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STATISTICAL BASED AN INVESTIGATION OF FAILURE OF POWER TRANSFORMERS AND REACTORS

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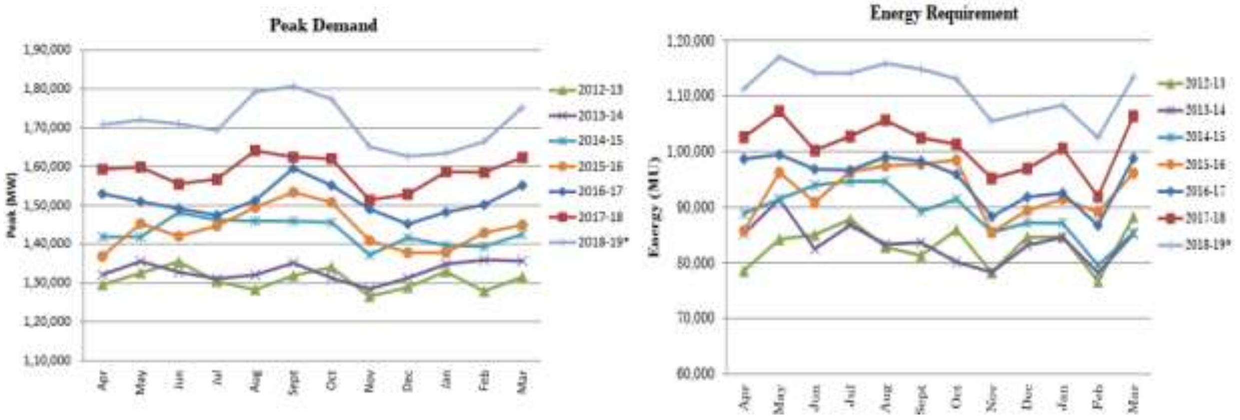
SUMMARY

Electricity is the backbone of any economy. Electrical energy is the indispensable force that drives all economic activity the greater the energy consumption, the more the economic activity, resulting in the emergence of growth. A steady growth in the economy is a prerequisite for any nation desirous of becoming a developed country. Demand of electricity in India is very high, to meet the growing demand, transformers are playing major role. As the demand of electricity increases, rate of failure of transformers & reactors is also increasing, below referred graph 1a & 1b & table 1 showing energy demand & requirement in India, (source: LGRB 2018-19 report of CEA).

This paper based on statistical analysis of catastrophic failures of transformer & reactors. They are designed & constructed in such a way to serve at least 35 years, but they failed very earlier. For the study we have collected data from different utilities across India i.e 21 transformer & 4 reactors of different voltage class. All they are failed between 1st sept. 2015 to 31st Dec 2016. Transformer and reactors are one of the most expensive equipment's of sub-station. Failure of these equipment's is just like an ice burg and its impact is unbelievable such as unbalancing of transmission system grid, reliability of network and as well as huge revenue loss and take hundreds of man hour to restore the service and restoring cost i.e lum-sum 50-60K USD which includes cost of arrangement of new part or complete tank, T&P, filter machine, oil storage tank, dry air generator, dismantling of bushing, turrets, cooler units ,Vehicle & Crane for lifting & shifting of materials , dragging, shifting of new transformer, re-erection of bushing, turrets, cooler units, testing & also arranging a team of experts for identifying the root cause of failure.

Around the world, utilities apply different approaches to estimate the actual stage of life of their assets. Two main methodologies can be distinguished here; bottom-up and top-down analysis. The bottom-up analysis focuses on the degradation and condition assessment of individual assets. The base for such an analysis is maintenance and diagnostics reports (e.g. DGA, PD-measurement, FRA, dielectric response), loading history and aging characteristics obtained through investigations performed on service-aged materials. The top-down analysis investigates the condition of the whole population by means of analytical tools (e.g. statistical distributions). In such approach, the information about number and ages of both failed and installed units are essential. Emphasis is put in this case on economic and strategic life-time assessment. Results of a top-down analysis are e.g. failure frequency, age of assets which are most likely to fail. However, both approaches have certain limitations, imposed by the differences in design and operating regimes.

The main aim of this paper is to discuss modes of failure, causes of failures, service life, failure trend based on statistical analysis. Study of every failure is important, they provide a key information to design more reliable and efficient product.



Graph- (1a) Peak demand V/s time & (1b) Energy required V/s time. source: LGRB 2018/19 report of CEA

	2016-17	2017-18	Actual growth (%)
Energy required	1,142,929	164,066	6.20
Peak demand (MU)	1,59,542	164,066	3.00
Energy supplied (MU)	11,35,334	12,04,697	6.00
Peak met (MW)	156,934	160,752	2.00

Table 1- Energy required V/s Supplied. source: LGRB 2018/19 report of CEA

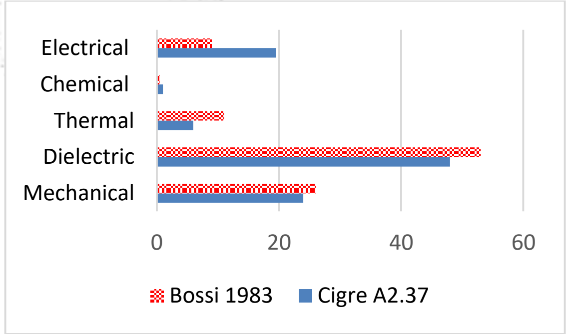
Key words – Transformer & Reactors, Failure, Faults, Overloading

A) Introduction

– Power transformers is playing an important role in the efficiency and reliability of power transmission networks and it is one of the most expensive equipment of transmission network. According to IEEE transformer failure can be defined as “The termination of the ability of a transformer to perform its specific function” [1]. Transformer manufacturers were increasing the capacity of their products & the same time their size was reduced, which increases the percentage of failure of transformer and reactor? Every failure of product gives an aid to improving design, to reduce engineering complexities, more stable network, assessing risk, optimizing maintenance, estimating life and manufacturing better equipment. Very broadly any failure can be caused due to combination of any electrical, mechanical and thermal events. To understand the cause of failure all factors such as design, erection methodology, test records, operating conditions and post energizing maintenance was studied.

In this paper we will study failure of 21 transformer which includes generating transformer, inter connecting transformer & 4 reactors from different utilities of different manufacturer of India. All these transformer & reactor are failed during the period of 1st September 2015 to 31st December 2016. Details of transformer & reactor [2].

Experts believe that failure increase with time span which is expressed by “Bathtub curve.” But available statistics have not yet revealed a correlation between the number of failures and proceeding years of service. In fact, the statistics show peak failures occurring around first 10 years after the transformer has been in commissioned, i.e 56% of the total data, Ref graph 1. From the records it is very clear that there is a big gap between dates of manufacturing and the date of commissioning of transformers & reactors. i.e 36% was commissioned after 1 year of reached at site. During our investigation some catastrophic damages was observed at site, such as burst & fire of bushing and main tank. As per CIGRE [3] report which indicates that the most frequent source of transformer failure can be attributed due to tap changer, bushing, paper oil insulation and the other mounted accessories of transformer. Based on earlier studies, faults can be classified in five categories or modes & their percentage of faults are described in Graph 2 and Table 2.



Graph 2– Comparison of failure mode in all transformer.

TANK

During the experiments by Electricity de lab in France in the year 2002 and the second by Brazilian high voltage laboratory CEPEL, in 2004 on large transformers, the Buchholz always failed to detect any gas and oil movement in respective time. During a transformer short-circuit, the electrical arc vaporizes oil and creates a dynamic pressure which travels at the speed of 1,200 meters per second (4,000 feet per second). Pressure build-up inside the tank which eventually leads to rupture is caused by the high amount of energy released by the arc. Were,

$$E_{arc} = 0.9VIt$$

E arc is arc energy, V is arc voltage, I is arc current & t is fault clearing time.

This phenomenon or energy occurs within a few milliseconds. Because of reflections in the tank the pressure peak will generate pressure waves. The integration of all the waves pressure peaks creates static pressure, i.e. arc energy with respect to pressure.

$$V = 55L\sqrt{P}$$

Were, L is arc length, P is absolute pressure

Then, the pressure becomes equal throughout the entire transformer tank within 50 to 100 milliseconds after the electrical arc and causes the transformer tank to rupture [4].

Fig 1- Catastrophic view of transformer after burst and fire.

TAP CHANGER

The On-load tap changer (OLTC) is the most complex component of the transformer and it is having moveable contacts too. At each switching cycle (“making contacts” and “breaking contacts”) it generates acoustic signals. Even low intensity sparking generates hundreds of temperatures, which reacts with the insulation & oil and produce fault gases. From the various studies it is found that OLTC is one of the major causes of failure of transformer. The acoustic signal generated during the OLTC switching cycle contains information about two diagnostic areas of the power switch. The first area is related to the assessment of the mechanical conditions of contacts and the transmission system. The second area is related to the switch diagnostics to identify the electrical nature of the defects, commonly known as detection of electric dis-charges with increased intensity.

WINDING

The function of the windings is to carry current. Faults that occur in the winding are due to these stresses [5]. These windings withstand dielectric, thermal and mechanical stress during this process, which caused deformation of windings. Fig 2 explains the deformation. Dielectric faults occur in the winding due to inter turn insulation breakdown. Insulation breakdown generally occur due over loading w.r.t rated design. The breakdown of the insulation results flashover between winding turns and cause short circuit.

Hotspot in winding is also one of the causes of failure, the main reasons of hot spot formations are- improper repair, bad maintenance, corrosion, manufacturing deficiencies, vibration and mechanical movement within the transformer & reactor.

BUSHING

Earlier study resulting around 17% of transformer failure are attributing due to failure of bushings. In our study we found that all the transformer & reactors are using condenser type OIP bushings. Major causes of failure of such bushing are –

a. High dielectric stress due to switching surge & lightning surge.

b. Ingress of moisture from cracks in percaline or gasket joints (oil level indicators).

c. Oil Leakage

d. Inadequate methodology of oil filling in bushing’s conservator.

e. Failure of improper earthing connection of the test cap.

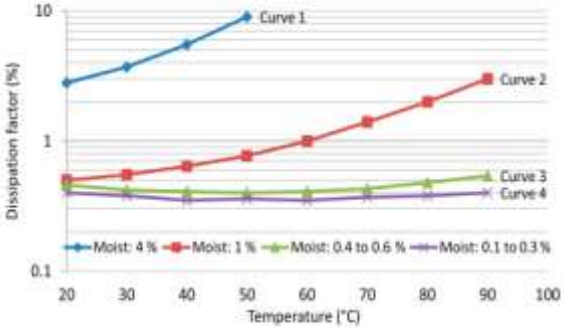
f. Improper fixing of test cap after tan delta & capacitance measurement.

g. Lead touching in corona or fire boll shield.

h. Hot spot development due to improper fixing of thimble or Loose connection between winding & bushing leads.

Bushings tan δ & Capacitance methodologies are

1. Conversional offline methodology.
2. Sum of currents method.
3. Absolute measurement voltage transformer reference method.
4. Dual transformer comparison method.



Graph 3- tan δ *as a function of temperature and moisture for OIP bushings.*

Curve 1 for the moisture content of 4%
Curve 2 for the moisture content of 1%
Curve 3 for the moisture content of .4% to .6%
Curve 4 for the moisture content of .1% to .3%

It can be observed from Curves 3 and 4 that the tan δ remains almost constant at temperatures from 20 °C to 90 °C. For Curve 2, the tan δ is 0.7 % at 50 °C and with a further rise in temperature the tan δ shows a rising trend from 0.7 % to 3 % at 90 °C. Curve 1 shows that the tan δ at 20 °C is as high as 2.8 %, but then abruptly rises to 9 % at 50 °C [6].

INSULATION

The insulation system of a power transformer and reactors mainly consists of two types. First are cellulose based different materials such as paper, board, woods which has very good mechanical strength, oil absorption and electrical resistance and another is mineral, synthetic or ester-based oils. The main aim of insulation is to increase breakdown voltage between the live conductors.

Insulations are hygroscopic in nature. Based on the physical and chemical properties of both cellulose materials and oil they react with increase of temperature, Hot spot, chattering, loose connection is the major source of degradation. Below referred fig showing damage of insulation & winding deformation.

Disruptive discharge can be defined as failure of insulation under electrical stress, which includes decreases of breakdown voltage & passage of current

Fig 2 & 3 – Winding deformation & insulation failure.

B) CONCEPT OF OVER LOADING

There is no such concreate evidence was found based on over loading, but it is important to discuss, Overloading is one of the major causes of insulation failure, arcing, high vibration, thermal heating, aging, stress building etc. There are three types of over loading.

SHORT TERM OVERLOADING

Short-time overloading is heavy loading of a transformer during a short time that causes the temperature to increase rapidly and exceed the limits defined by the name-plate ratings. In this type of loading, the hot-spot temperature may rise to 180°C for a short time period [7] with severe loss of insulation life.

PLLANED OVERLOADING

Planned loading occurs when the utility operator plans to overload the transformer during specific time that is more typical in utility operation. The hot-spot temperature may rise to 120-130°C during this type of loading. No-system outage planned repetitive loads and shorter life expectancy are the characteristics of this type of loading [7]. For this loading type, calculations can be made to define the time in which the acceptable loss of life can be achieved.

LONG-TIME OVERLOADING

Overloading, the transformer is operated beyond its name plate rating for a long time, from several hours to several months, carrying emergency loads. It might occur one or two times during the normal life of the transformer. Long-time overloading occurs because of an outage in a power system or contingencies on the transmission system. However, the risk of failure is greater than the planned overloading and the hot spot temperature can rise to 120°C -140°C under operation [7]. For this loading type calculations can be made, to evaluate the acceptable loss of insulation life during a specific load cycle.

C) RISK ASSOCIATED WITH OVER LOADING

There are risks associated with overloading transformers especially for short-time overloading. For undesirable events, the magnitude of the risks depends on the quantity of free gas, moisture content of oil and insulation, and voltage. Some of these undesirable events [7][8] are –

1) Gas bubbling from the insulated conductors and insulation adjacent to the metallic structural parts may reduce and the dielectric strength. Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.

2) Mechanical or dielectric failures due to thermal expansion of conductors, insulation materials and structural parts.

3) Increasing pressure in the bushings could result in leaking gaskets, loss of oil and extreme dielectric failure.

4) Increased resistance in the contacts of the tap-changer that may result from an increasing of oil-decomposition products.

5)Breaking of very high current in the tap-changer could be risky.

D) PRE-COMMISSIONING TESTING

We have analyzed and compared complete low voltage test results of magnetizing current, voltage ratio, winding resistance, magnetic balance, CT test reports, tan delta & capacitance of both bushing & winding, insulation resistance (IR), polarizing index (PI), insulation between core channel & earth, SFRA, these tests are conducted during pre-erection & pre-commissioning of the job. Oil test parameters (PPM, BDV & DGA) was also tested as per IEEE standards C57.104 threshold level for key dissolved gases in insulating oil [10].

After tripping the jobs, enough energy released to generate hydrocarbons from insulating oil, to analyze the impact DGA test was carried out. In most test results H2, C2H2, CO & CO2 was found. Disturbance recorder (DR) pattern was also examined to know level of high currents & the phase through which it passed.

During the periodic maintenance of the transformer, some transformers are showing high winding resistance, low insulation between core & channel or channel & tank body or core and tank body, High tan delta values (bushing was also replaced many times).

Some common but important observations they are –

1) In some sub stations, there is No preventive maintenance program was scheduled since commissioning.

2) No periodic dissolved gas analysis DGA, moisture content & BDV was tested for record.

3) If fault gases were detected, does degassing was done?

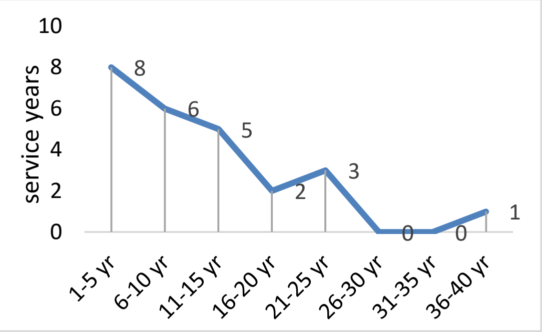
4) Does transformer was heavily loaded in past?

5) All the transformers which are having tertiary
voltage source they are unloaded or open ended.

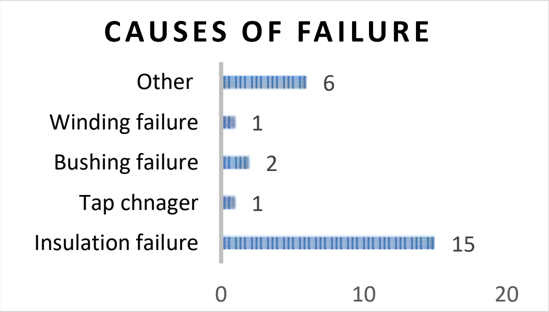
6) Time was not synchronizing with GPS to know actual event w.r.t nearby sub-station, power plant, lab, utilities.

E) STATISTICAL DATA

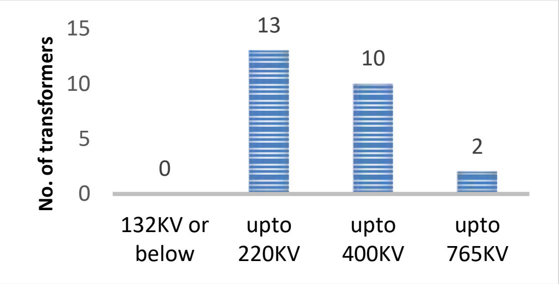
Failure data are further classified regarding to primary location of major failures i.e. failure of insulation, followed by other regions as ageing, long storage are the major contributors, refer graph 4. Mostly 220KV jobs was failed at site i.e. 52 %, refer graph 5. Avg life of 220kv, 400kv & 765kv is must lesser then its standard life, they are 13.1yr, 9Yr & 2yr respectively, refer graph 5. Specifically, Avg life of ICT is 10.8yr, GSU 15.3yr and reactor 5.7yr, refer graph 6.



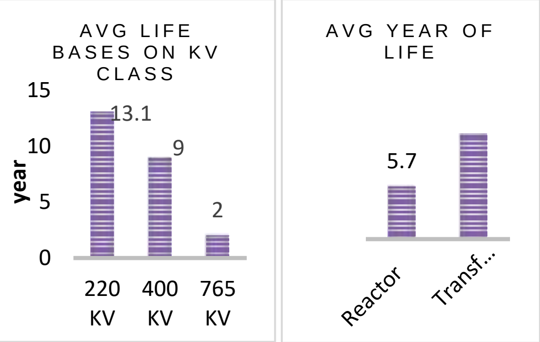
Graph 1- Transformers & reactor service life



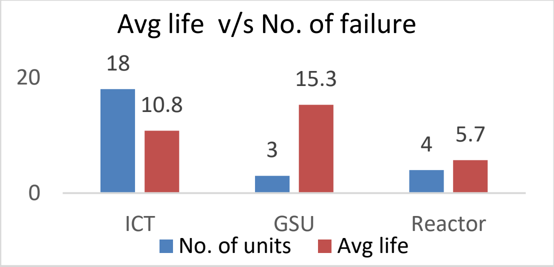
Graph 4 – Area causing failures



Graph 5 - Classification of failure based on voltage class



Graph 6 (a)- Average life based on voltage class (b) based on type of equipment.



Graph 7 - Average life w.r.t equipment type

F) CONCLUSION & RECOMMENDATION

1)During engineering following points must be considered as Minimal joints in windings, minimal nut-bolts fixing arrangements.

2)We recommend using at least 3 PRD, 1 in each phase of 5 limbed 3 phase transforms. To reduce main tank rapture.

3) Time based maintenance is not enough to monitor the health of equipment. Condition based maintenance practice should be followed.

4) OLTC is one of the contributors to the failure of transformer. Possibility of eliminating OLTC from 400kV & 765kV class transformers should be considered in consultation with central authorities. utilities like NHPC & NTPC have taken proactive step by eliminating tap changer from GT's.

5) Fiber Optic Sensors for hot spot monitoring of winding can be considered for all sub-station's transformers & reactors.

6) For long time storage of power transformer & reactors, customer must follow OEM guidelines.

7) Based on the data, average life of transformer & reactor is much lesser than recommended years. It is recommended to maintain a schedule for precautionary maintenance as per standards or OEM guidelines.

8)We recommend using at least 3 PRD, 1 in each phase of 5 limbed 3 phase transforms. To reduce main tank rapture.

9) Time based maintenance is not enough to monitor the health of equipment. Condition based maintenance practice should be followed.

G) BIBLIOGRAPHY

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Failure location	**Description**	**Failure cause**	**Description**	**Failure cause**	**Description**	
Winding		Inherent Deficiency	Inadequate Specification	Dielectric	Partial discharge	
			Inadequate design		Tracking	
Winding	Between Windings	Inherent Deficiency	Inherent material defect		Flashover	
connections	Tap leads		Improper factory assembly	Electrical	Over circuit	
	To Bushings		Improper site assembly		Short circuit	
Mechanical	Clamping's		Improper Maintenance		Poor joints	
Structure	Coil blocking		Improper repair		Poor contacts	
	Lead support		Improper adjustments	Thermal	General	
Insulation	Major	System events	Overload		overheating	
	Minor		Load removal		Localized hotspot	
	Material - liquid, gas		Over -Voltage	Physical chemistry	Contamination	Moisture
Tank			Resonance			Partials
Tap changer	Selector		Short circuit			Gas
	Divertor	External events	Vandalism	Mechanical	Bending	
	Drive Motor &		Impact of external objects		Breaking	
	Couplings				Displacement	
	Control system	environmental	Lightning		Loosening	
Magnetic circuit			High ambient		Vibration	
			Low ambient			
			Rain			
			Water ingress			
			Wind			
			Seismic			
		Improper application				
		Abnormal deterioration				

Table 2 classification into failure location, failure causes and failure mode.