoring focused on maintaining the equipment functional serviceability. Typical scenarios of transformer failures are presented based on the analysis of large power transformer failures in the recent years. Using the experience with in-field assessment of the conditions of large power transformers the paper attempts to answer some questions: How to move to a condition-based methodology? What are the really effective diagnostic methods? What are the problems with the detection and identification of typical failures? What can be done if a transformer shows symptoms of abnormality?

Key words: Power transformer- Diagnostics- On-line monitoring.

Introduction

The maintenance policy for HV power apparatus in the CIS countries is changing under the pressure of economical considerations. Recently the Ukrainian electric power utilities have approved the following concepts for Life Management of power transformers and reactors proposed by ZTZ-Service [1]:

- Condition based maintenance instead of traditional time-based maintenance (that included a major overhaul of the equipment after every 12 years of service)
- Continuity of supply, especially for GSU transformers of nuclear power plants
- Minimizing the remedy actions, just to provide serviceability of the equipment
- Comprehensive life extension program with the goal to guarantee a reliable and prolonged service
- Priority in in-field repair and refurbishment works, especially for on-line processing procedures

Correspondingly, some complex problems have arisen:

- How to move from time-based to condition based maintenance?
- How to use reliability centered maintenance methodology, particularly for the equipment, which shows a symptom of abnormality?

- How to assess and extent the life of assets?
- How to prevent sudden failures, particularly catastrophic ones?

The goal of this paper is to discuss some considerations in condition-based methodology on the basis of ZTZ-Service Co experience and current activity of CIGRE SC-12, especially Working Group WG12.18 “Life Management of Transformers”[2, 3].

Conditions of a transformer during its life cycle

Functional serviceability of a transformer may be determined by its four key properties:

- *Electromagnetic ability and integrity*- an ability to transfer electromagnetic energy at specified conditions, including permissible overexcitation and overloading, without the general overheating, excessive losses**,** appearance of localized hot-spots, gassing, excessive vibration and sound.
- *Integrity of current carrying circuit.*
- *Dielectric withstand strength* under the influence of the specified operational stresses, considering a permissible level of deterioration.
- *Mechanical withstand strength* under the effect of specified through-fault currents;

A failure occurs when the withstand strength of the transformer with respect to one of its key properties is exceeded by operating stresses. Sometimes the transformer can keep serviceability being in a faulty condition (overheating, gassing) but it will fail immediately if a short-circuit or open-circuit happens. The withstand strength of a transformer decreases naturally over its life due to various aging processes during fault-free operation (expected degradation) It may deteriorate faster than normal (unexpected degradation) under the influence of agents of deterioration.

The CIGRE WG12.18 suggested to distinguish between reversible abnormalities (referred to as defects) and irreversible ones (faults). Correspondingly four grades have been established [3]:

- *Normal conditions*- no obvious problems, that means defect-free conditions (on the base of physical consideration), or a specified condition after manufacturing, or a permissible condition in service [4], or 100 % good [5]
- *Defective condition***-** an asset life may be adversely affected in a long term
- *Faulty condition***-** a short term reliability likely is reduced. It may or may not be possible to improve conditions by a remedial action
- *Failed condition-* an asset cannot remain in service. Remedial action is required before the equipment can be returned in service.

The stated conditions characterize the state of health of the equipment. The life management of transformers shall follow the same process for the resolution of problems as it is done in the management of human health: *symptoms of illness – anamnesis – focused examination – diagnosis – cure.*

One may assume the architecture of the condition-based monitoring as a system of inquiries about possible defective conditions, which may disturb at least one of the key functional properties. However characteristics of a defective condition, considering its possible evolving in the failure, shall be defined clearly.

Concepts of condition based methodology

- A transformer is considered to consist not of just some typical components but of a number of functional subsystems, which include relevant components.

- A frame-work of the monitoring and diagnostic system is transformer **failure model**. It defines the possible defects and “sensitive points” in the particular type of the equipment on the basis of the design review and in-field histories. A failure model shall identify the goal of the condition monitoring (what to look for?)

- The condition-based monitoring is considered as a test-questionnaire in terms to detect a possible defective condition of the certain functional subsystem, which may lead to malfunction. For instance: is there excessive water or particle contamination?(dielectric), abnormal heating?(load transfer), winding distortion?(mechanical defect), etc.

- The test program is focused on a detection of possible defect utilizing a group of methods, which characterize the particular defect. . At least two procedures are necessary to quantify the defect, as well as to ascertain its presence. The correlation between relevant methods is to be considered.

- Multi-step diagnostic procedures are typically advised: Indication - Detection (In-Service or On-Line procedures) - Confirmation (Complementary tests) - Prediction (Functional-mode tests) - Verification (Internal inspection).

Functional failure model

A transformer failure model has 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?

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.

A Functional Failure Model of large core form power transformers with oil-barrier insulation, that have been advised on the basis of many years experience [1, 6] is shown in Appendix 1. A transformer is considered to consist of the following functional systems and relevant components: Electromagnetic circuit - Current carrying circuit - Dielectric system - Mechanical structure - Cooling system – Bushings - LTC (if any) - Oil preservation and expansion system - Protection and Monitoring system.

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 dielectric health. Impurities in oil may migrate under impact of temperature and electromagnetic field. Aggressive oil decays products being adsorbed by insulation can destroy the cellulose and also kill new oil after refilling.

Design review is the first step in the condition assessment

Design review is a vital mean to gain an insight into transformer structural features. CIGRE set up a special WG 12.22 to develop "Guide Lines for Transformer design review". Our experience has shown that the life assessment program shall include [8]:

- Evaluation of maximum temperatures of windings and oil in real operative conditions and of the temperature distribution across the transformer.
- Estimation of the dielectric safety margin and the sensitivity of "weak " points to normal deterioration.
- Estimation of the mechanical margin for windings in real operative conditions (magnitude of through-fault current) [7].
- Assessing the "sensitive points" and possible failure modes for bushings, LTCs, and other components.
- Assessment of the controllability and testability of the equipment, and particularly the presence of elements that may mask the change in a transformer condition or even prevent the condition assessment.

Defective condition and its characteristics. Failure mechanisms

Electromagnetic circuit. Experience has shown that defective /faulty conditions typically are attributed to the following abnormal states:

- General overheating, namely, abnormal rise of the oil temperature due to cooling deficiency, poor distribution of oil flow, core overheating
- Local core overheating associated with the main magnetic flux
- Local core overheating associated with a stray flux

Faults caused by the closed loops between adjacent members linked by the main flux are the most dangerous. Shorted winding strands (turn-to-turn or layer-to-layer short circuit) cause transformer malfunction immediately. Closed loops in the core (insulated bolts, pressing bolts, pressing metal rings) cause typically an intensive gas generation, activating the Buchholz relay and also may be attributed to failed condition.

Faults associated with a stray flux (including short circuit between winding parallels) allow to continue transformer operation on the condition of load limitation. Three failure mechanisms may be advised:

- Local overheating due to excessive eddy current losses resulting in generation of gas, carbon and other degradation products, and in insulation deterioration
- Close loops between adjacent members linked by stray flux, if accompanied with poor contacts, result in overheating, sparking and arcing, and in insulation deterioration
- Sparking due to a floating potential (e.g. ungrounded magnetic shields)

The characteristics of the defective condition are:

- Rise of temperature (in correlation with the load)
- Faulty gas generation
- Appearance of other products of degradation (metals, furans, if adjacent insulation involved)
- PD activity

- Fast deterioration of oil
- Change in vibro-acoustic spectrum affected by the residual clamping force in the core [9]
- Increase of no-load losses and magnetizing current if the problem is associated with the main magnetic flux
- Change of no-load losses if the problem is associated with the stray flux

However, there is still a deficit of effective diagnostic tools to identify the faults attributed to overheating in small amounts of material and to heating the oil up to comparatively low temperatures (below oil boiling temperature)

Current carrying circuit. The following typical scenario of an equipment failure may be suggested:

- *Fixed connection*: Local heating in places of poor joints, increasing contact resistance, oil overheating, pyrolytic carbon growth, gas generation, coking, impairment of heat exchange, melting the copper, or breakdown of oil due to severe contamination
- *Movable (LTC) connection:* formation of film coating reducing the contact surface, increasing the contact resistance and temperature. A progressive rise of contact resistance results in the progressive rise of temperature, gas generation, irreversible degradation of the contacts, coking, open-circuit or short-circuit occurrences.

Life testing of LTC contacts at ZTZ-Service has shown that the process of film coating formation may be expressed as following:

$$S = k_1 \cdot \theta^{k_2}_{oil}\, t^{k_3} \qquad (1)$$

where S is the film thickness; θ_{oil} is oil temperature; t-time (hours), k_1, k_2, k_3 are the coefficients that depend of the contacts material and oil composition and quality. Typically k_3=0.6-0.75, k_2=3.5-4.5.

The defective condition may be characterized by:

- Increasing in the contact resistance by three times or more
- Rise in oil temperature in the vicinity of contact –over 100-105^0 C

The faulty condition (erosion of the surface) is expected when the contact resistance is increased by 5-10 times.

The characteristics of defective/faulty conditions are:

- *Rise in contact transient resistance.* Taking into account that the initial value of contact resistance is 150-200 μOhm per coupling, the test procedure has to consider detecting change in resistance by 600-1000 μOhm. Therefore, the conventional resistance measurement [4] can indicate the abnormality only if winding resistance is 0.1 Ohm or less.
- *Change in the contact resistance with current* due to rise of breakdown voltage of the coating film.

- *Dissolved fault gases*. The traditional DGA is effective only when the contact temperature exceed 350-400^{0}C, due to a low rate of gas generation at temperatures below the boiling point.
- *Rise of the oil temperature in the LTC compartment*. The method has been effectively approved by practical experience [10]. Possible rise of contact resistance can be estimated using rise of the oil temperature, considering the total cooling surface of the LTC compartment, the normal rise of oil temperature above ambient one and the current magnitude. However the method can detect only severe contact deterioration. Presuming cooling surface of 3 sq.m, and normal rise of the oil temperature 10^{0}C, one can show that increasing the temperature by 5^{0}C may be caused by the dissipation of additional power $\leq$ 200 W. Correspondingly, it is possible to detect the increase in contact resistance by about 1200 µOhm at the current of 400 A or about 2000 µOhm at the current of 300A.

The condition assessment for both "electromagnetic circuit" and "current carrying circuit " may be reduced to the following questionnaire:

- What is the general thermal health of the transformer?
  Procedures: Temperature in relation to load, thermo-vision.
- Is there any external overheating?
  Procedures: Thermovision, on maximum load.
- Are there symptoms of internal overheating, sparking, and arcing?
  Procedures: DGA, advanced DGA including C3-C5 hydrocarbons.
- Does the gassing associate with the main flux, or with stray flux, or with more dangerous problems that involve contacts (joints) overheating?
  Procedures: Contact resistance test, measurement of no-load and on-load current and losses.
- Are there signs of other abnormalities: unusual noise, **c**hange in vibro-acoustic spectrum vibration?
  Procedures: Vibro-acoustic monitoring.

Dielectric system of Major Insulation. The typical defects in the major insulation are:

- Excessive moisture in the cellulose insulation. This defect is inherent basically to the transformers with open-breathing preservation system or to those which have an insufficient sealing. Distribution of the moisture during the transformer life is kept quite non-uniform. Most of water is stored in so called "cold thin structures", namely in the thin pressboard barriers that operate at bulk oil temperature [11].
- Oil contamination with water, particles and oil aging products. The majority of problems is caused by these defects in the space "HV winding (HV bushing) –Tank".
- Insulation surface contamination in the forms of the adsorption of oil aging products on a cellulose surface or deposit of conducting particles and insoluble aging products in areas of high electrical stresses. The surface contamination can cause a distortion of electrical field and a reduction in the impulse strength of the insulation system.
- Partial discharges in weakened insulation spots.

Typical defects in Minor (Turn & Coils) Insulation:

- Overheating leading to accelerated insulation aging.
- Excessive moisture content leading to bubbles appearing at some zones with elevated temperatures.

- Surface contamination with conducting particles and oil aging products.

Above mentioned defects may cause a sharp change in electric parameters of the minor insulation, However, they lead to only a minor impact on the overall dielectric characteristics of the whole transformer, due to relatively high capacitances of turn insulation.

Fig. 1 shows the model of failure mechanisms of insulation under dangerous effect of degradation factors (see also [11]). It is important to emphasize that the condition-monitoring of the transformer contaminated with water shall consider also the contamination of oil with particles and aging products.

It is possible to define two critical stages of dielectric withstand strength degradation:

- *Defective condition:* reduction of the initial withstands strength under the impact of the degradation agents. It results in appearance of usually nondestructive partial discharges (PD) at operating voltage and reduction in impulse withstand strength.
- *Faulty condition:* appearance of destructive PD , progressing surface discharges, and creeping discharge occurrence.

The typical failure scenario for an initially defect-free insulation is as follows:
Contamination ⇒Occurrence of moderate PD⇒Occurrence of destructive PD⇒ Gas generation⇒Progressing PD, accompanied with gas generation⇒ tracking/treeing, accompanied with gassing and changing dielectric characteristics, critical pre-failure PD ⇒Breakdown.

ZTZ-Service has advised the following criteria for the evaluation of a defective insulation state:

- *The level of water in oil*, that may result in an increase of the relative saturation over 40-50% (considering the level of particles contamination) in the range of operating temperatures. Total water in oil including bounded water shall be considered here.
- *Water in solid insulation* in the compliance with the above stated level of water in oil. The corresponding water content in barriers exceeds typically 1.5-2%.
- *Particles in oil:* the number of particles in the range 5-150 μm more then 3200 in 10 ml of oil (in agreement with CIGRE WG12.17 recommendations). The presence of visible and conducting (metals, carbon) particles is considered as a critical condition.
- *Critical oil aging*: possible appearance of sludge in oil in the period between the tests. The end of the induction period (trend of accelerated degradation). The presence of acids and non-acid polar that accelerate cellulose decomposition.
- *Bubbles in oil* including C_2H_2 generation due to high temperatures (>800^0C) when the bubbles evolution is practically an inevitable phenomenon.
- *PD*: apparent PD of 1000 pC and above, PD energy of 0.1 W and above; symptoms of PD in the oil-barrier structure through DGA analysis.

The condition assessment of the dielectric system may be reduced to the following questionnaire:

- What is the level of contamination with water and particles? Shall we expect a substantial reduction in the dielectric margin at operating temperatures?

Test procedures: WHRT (Water Heat Run Test[11]); particles in oil; PD parameters- apparent charge magnitude, Pulse repetition rate, Discharge Power, PD Signature; Temperature response of insulation power factor (PF).

- What is the level of water content in solid insulation? Shall we expect bubbling evolution at overloading?
  Test procedures: WHRT, estimation of water content using temperature response of PF and insulation resistance, test on oil aging products, especially interfacial tension
- Shall we expect a substantial insulation surface contamination?
  Test procedures: PD measurement, temperature response of PF, particles, and oil tests.

Mechanical withstands strength. The following typical scenarios of a transformer failure have been experienced:

- Loosening clamping- Distortion of winding geometry $\Rightarrow$PD appearance $\Rightarrow$Creeping discharge progressing $\Rightarrow$Breakdown.
- Distortion of winding geometry + Switching surge $\Rightarrow$Flashover between coils (sometimes with restoring withstand strength)$\Rightarrow$Gas evolution.

Experience has shown that over 90 % of mechanical-mode failures have been associated with radial buckling of internal windings. Experience has confirmed also that a damaged transformer may keep serviceability for years until an insulation failure occurs. The winding buckling results in change (decrease) of the winding diameter, and of the dimension of leakage channel.

The following diagnostic characteristics have been used to detect winding movement: winding capacitance, short circuit reactance (impedance), low voltage impulses, Frequency Response Analysis of transfer function, Frequency Response of stray losses. ZTZ-Service has utilized different techniques and has found that the preferable one is the relative change of leakage reactance with respect to moved winding (or reactance response of the winding in question).

The leakage reactance Z_L may be expressed as

$$Z_L = \omega \cdot \mu_o \cdot \rho \cdot W^2 \cdot \frac{D_{av} \cdot \delta}{H}, \tag{2}$$

where W is the number of turns; D_{av} – its average diameter; δ is the reduced value of the leakage channel.

The change of the winding diameter and leakage channel by ΔX results in the change of relative value of leakage reactance

$$\Delta Z_L \cong (m-n) \cdot \Delta X \;;$$

where (m-n) are given winding dimensions.

The value of ΔX may be positive or negative with respect to different windings. Thus the image of the faulty winding can be determined. The reduction in the winding diameter by 10 mm and the corresponding relative change in the leakage reactance are presumed as defective condition.

This technique allows to identify the faulty winding and to evaluate the level of distortion. During the last 15 years about 40 damaged transformers were identified in-field and thediagnosis was verified by later inspection.

The condition assessment of mechanical withstands strength of a transformer may be reduced to the following questionnaire:

- What is the mechanical safety margin of the windings?
  Procedure: Design review
- What can be learned from transformer history (fault current events with current magnitudes above 70 % of rated short circuit current). How could the winding suffer?
  What's the leakage reactance and transfer function response to movement of the winding in question?
  Procedures: Calculations, the diagnostic matrix determination.
- How to find the problem?
  Procedures: Leakage reactance, FRA and winding capacitance measurements to detect and identify the problem.

What can be done if a transformer has a problem (history cases)

Here are some typical problems that require a prompt decision:

- What to do if a transformer is gassing?
- What to do if a unit was subjected to unusual event?
- How to identify dielectric health of the unit after a long service?
- What to do if unusual insulation PF has been tested?

ZTZ-Service has implemented several diagnostic techniques to identify seriousness of a detected abnormality and to decide on the continuing of the operation of a defective transformer. Those are:

- Model (flow-chart) of a gassing transformer;
- In-Field Heat Run Test, similar to a well known factory Heat Run Test, to predict the condition of the unit after increasing load
- Water Heat Run Test with the goals: to assess the transformer health under rated conditions – the maximum permissible temperature; to estimate the level of water contamination using the build-up of water content in oil with time and temperature; to evaluate possible state of water and the distribution of water within a transformer using the rate of building-up of water in oil.
- Identification of the transformer conditions using electrical PD measurement.
- Identification of the insulation conditions using temperature response of dielectric characteristics and insulation design features [12].
- Identification of the mechanical strength of the windings
- Identification of the bushings conditions using temperature response of PF [13]

A transformer is gassing. What to do? Fig. 2 shows a diagnostic flow chart that has been developed on the basis of many years experience. To find a solution for the problem "What to do if the transformer shows clear symptoms of abnormality" it is necessary to answer the questions:is the source of gas generation internal or external? Does the problem associated with thermal or electric faults, with operative voltage or magnetic flux, with main flux or with stray flux? What may happen if the load will be increased? The diagnostic model in Fig.2 may help to answer these questions in some instances

Case #1. Gassing of the transformer caused by dangerous overheating of the contacts of leads. An auxiliary transformer of a 1000 MW nuclear power plant unit unit, 63 MVA 24/6.3/6.3 kV,1515.5/2887/2887 A, Delta/Delta connected, was in the service since 1984. In December 1997 DGA analysis revealed a clear symptoms of thermal decomposition products, with a rapid rise of the rate of gas generation (Table 1). ZTZ-Service advised to check the influence of load on gas generation After current decrease the gas generation practically stopped. It was concluded that the problem is in the current flow circuit and the relevant winding resistance test was advised (Table 2). The test of LV2 winding has shown the presence of defect in phase" **b".**

Table 1. DGA results for the 63 MVA transformer

Data of tests	H2	CH4	C2H2	C2H4	C2H6	CO	CO2	C3H6 C3H8	C4H8
14.11.95	**5**	**2.5**	**<0.1**	**43**	**<1**	**165**	**506**	**84**	**392**
08.12.97	**78**	**259**	**<0.1**	**640**	**117**	**219**	**1827**	**276**	**639**
11.12.97	**64**	**347**	**1.4**	**883**	**147**	**266**	**2402**	**610**	**616**
29.01.98 *	**37**	**247**	**<1**	**798**	**35**	**190**	**1837**	**644**	**670**

∗) After decreasing the load

Table 2. Resistance test on the 63 MVA transformer

Winding	Resistance, µΩ			Difference between phases
	a-b	b-c	c-a	
LV1	**2582**	**2626**	**2610**	**1.7 %**
LV2	**2992**	**2840**	**2780**	**7.6 % or 212 µΩ**

The operating current of 1440 A could produce in the place of poor coupling a local "heater" of 440 W, good enough to cause gas generation.

Inspection confirmed overheating and melting of the LV2 connection to the 6.3 kV bushing and a severe contamination of insulation between phases. A possible catastrophic failure was prevented.

Case 2. The identification of the gas generation source through In-Field Heat Run Test. A single-phase autotransformer, 333 MVA, 750/330/35 kV, in service since 1991, has shown the symptoms of arcing in oil after a through-fault event. The fault involved, likely, a cellulose decomposition. The first question was whether the fault involves major insulation. This presumption was rejected by PD-acoustic test at voltages of 1.0 and 1.05 of rated one. PD test rejected also faults associated with the main magnetic flux. However, it was found some correlation between gas generation and the load. After design review it was supposed that the source of gas generation is attributed to the magnetic shields on the tank wall. Heat Run Test (assessment of the transformer health on maximum possible load) was advised and implemented. The unit was loaded from usual 50-60 % of rated power to the maximum possible 75 %. The test was carried out during 24 hours and showed a rapid rise in the rate of gas generation, especially C2H2 (Table 3). It was concluded that transformer operation can be continued at limited load until the planning repair. Further inspection confirmed traces of PD activity on the edges of the shields and carbonization of the adjacent insulation.

Table 3. DGA results for the 333 MVA transformer

Data of tests	H2	CH4	CO	CO2	C2H4	C2H6	C2H2	C3H6	1-C4H8
03.08.1994	1	1	40	630	4	1	<0.1		
06.09.94	23	10	130	410	26	1	5		
07.10.94 rise of load	38	19	90	540	36	4	12		
10.07 95	48	78	408	1327	78	19	12.6		
15.07 13-00	63	56	446	1286	123	44..8	10		
16.07.8-00♦	44	62.4	397	1479	123	25..9	26..9		
16.07 19-50	69.7	62.2	376	1745	121	23.4	66.9	209	771
17.07 19-50	103.4	97.2	398	2164	396	112	106.4	864..8	2258

♦Starting Heat Run Test

Case # 3. Continuation of the gassing transformer operation on the basis of Heat Run Test.

A 250 MVA, 330/150 kV autotransformer has shown symptoms of oil overheating and arcing after 20 years of service. It was critical to continue its operation. On the basis of the test program performed by ZTZ-Service it was suggested that the problem was associated with the stray magnetic flux . The Heat Run Test was advised to determine the serviceability of the unit. Its results (Table 4) has shown that an increase in the load leads to an intensive rise of temperature in the vicinity of the faulty place. The unit was left in operation with a load limitation.

Table 4. Heat Run Test of the 250 MVA transformer

Load	Dissolved in oil gases, ppm						
	CO2	CO	H2	CH4	C2H4	C2H2	C2H6
60 % of rated	1329	152	695	**1274**	**2820**	**Traces**	**297**
Rated	1298	127	534	**1518**	**3034**	**33**	**354**

Case # 4. The assessment of the seriousness of a gas generation in a 300 MVA , 500 kV transformer. One of two sister shell-type autotransformers has shown a generation of faulty gases, likely associated with combination of PD activity, localized oil heating, and cellulose decomposition (Table 5). The continuing of operation of the both units was very critical. The problem arose how serious is the symptom of abnormality? Will it progress to affect the insulation system? To assess the problem PD electrical test had been advised. The test was performed by ZTZ-Service using Cutler-Hammer UPDA Analyzer [15]. Analysis of PD characteristics (Table 6) has pointed out at the defective condition of the transformer. Particularly, a severe oil contamination (judging by high pulse repetition rate) and the presence of a source of PD generation on the phase U close to the HV terminal have been admitted. However, the measured level of ionization could not cause a severe destruction of insulating material and the observed rate of gas generation. It was supposed that the problem is not attributed to PD in the major insulation and the unit may be left in operation for a certain time (at least for one year). Unfortunately it was not possible to perform PD test at fully loaded transformer in order to see the possible correlation of PD source with stray flux.

Table 5. DGA data for the 300 MVA, 500 kV transformer

Object	**Data**	**H2**	**CH4**	**C2H6**	**C2H4**	**C2H2**	**CO**	**CO2**
		[ppm]						
T1RS	27.09.97	**1**	**1**	**4**	**1**	**1**	**4**	**49**
T1RS	17.10.97	**53**	**2**	**1**	**1**	**2**	**46**	**235**
T1RS	12.11.97	**154**	**6**	**2**	**3**	**2**	**105**	**684**
T1RS	14.05.98	**447**	**32**	**11**	**23**	**1**	**580**	**1920**
T1RS	30.06.98	**563**	**151**	**50**	**148**	**1**	**605**	**1757**
T1RS	23.07.98	**557**	**155**	**45**	**156**	**<1**	**588**	**1720**
T1RS	02.09.98	**674**	**204**	**70**	**217**	**<1**	**722**	**2174**

Table 6. PD Test report on the 500 kV transformer of 07.22.98

Object	Sensor	noise, [pC]	Maximum Pulse Magnitude [pC]	Repetition Rate [ppc]	PD Power [mW]
T1RS, Gassing;	Bushing U	127	**1,270**	100	**107**
	Bushing V	127	225	1000	471
	Bushing W	142	252	1800	806
	Neutral	37.8	0	0.759	0.00046

Case # 5. Assessment of the transformer condition after severe through-fault event. A 250 MVA, 330/150 kV autotransformer after 12 years in service was subjected to a severe through-fault event due to failure of a lighting arrester during a hurricane. The following diagnostic procedures have been implemented:

- Design review: estimation of mechanical safety margin. It was found that the sensitive point of the transformer is the common winding which may have insufficient margin if winding clamping is loosened.
- Estimation of leakage reactance (LR) response to movement of the common winding. The results are shown in the Fig. 3 as a relative change of LR between Series winding (SW) and Common winding (CW), CW and Tertiary Winding (TW), and between SW and TW.
- Three conditions have been studied:
  Change of the winding diameter by 5mm-reversible (defect-free)
  Change of the diameter by 5-10 mm-possible movement (defective condition).
  Change of the diameter more then 10 mm-critical faulty condition.
  Common winding (CW) buckling results in increasing LR SW- CW, decreasing LR TW-SW, and CW-TW.
- Leakage reactance test (Table 7).

Table 7. Leakage Reactance Tests on the 250 MVA transformer

Tests	**Phase**	**Z_L, Ω**	**Name plate**	**ΔZ_L, %**
CW-TW	A	39.08	41.74	**-6.37**
	B	41.40		-0.80
	C	42.19		1.06
SW-CW	A	46.62	44.46	**4.87**
	B	45.54		2.44
	C	45.23		1.73
TW-SW	A	226.45	231.88	**-2.34**
	B	229.77		-0.91
	C	234.74		1.23

Test results have shown clear symptoms of distortion of the Common winding, phase A. The internal inspection has confirmed the problem. Taking into account that the condition of the winding has not been yet critical, and there was no reserve unit, a decision was made to continue service of the unit. The transformer is still in operation.

Conclusion

The architecture of the condition–based maintenance is considered as a system of inquiries about possible defective conditions that may disturb at least one of the key functional properties of the transformer. Characteristics of a defective condition considering its possible evolving in failure shall be defined clearly. A frame-work of the monitoring and diagnostic system is transformer failure model that advises on possible defects and “sensitive points” in the particular type of the equipment on the basis of the design review and in-field history.

Monitoring and diagnostic technique calls for a substantial advancement to meet the pressing need of utilities in economical and reliable maintenance. Some new (non-traditional) methods may be advised to assess and extent the life of assets.

Experience has shown that in many cases reliable decisions could be found to continue the transformer operation even if the transformer shows clear symptoms of abnormality.

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BIOGRAPHY

Dr. Victor Sokolov, a CIGRE Member and the Convenor of CIGRE WG 12-18, obtained his MSEE in 1962 from the Kharkov Polytechnic University, and Ph. D. in High Voltage Technology in 1982 from the Kiev Polytechic University. Dr. Sokolov possess a world level expertise in all questions of designing, producing, testing and maintaining of power transformers. He is an author of numerous publications. Now he is the Technical Director of the Scientific-Engineering Center “ZTZ-Service” (Ukraine).

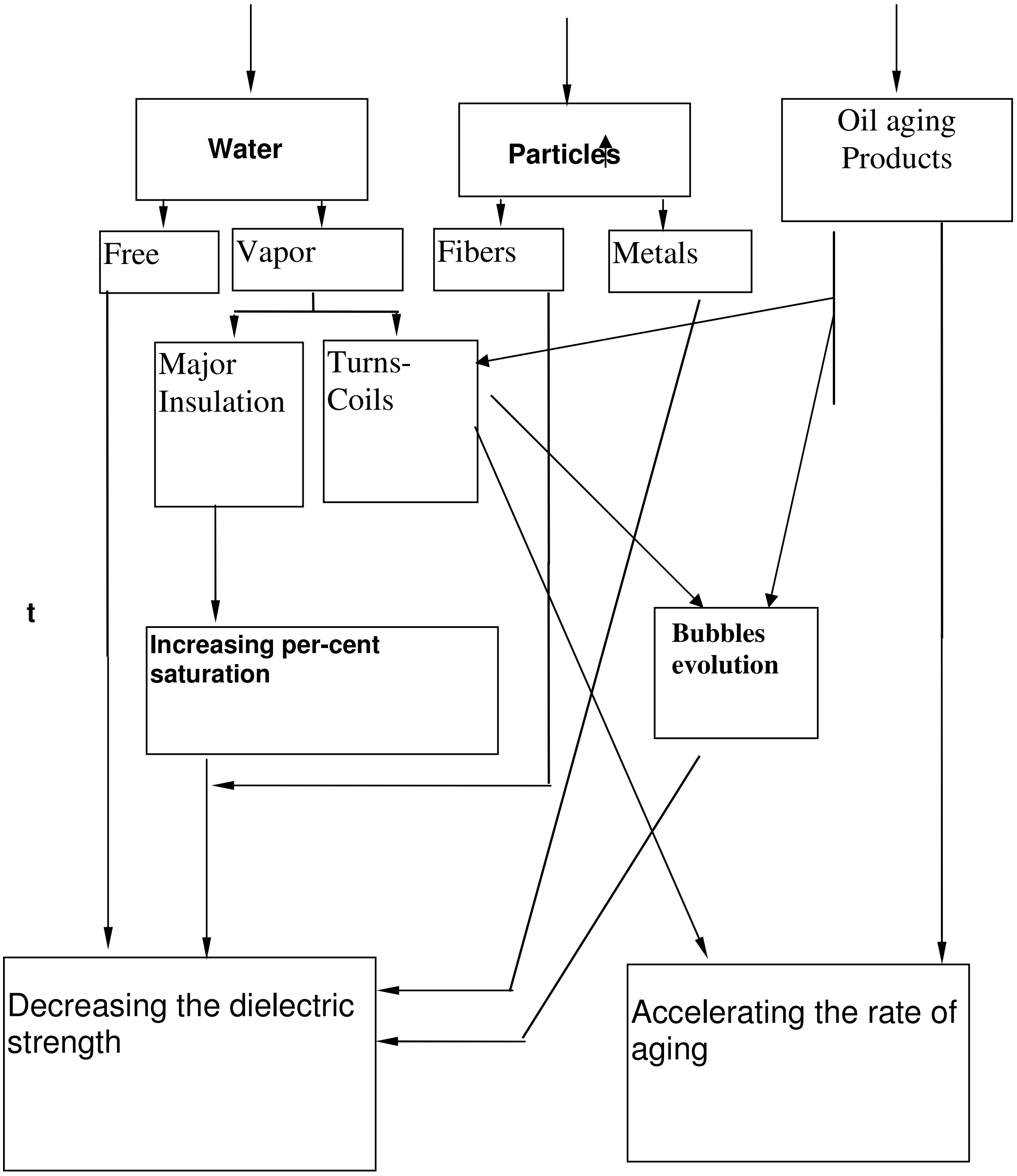
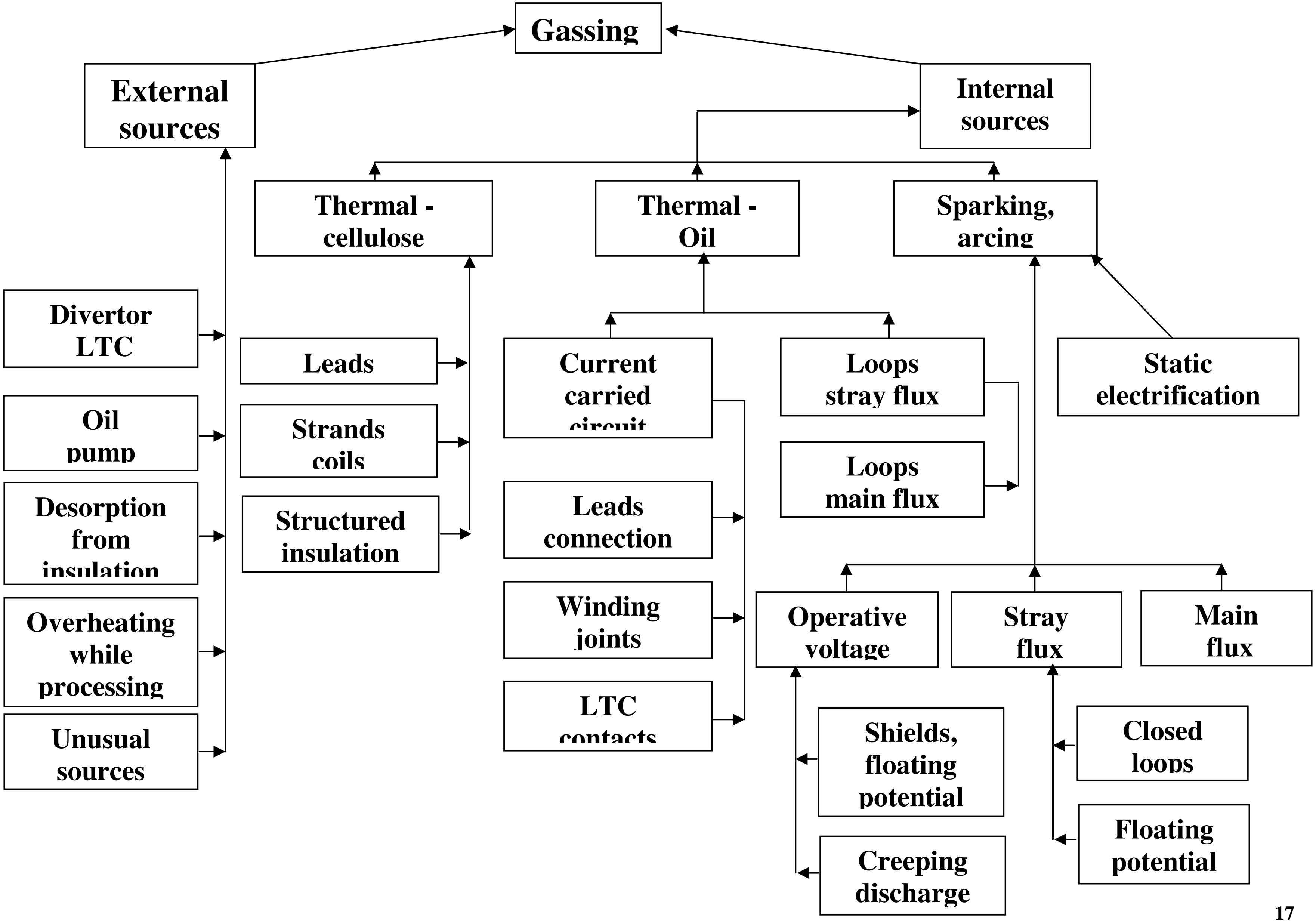


Figure 1. Dangerous Effects of Degradation Factors

Figure 2. Model of gassing transformer



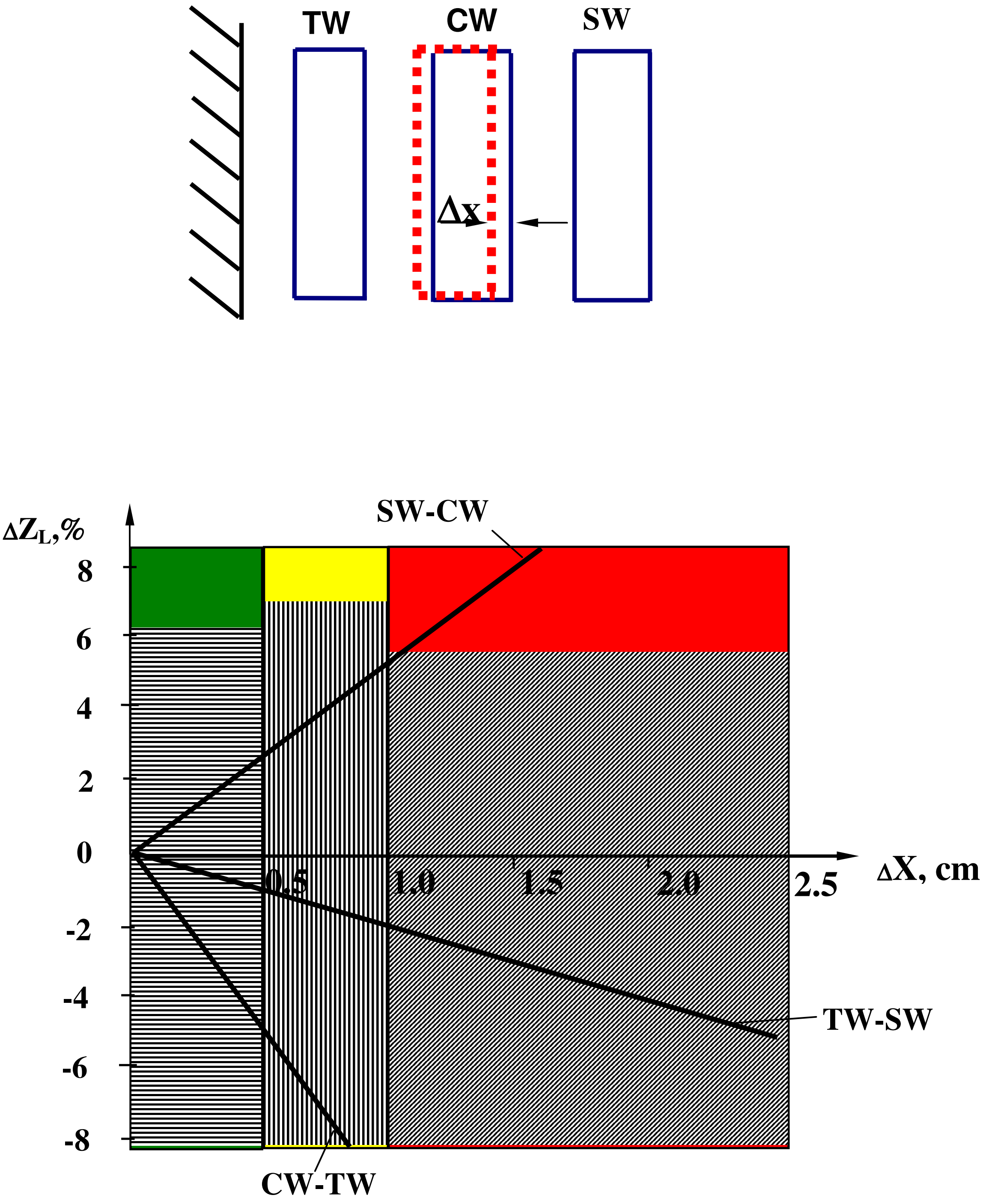


Figure 3. The evaluation of relative change in the leakage reactance for the case of the Common Winding Movement

Appendix 1

FUNCTIONAL FAILURE MODEL OF POWER TRANSFORMER

SYSTEM, COMPONENTS	DEFECT	FAULT AND FAILURE-MODE
Elecrtomagnetic circuit Core Structure insulation Clamping structure Magnetic shields Grounding circuit Windings (turns, parallels)	Loosening clamping Short-circuit(open-circuit) in grounding circuit Abnormal circulating current Floating potential Aging lamination Insulation degradation	General overheating Localized hot spot Sparking/discharges Gassing ↓ →Failure
Current carrying circuit Winding strands ,leads, Connection,joins,contacts	Poor joint Poor contacts Contact deterioration	Localized hot spot Open-circuit Short-circuit
Dielectric system • Major insulation • Minor insulation • Leads insulation • Electrostatic shields	Excessive water Oil contamination Surface contamination Abnormal aged oil Abnormal cellulose aging PD of low energy	Destructive PD Localized tracking Creeping discharge Excessive aged/overheated cellulose Flashover

Mechanical	Loosening clamping	Winding distortion
Windings		Radial buckling
Clamping		axial
Leads support		twisting
		Failure of insulation
Cooling system	Contamination	Cooling deficiency
Heat exchanger	Wrong rotation, Bearings	General overheating
Pumps	overheating ,failure	Penetration of decay product
Fans	malfunction	into oil
Piping external and internal	Poor oil f low	
Bushings	Local defect: moisture, air,	Ionization
Condenser core	overstressing, X-wax	Dielectric overheating
	Aging, oil instability	Thermal run away
Core surface, oil	oversaturation	↓
	oil contamination ,	
	moisture ,	Flashover
Conductor	Aging	Explosion
	Poor contact, Overheating	
	Mechanical damage	
OLTC		
Motor driver, shaft		Cooking
couplings, fixing	Contacts overheating	Discharges
Selector & reversor	Contamination	Malfunction
	Contacts wearing out	Dielectric breakdown
Divertor switch	Contamination	
	Mechanical deficiency	
		Malfunction
Oil preservation & expansion	Low oil level	
Tank, conservator,	Poor sealing	
Preserving components,		
piping		