RELIABILITY PROBLEMS WITH LARGE POWER TRANSFORMERS AND SHUNT REACTORS. TYPICAL FAILURE MODES AND FAILURE CAUSES

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Abstract

The paper presents failure analysis of Large Power Transformers and Shunt Reactors basically on the failure statistics available in CIS countries, and discussion on typical failure - modes and failure cause of aged transformer population.

Introduction

A failure is usually a "tuning fork" of Life Management procedures. Failure analysis delivers a key information allowing to determine "what happened" and "what to do" in terms of managing network reliability, risk assessment, maintenance optimization, estimation end of life, and on the other hand improving design and manufacturing of an equipment.
Early CIGRE survey [1], which summarized over 1,000 failures of power transformers rated 72 kV and above for the period 1968-1978 considered failures of the units not older than 20 years and marginally contributes to understanding of aging problems. It's important to emphasize that up to 35% failures was associated with design deficiencies, which correspondingly could affect further life of relevant transformers families
IEEE Guide [2] that summarized 164 failure events suggested similar conclusion. Large number of cases (51%) was found to be associated with dielectric faults basically due to design and manufacturing problems.
Apparently, most of design related problems revealed have been timely corrected and reliability related quantities suggested by e.g. CIGRE and IEEE hardly may be inherent to today operated population.
In 1999 EPRI presented failure survey [3] in GSU transformers installed in the US covering about 25% of population. Totally 45 failures was observed. It was found that failures are basically associated with bushings and winding insulation but minor effect of external exposure factors on transformer reliability was observed.
Failure analysis presented in 2000 by the Hartford Steam Boiler Inspection & Insurance [4] examines history of failures for all types of transformers in the US over a twenty-year period, from 1980 through 1999. Failure statistics revealed an important trend, which likely is inherent to most service aged large EHV transformers. It was shown that most failures occur due to impairment of equipment condition in service, and in many instances external exposure, particularly system disturbance and short-circuits involved.

Global changes in power industry, namely segregation, privatization and followed competition affected dramatically on reliability related information. For instance in 1998 about 50 Doble clients contributed to the Technical Questionnaire on large power transformer failures reporting on 166 events including one client who reported on 35 failures. In 2002 presented information contained less that 20 failure events. However at the same time SERGI Co collected through Internet information about 730 transformer explosion and fire incidents showing a clear trend of increasing number of failures with years (60 in 1999, 95 in 2000, 130- in 2001, and 190 in 2002). Thus, lose of reliability information is becoming a vital problem.

Many experts consider failure histogram as a "bathtub curve" reasonably expecting rise of failures with years. However statistics available has not exhibited yet correlation between number of failures and transformer years showing peak of failures around 19-21 years. In spite of the fact that a huge transformer population has already been in service for 25-40 and more years there is still little information available about the units that have failed primarily due to thermal degradation of insulation material.

Failure modes and causes may differ markedly depending on users specification,
transformer application and design pecularity, particularly on sensitivity of design to service deterioration and external exposure. In order to understand cause of failure properly all the factors: design, operation condition and possible deterioration of safety margin with years should be considered in integrity.

This paper is attempt to look into large power transformer reliability on the base of ZTZ-Service database statistics . Typical failure-modes and failure causes are discussed, using design review as a main instrument of investigation

Failure statistics

ZTZ-Service database covers failure events since 1955. Observed equipment include large power transformers of different application including over

5,000 of units rated 100 MVA and above and shunt reactors 400-750 kV. Since 1994 date-base have been supplementing also with collection of worldwide failure events.

Statistical distribution in 1955-1977

Early analysis of transformers failures for the period 1955-1977 [5] had shown that failure statistics corresponded to Weibull distribution

$$\lambda(t) = \exp(\frac{b}{a}) \cdot (\frac{t}{a})^{b-1}$$

with form parameter b=0.3-0.75.
Improvement of transformer design with years resulted in increase of form parameter and approaching curve shape to exponential one

Statistical distribution in 1963-2005

Fig.1 - 4 present statistical distribution of large power transformers over 100 MVA in a wide time-span. Four large groups of transformers of fairly same type have been analyzed: autotransformers 125-200 MVA, 220/110 kV (observation period 1964-2005, 27,505 transformer-years), 125-200 MVA, 330/110 kV (1963-2005, 9,477 transformer-years; 167 MVA 500/220 kV (1965-2005, 13,749 transformer-years), and generator transformers 400 MVA, 330 kV (1969-2005, 1,600 transformer-years)

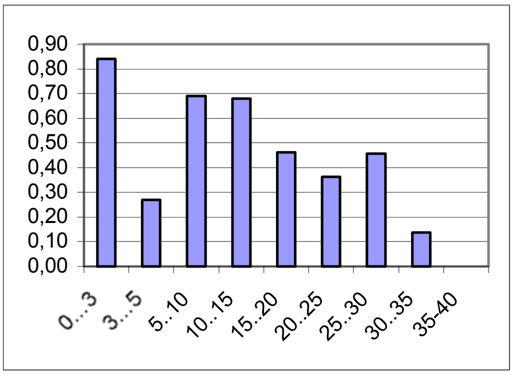

Figure 1
Bar graphs of failure rates of autotransformers 220/110 kV

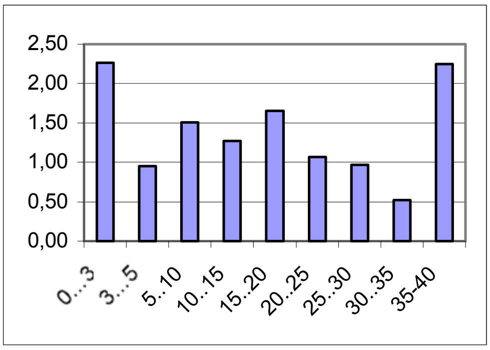

Figure 2
Bar graphs of failure rates of autotransformers 330/110 kV

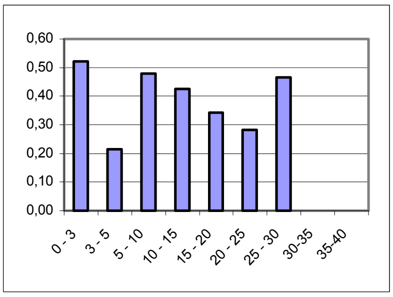

Figure 3
Bar graphs of failure rates of autotransformers 500/220 kV

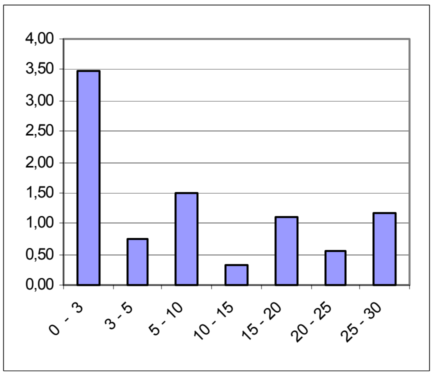

Figure 4
Bar graphs of failure rates of generator transformers 400 MVA, 330 kV

It was found that aging profile cannot be approximated with single function due to presence of several mechanisms of degradation.
Strongly pronounced wear in period (first three years) follows with rise in failure rate in time range 7-15 years, mainly due to weak design of bushings and LTC , dielectric degradation of winding insulation and mechanical movement of windings. One can observe also wear in period of OLTC design.
Failures after 25 are also associated with bushings and OLTC of certain design and insulation dielectric degradation. There is no obvious symptom of failures due to paper aging
One can declare that failure profile in the time range until 35-40 so far consists of wear-in in company with random failures and wear out of some weak components.

Failure causes

Basically three main causes of failure may be considered:
1) Originally insufficient safety margin due to underestimation operational stresses (poor specification), design deficiencies, manufacturing weaknesses, or material defects.
2)Operation stresses exceed specified quantities (unusual event, operational error)
3) Critical deterioration of safety margin including inadequate maintenance, low quality repair.

Table 1

Major failures of power transformers rated 100 MVA and above

Failure -mode	Component	Doble clients 1996-98, %	ZTZ-Service 2000-2005,%		
			GSU	Shunt reactors	Transmission
Dielectric	Winding minor insulation		37.8	38.4	14.3
	Major insulation	13.4	11.2	11.5	17.3
Thermal	Conductor insulation	5.8	13.3	-	4.8
Mechanical	Winding distortion	12.5	4.4		9.5
Magnetic circuit	Core/magnetic shields*	5.8	4.4	38.4	4.8
Current carrying	Leads, connection	3.8	13.3	7.7	3.2
Accessories	Bushing	9.6	13.3		38
	OLTC**	15.4	4.4		7.9
	DETC	3.8	2.1		-
Others		6.9	-	4	-
Total number of failures		52-100%	45-100%	25 100%	63-100%
Average age		22.4	21		20.5
Over 25 years,%		43	44.1	-	32
Less than 5 years, %		7.5	2.94	24	9.4

*Only force outages considered

** Only major failures

Apparently, with years one can expect gain in weight of the third cause and automatically increase influence of initial design margin as well as operational stresses. The entire factors should be considered in integrity.

Table 2

Failure modes of power station transformers of different application

Mode	GSU	Auxiliary	Start up
Dielectric	49	28.5	35.7
Thermal	13.3		7.2
Mechanical	4.4	14.3	28.5
Core	4.4		-
Leads	13.3	14.3	
Bushings	13.3		14.3
OLTC	6.5.	42.8	14.3
Total failures,%	100	100	100

In period 2000-2005 was documented 108 major failures of large power transformers manufactured by 9 different companies . Table 1 allows to examine failure-modes of generator and transmission transformers, and shunt reactors separately and compare with relevant data reported in 1996-98 by Doble clients (52 failures).

Table 2 shows failure –modes for transformers of different application

The data show that average age of failed transformer is still between 20-22 years however contribution of generation "after 25" is becoming more weighty

Transformer application predetermines likely failure -modes

Transmission transformers: Dielectric mode HV and TW windings insulation, bushings, movement of common and tertiary windings

Generator transformers :

Dielectric mode windings (HV) insulation; trend to increasing thermal-mode failures; Leads and connections overheating

Auxiliary power plant transformers

OLTC insulation contamination & contacts heating

Leads and connection

Winding (LV,TW) movement

Dielectric-mode failures

Damage of major insulation has been observed in 11% of failed generator transformer and in 17% of transmission transformers 220-500 kV. Failure-modes were associated with of oil gap breakdown (particularly of large gap "shield of bushing-turret"), surface contamination and degradation of impulse strength, and critical overvoltage (resonance-mode).

Damage of minor winding insulation occurred predominantly on HV windings (about 80%) and fairly stressed Regulating Windings (RW) due to free water enter, contamination with particles and degradation of impulse strength, wearing out of tap coils of HV winding, which subjected to frequent mechanical and electrical stress, underestimated impulse overvoltage and poor performance.

Three failure mechanisms are typically involved: breakdown of oil gap; surface discharge, and creeping discharge

Large oil gap. Large oil gaps, particularly those that not divided by barriers are very sensitive to oil contamination with particles and also to distortion of electrical field on electrodes**.**

Several failure cases occurred due to poor performance of 500 kV bushing shield, namely hidden defect of the metallic mesh with presence of sharp ages. (Fig.5). That resulted in PD activity under effect of switching surge and power arc to the turret

Figure 5
Hidden defect of metallic mesh

Breakdown of oil duct due to free water. Poor or deteriorated top sealing of draw lead bushings as well as poor sealing of explosion vent remained to be repeated worldwide cause allowing penetration of rain water into transformer and resulting in of a sudden breakdown oil duct between coils of HV or RW windings .

Figure 6
Short-circuit between coils due to introducing free water through poor bushing top sealing

Underestimating impulse overvoltage. This phenomenon is basically related to underestimation of impulse transient function. E.g. 220 kV transformer, which was frequently subjected switching transient during vacuum circuit breaker commutations failed due to short circuit between coils of Tap Winding (Fig 7)

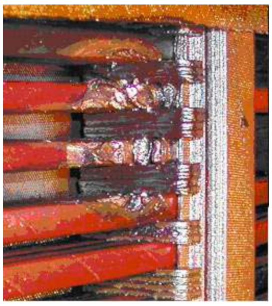

Figure 7
Short-circuit between the coils of Tap Winding

Design review shown that Tap Winding is the most stressed. Whereas voltage between coils HV winding was 2.4 kV, that between the TW coils was 6.4 kV. Analysis shown that voltage rise in TW depends on tap position. The largest stress occur when only one step was involved. In this case voltage between the coils could reach critical level 80kV. Moreover it was found that resonance frequency is equal to 19-11 kHz and resonance can occur just during circuit breaker commutation.

Surface discharge. Occurrence of surface discharge is associated with increased voltage (transit overvoltage). Apparently, contamination of surface with conductive particles reduces the value of critical field intensity.

General "aging" problem is accumulation of conductive and polar particles in oil and depositing them on the surface. Insulation surface contamination has been observed in the form of the adsorption of oil aging products with cellulose or deposit of conducting particles and insoluble aging products in areas of high electrical stresses. Contamination can cause a distortion of electrical field and a reduction in the electrical strength resulting in breakdown between coils and flashing over HV winding under effect of switching surge and lighting impulses.

Figure 8
Failure of 330 kV winding contaminated with conductive oil by-products under lighting surge

Thermal-mode failures

Analysis has shown the following failure causes:

Overheating of tap leads located between regulating coils of HV winding connected to no-load tap changer. Events occurred after 30-37 years service. Overheating of the coils of winding blocked with angle collars preventing oil flow and proper cooling. Underestimation of winding temperature, especially of LV winding in large generator transformers with OFAF cooling system.
Hence the main reason of failures was not normal aging but design deficiency

Figure 9
Failure of 700 MVA generator transformer after 25 years due to overheating the two top coils of LV winding (CTC wire) resulting in short circuit between parallels and then between turns

Experience has shown that aging profile of large transformer is typically greatly nonuniform. There have been numerous transformers particularly large generator transformers where DP level of some top winding components could be expected less than 300-250. However a huge transformer population, which exhibit in some location DP <250 still operates quite satisfactory.
The question comes: Maybe mechanical weakness of conductor insulation is not so dangerous as it was traditionally suggested?
This issue requires special discussion. Conductor insulation is subjected basically to compressive stress. Reduction of DP below 200-250 would be likely not so critical for continuous disc windings and particularly for layer windings.
The exception would be for CTC (continuously transposed conductor) wire, which could be subjected to very high compressive stresses. It’s remarkable that for the last years there have been a number of transformer failures associated with short-circuit between CTC wire strands because of overheating and critical decomposition of insulation.
More sensitive to aging deterioration could be also winding construction allowing conductors titling and bending under short-circuit stresses, and having sensitive spots affecting by mechanical stresses e.g. unsuccessful transpositions.

Damage of leads and connections

Over 13% of failures of generator transformers are associated with overheating leads and connections. Basically three failure modes have been observed: Overheating the insulation of winding exit leads; Overheating soldered connections; Overheating bolted connection to bushings

Overheating leads insulation
There have been observed several cases associated with overheating of winding leads that were performed with the same wire as a winding, what is typical when winding is performed from CTC wire

Figure 10
Overheating and burning out leads insulation in 700 MVA GSU transformer
Left: Overheating and short-circuit between parallels of LV lead exit
Right:burning out internal layers of HV lead

Design review and relevant calculations have shown that performance leads by winding wire without increasing cross -section can be a subject of special concern especially when a thick lead insulation is used .One should emphasize that design review is likely the only effective tool to identify the problem. Considering a limited amount of overheated insulation DGA and Furans analysis show clear symptoms of fault only on the stage when short-circuit between strands and insulating burning occur.

Mechanical –mode failures

About 10% of transformers failed due to movement of winding under effect of short-circuit stress. Most of failures (70%) occurred after 28-42 years of service and others in mid-age
(14-16 years).
80% of failures occurred due to radial buckling of the common windings of autotransformers
and LV windings of step-down transformers
One generator transformer failed under effect of short-circuit on LV side

Tilting-mode deformation and significantly loosed winding clamping was revealed on the LV winding of step-down transformer that experienced 3 phases short-circuit with limited current but for long duration (during 1,530 sec).
Tilting of conductors of HV winding was found also in GSU transformer as a results of short-circuit event on HV side. It was revealed that the 300 kV winding performed as helical type and safety margin to axial stresses was only 0.84.

Design review using modern method reveled that in most cases dynamic stability was not sufficient to stand specified stresses. We used the method, which was developed by Dr. Lazarev (Zaporozhye). The method allows pinpointing not only likely damaged winding but also form of loss stability). In most cases when for winding was used wire from annealed copper with yield strength of the conductors around 80 MPA predominantly radial form of loss stability could be anticipated.
For example step-down 80/33 kV transformer failed due to dramatic distortion of LV winding (Fig 11). It was found that transformer, which was manufactured in 1974 has very low radial stability (Tabl. 1). Taking into account a long service life and inevitable loosing the winding claming half-shifted for of deformation was expected

Table 3

Winding, tap position	Safety margin	
	Radial	Axial
RW, max	6.4	6.4
LV, max	0.54	0.94
HV, max	-	3.63

Figure 11
Radial buckling of LV winding after 3 phases short-circuit on LV side
Half-shifted form of of loss stability revealed.

Failures associated with magnetic circuit

There were a few cases of major failures associated with faults in magnetic circuit system however a number of cases occurred, which caused intensive gas generation and scheduled but unwanted outage.

Likely defects can be grouped under two general headings: 1) Defects associated with main magnetic flux, and 2)Those associated with stray flux.

Defects associated with main magnetic flux form loops for circulation current linked with main flux. In fact this group makes up about 20% however it results in dissipation of high energy and intensive gas generation with activation of Buchholz relay. The cases observed were basically attributed to loosening winding press bolts and short-circuit to metallic press rings or to core yoke.
Defects associated with stray magnetic flux present the main cause of localized oil overheating and gas generation. They can be classified into two groups:

1) Overheating under effect of eddy current induced by intensive stray flux;
2) Overheating and (or) sparking in a loop for circulating current, linked with stray flux.

In the first group typical defects are overheating of core frame due to absence or improper disposition of magnetic shields on the frame (Fig.12), overheating of pressing of the pressure bolt that situated just under the core yoke, overheating a part of the tank wall due to improper shielding

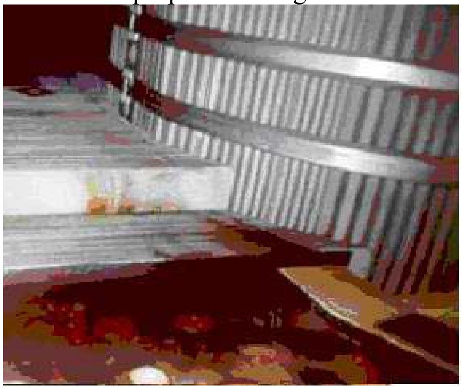

Figure 12
Overheating the bottom frame and adjusted insulation in 730 MVA generator transformer due to improper disposition of magnetic shields

There have been observed two mechanisms of overheating of members that form loop for circulating current:
Loose contact in circulating loop provided with construction (Fig. 13)
Shorting between core members forming the loop:

- Shorting magnetic shunts to core and the tank
- Shorting bottom frame to tank
- Shorting top frame to tank

The latter forms loop of large dimensions, allowing induced voltage up to 10 V resulting in heating and arcing.

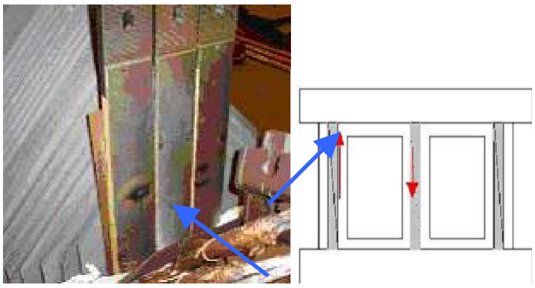

Figure 13
Overheating in the loosed place between members forming loop for circulating current in 700 MVA transformer

Bushings failure

HV bushing remains one of the weakest transformer components responsible sometimes for more than 30% of transformer failures..
Recently it was reported[6] 63 failures of bushings on large power transformer since 1995 only from one manufacturer. It is remarkable that age of failed bushings was between 2 and 15 years only. 15 failures were accompanied with explosion and likely destroying the transformers. 49 bushings were removed from service due to exhibiting PD- mode gases. 12 failures were associated with overheating paper of the core however only after 6-8 years of service.

Failure –modes. Experience revealed the following failure-modes:
Internal discharges leading to internal gas and pressure build up and ultimately an electrical breakdown between the central conducting tube and the bushing flange, which could be caused by the paper not being properly impregnated with oil.
Design review of some core construction revealed overstressing of condenser layers and possible mechanical sliding (displacement) across the central tube
Mechanical failure of the central support tube allowing loss of oil within the bushing.
High temperature of central tube and adjusted paper, during overloading.
Deterioration of copper grounding layer in contact with aluminum foil.
Vacuum formation in oil-gas separation system due to underestimation of volume of nitrogen cushion, followed with water enter
Effect of conductive residue on porcelain. A special attention deserves failure-mode associated with degradation of the dielectric withstands strength of oil and across the core or porcelain surface that progresses in flashover along the surface and practically inevitable explosion. These phenomena are typically originated from critical aging the oil, formation of semi-conductive residue on the lower porcelain;
Discharges across the inner part of the transformer end porcelain are outcome of a typical aging-mode phenomena in the bushing. The failure process is initiated and developing within the oil channel between the core and lower porcelain.
Another option is formation conductive residue on the external porcelain surface by means of attracting conductive by-products from transformer oil.

Figure 14
Internal staining with aged oil by-products containing metal colloids

Impact of transformer on bushing state The transformer in many of instances specifies the oil temperature within the bushing**.**
Hot transformer oil is one of the main sources of the bushing heating. Another two sources are dielectric losses in the core and resistance losses in the central conductor. Heat radiated from the tank top cover is a source of elevating temperature of cooling medium (air around the bushing).
Current density through the central conductor and actual transformer /bushing current ratio including permissible transformer overloading determine hot spot temperature within the bushing, which affects paper temperature.
The transformer affects on distortion of electrical field within and around the bushing.
Strengthening electrical field within the bushing, specifically, in the oil between the core and lower porcelain due to approach of conductive layers to the grounded components and transformer winding should be considered.
Accordingly contamination of transformer oil with conductive particles may results in attracting them by bushing electrical field and depositing on the surface (porcelain) dramatically deteriorated dielectric strength.

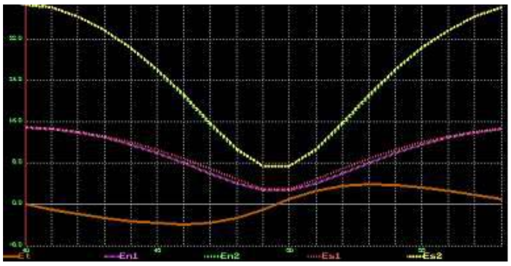

Figure 12
Electrical field of the bushing porcelain surface
The electrical field intensity across the porcelain surface facing the tank wall may be as much as 6 times greater than that on the opposite side

Failure of OLTC

Failure analysis incorporating design review both OLTC and transformer itself allows to highlight some factors that impact on reliability issues:
Specifying the large generator transformer with LTC or DETC predetermines
a long term contacts operation in one or two tap positions and complicates significantly transformer design. In many instances mechanical and dielectric performance of the transformer is determined by state of tap winding and leads.
Choice type of OLTC with a low ratio of the maximum rated through fault current of LTC
and the maximum current of transformer. According to IEC 60542 this ratio shall be at least 120%, and temperature rise of LTC contacts above the oil shall be not more than 20C. Experience has shown that for rarely moved contacts temperature rise shall be less that 15C
Underestimation of impulse transfer function allowing in some cases voltage value between steps or with respect to ground above the test voltage of OLTC.
Many failures initiated with short-circuit between steps in diverter or selector switches were accompanied with distortion of Tap winding. In fact rare transformer is designed to stand short-circuit between LTC taps. Accordingly a comparatively minor failure in OLTC (e.g. burning out resistance) has been resulted in major transformer failure and long-term unit non-availability.
Experience highlights necessity to pay more attention to diverter switch reliability.
Particularly the following factors should be considered:
Aging deterioration of oil due to effect of a high resistors temperature. By-products sediment on insulating surfaces affect on degradation of dielectric strength.Mixture of carbon, water and polymerized by-products hardly can be filtered out properly.
Temperature rise of shunt contacts can sometimes exceed temperature rise of selector and reverser contacts making a week spot that requires special attention.Contact overheating can result if flashover between the phases followed with explosion and fire.

Figure 13
Insulation contamination and PD activity in diverter switch

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