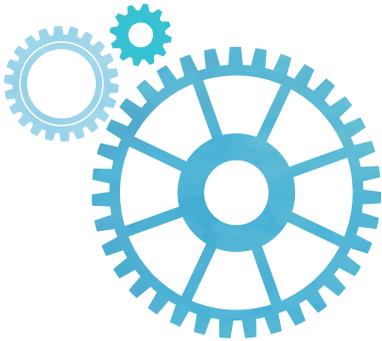


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FMECA Analysis for the Assessing of Maintenance Activity for Power Transformers

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Abstract—A serious failure of a large power transformer can generate substantial costs for the transport to factory, repair and financial losses resulting from power interruption. Therefore, utilities have a clear incentive to assess the actual condition of high voltage transformers, with the aim to minimize the risk of failures and avoid forced unexpected outages. Special attention in this respect is given to large transformers. In this paper, a general FMECA for outage causes of 220 kV power transformers is presented, including the local and final effects, and recommended actions to avoid these outages. Assignment of risk priority numbers to the various outage causes, which might occur at this voltage level, are carefully considered.

Keywords—Transformer Failures, FMECA.

I. INTRODUCTION

According to ANSI/IEEE C57.117-1986 [1], a transformer is a static electric device consisting of a winding or two, or more coupled windings, with a magnetic core for introducing mutual coupling between electric circuits through electromagnetic induction.

The transformer includes all transformer-related components, such as bushings, load tap changers, fans, temperature gauges, etc., and excludes all system-related components (e.g. surge arresters, grounding resistors, high-voltage switches, low-voltage switches and house service equipment).

Transformers can be classified into many types such as power transformers, autotransformers, regulating transformers, etc. Based on their application, transformers are classified into substation transformers, transmission tie transformers, unit transformers, etc. The study reported in this paper considers 220 kV power transformers for utility applications.

Transformers have a key role in power systems and their reliability directly affects the reliability of the whole network. Outage of transformers is considered a failure, since it is an event that determines a fault state (the transformer cannot perform its specified function) [1].

Generally, transformer outages are either forced or scheduled, and both are done by means of switching operations. Forced outages of transformers are mainly due to automatic switching operations performed by protection systems [2], [3], [4]. They are caused by either external (such as transmission line faults) or internal causes (such as core failure and winding failure). In [3] and [4] more details about failure statistics of transformer subassemblies are given. For the

purpose of abbreviation in this paper, the term ‘outage’ will refer to ‘forced outage’.

Transformers outages are classified according to their operating voltage level in the network. In this paper the 220 kV voltage level was selected, because it is considered one of the oldest transmission networks in many European countries[5], [6]. For instance, the generation plants in Germany are linked to the unified Grid through 220 kV level [7]. In both Romania and Switzerland, the 220 kV system is considered the backbone of transmission network [8],[9].

Since large groups of transformers operating in the world have already exceeded 30-year exploitation period [25], in the literature several surveys highlighting the outage causes of transformers can be found. A ten years survey by a CIGRÉ working group, on internal failures in large substation utility transformers [2] pointed out that about 41 % of failures were due to on-load tap changers (OLTC) and about 19 % were due to the windings. The number of transformers, under investigation, with on load tap changer was 15786 unit-years and voltage level ranges from 100 kV to 300 kV. The total numbers of failures were 370 during the study period 1968-1978. Fig. 1 shows the percentage failure distribution for power transformers with on-load tap changers [2].

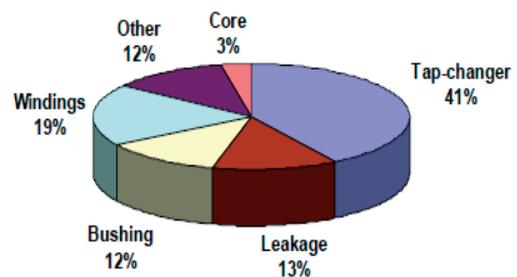


Fig. 1. Percentage failure of power transformers (CIGRE survey).

Transformer internal failure data analysis in South Africa in the period 1985-1995 is presented in [3]. The failure analysis was based on 188 outages of transformers with a rated voltage ranging from 88 kV to 765 kV and rated power from 20 to 800 MVA. Considering 100-400MVA transformers, the total number of failures for general ageing, core problems, lighting/switching, others, short circuit, and tap changers were 15, 8, 2, 15, 1, and 5 respectively. In 2006 this investigation was extended for units failing in the period 1996 to 2006, and was based on failure study of step-up generator, transmission and

distribution transformer failures. Bushings, tap changers and windings represent about 79% of outage causes during this study period. The contribution of core related failures was 2% only [4].

Another study was done on 50 outages of 500 transformers with rated power ranging from 14MVA to 175 MVA [19]. Tap changer and bushing failure were the dominant causes of outage for transformers having a rated voltage ranging from 110 to 150 kV. In [20] the failure statistics of transformers in Thailand was studied by considering the scattering of history data. The data were collected from 44 transformers with rated voltage of 230/115/22 kV with total 68 minor failures. The failure statistical analysis shows that other failure was the highest, 41.3%, followed by bushing, 31.7%, tap changer, 17.5%, leakage 7.9 % and winding 1.6%. Outage data analysis for power transformers in Egypt over the period 2002-2009 is presented in [21], [22], [23], [9].

TABLE I. TRANSFORMERS OUTAGE CAUSES

Failure	Outage Cause	
	Outage category	
Minor	Electrical outage	<ul style="list-style-type: none"> • Buchholz & Pressure relief (B&P) • Over current (OC) • Earth fault protection (EFP) • Differential protection (DP) • Outage of incomers (OI) • Bus bar protection (BBP)
	Mechanical outage	<ul style="list-style-type: none"> • Breakdown & Damage (B&D)* • Fire Fighting System (FFS) • Hot spots (HS) • Oil, Air or SF6 leakage • Flash over (FO)
	Environmental outage	<ul style="list-style-type: none"> • Bad weather (BW) • Animal & birds (A&B) • Human mistakes (HM)
	Others outage	<ul style="list-style-type: none"> • No Flags (NF) • Others
Major	<ul style="list-style-type: none"> • Tap changer • Winding • Core • Bushing • Tank and Conservator • Insulation deterioration 	

* B&D include external equipment failures in transformer circuit (current & potential transformer, surge arrestor, etc.)

Surveys and reports put in evidence two main kinds of failure sources of transformer outages. Major failures, those that are severe and require the removal of transformer to be reprocessed under factory conditions or its replacement. Minor failures can be repair on site. An overall view on general outage causes of transformers, according to previous surveys, is shown in Table 1. The others outage causes are related to over flux tripping, circuit breaker failure, low oil level, etc.

This paper is organized as follows, in section II the qualitative and quantitative failure modes and effect analysis (FMEA and FMECA) is discussed, while in section III FMEA on power transformers is reported.

II. FMECA

IEC-60182 [10] defines FMEA as a systematic procedure for the analysis of a system which target is the identification of the potential failure modes, their causes and effects on system performance. It is a bottom up failure analysis method that highlights common failure causes of the system and provide a rank for each failure mode related to element importance. Additionally, it focuses on system parts and/or functions that are most likely to fail. MIL-Std-1629A [11] considers the usefulness of the FMEA as a reliability tool during design phase for decision making process upon the effectiveness of system functional failures and problems information. On other hand, TM 5-698-4 standard [12] and ANSI/IEEE std. 352 [13] depict the importance of FMEA for safety analysis, maintainability plan analysis and failure detection.

FMEA should include a list of equipment failure modes, like that shown in table 1, reasons of these failures, local effects that refer to the consequences of each possible failure on the system element, final effects that describe the impact of that possible failures on the whole system, an alternative provision or recommended corrective actions to avoid these failures [10], [11], [12], [13]. Finally, a critically analysis (CA) allowing to assign a Risk Priority Number (RPN) to each failure mode must be done:

$$RPN=S \times O \times D \tag{1}$$

where *S* (Severity) represents the severity on the base of the assessment of the worst potential consequences resulting from an item failure, *O* (Occurrence) denotes the probability of failure mode occurrence and *D* (Detection) represents the chance to identify and eliminate the failure before the system or customer is affected. Fig. 2 shows a schematic diagram of the necessary steps to carry out both FMEA and CA.

In this way the definition of RPN allows to introduce the criticality of outages (FMECA). The criteria for selecting severity, occurrence, and detection values depends on standards [10], [11], [12]. In this paper, an analysis based on IEC-60182 evaluation criteria, as shown in TABLE II. is applied to power transformers.

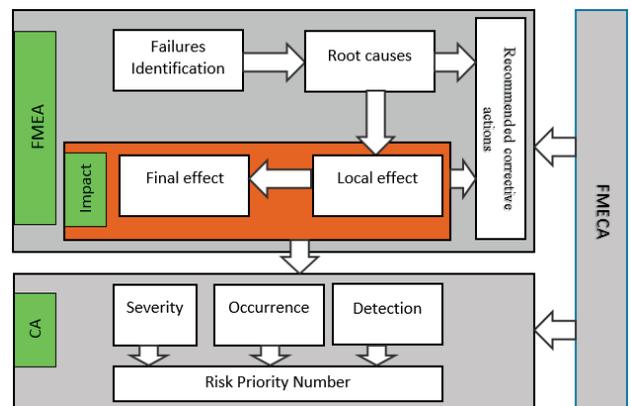


Fig. 2 Schematic Diagram of FMECA

TABLE II. IEC-60182 EVALUATION CRITERIA FOR OCCURRENCE, SEVERITY AND DETECTION

Occurrence (<i>O</i>)	Severity (<i>S</i>)	Detection (<i>D</i>)	Ranking
Failure is unlikely	No discernible effect	Almost certain	1
Low: Relatively few failures	Very minor	Very high	2
	Minor	High	3
Moderate: Occasional failures	Very low	Moderately high	4
	Low	Moderate	5
	Moderate	Low	6
High: Repeated Failures	High	Very low	7
	Very high	Remote	8
Very high: Failure is almost unavoidable	Hazardous with warning	Very remote	9
	Hazardous without warning	Absolutely uncertain	10

III. FMECA FOR 220 kV TRANSFORMERS

The FMECA of functional/components minor and major failures of in-service transformers are estimated in Table III and Table IV respectively. In these tables attention is given to all possible major and minor failures that might result in interruption of transformer service. The impact of minor failures are not significant on transformer life. Therefore, the final effects of minor failures are interpreted in terms of transformer repair time duration. However, the frequent over current outages in the long run, resulting from overloading, lead to insulation degradation over time [14]. Also operation of Buchholz and pressure relief gives a strong indication to high percentage of combustion gases that are considered the catalyst agent for transformer ageing [15].

As reported in Table III overcurrent outages scores the highest RPN. Nowadays, the goal for the majority of transmission dispatch centers is the operation of transformers within IEC-60354 loading limit [16]. However, their ultimate challenge is the rapid growth of loads. Consequently, transformers are tripped frequently by overcurrent protection.

On other hand, earth fault and differential protection have the same high RPN. Their occurrence represent a hazard for the transformer operation. Generally, the low voltage side of 220 kV transformers feed medium level transformers, 132kV, 66 kV, or 33 kV, and they are quite far from the unbalance in the distribution system. Therefore, the activation of earth fault protection in 220 kV requires more attention and investigation for recognizing the fault nature. The differential protection operates if there is a disturbance in the protection zone, its operation gives a strong indication to utilities for a serious hazard within this zone. This will require site tests for the transformer including gas analysis. Buchholz and pressure relief are utterly similar to differential protection, its protective zone is limited to the transformer body.

Outage of incomers is a source of disturbance for utilities network operation, these outages occur frequently in transmission networks that have limited generation capabilities. It is associated with the disappearance of voltage from the 220 kV busbar. This will force the transmission utility to disconnect the transformer from both sides and reconnect it again.

Table IV assigned the highest RPN in transformer major failures to insulation deterioration and on-load tap changer respectively. Insulation deterioration is an irreversible phenomena associated with transformers in service that results from oxygen, moisture and temperature. Moreover, it is considered the major reason of transformer failures before reaching their designed expected life [17]. Tap changer is the only moveable element in the transformer, and had been prone to a range of failures associated with the switching contacts and drive mechanism. Therefore, the condition of the tap changer oil and its contacts resistance are the most encountered problems to power utilities [18]. Nowadays, large number of utilities mount filter units externally on the tap changer compartment. However, these units reduce the filtration periods of the oil but don't give a clear view on the state of the switching contacts. Thus, the contacts degradation and mechanical defects can remain undetected.

Core and windings failures are the most catastrophic scenarios of transformers outages, they require an immediate replacement of the transformer and, in case a spare transformer is not directly available, additional costs for not delivered power and penalty costs should also be considered. The frequency of their occurrence is very low but their impact on the network operation is extremely high.

TABLE III. MINOR FAILURES FMECA OF TRANSFORMERS

Failure	Outage mode	Possible outage cause	Local effect	Final effect	Compensating provision against failure	S	O	D	RPN
Minor	B & P	Internal arcs	Excessive pressure and combustion gases	Long repair time & long term transformer ageing	Dissolved gas analysis Condition monitoring	5	5	2	50
	OC	Overloading / External faults	Thermal ageing	Intermediate repair time & long term transformer ageing	System monitoring	6	6	2	72
	EFP	Winding inter turn / core/ external faults	Loss of power	Short repair time	System monitoring	5	4	3	60
	DP	Internal fault within the protected region	Loss of power	Intermediate repair time	Preventive maintenance of transformer switchgear/accessories	5	4	3	60
	OI	Voltage of HV bus bar disappeared as a result of power generation outages/ faults at BB incomers	Immediate shutdown of transformer and loss of power	Short repair time	System monitoring	6	4	2	48
	BBP	Internal fault within the protected region	Power interruption	Short repair time	Protection design and proper setting of protection relays	7	3	2	42
	B & D	Breakdown & damage of transformer/main circuit HV equipment	Power Interruption during the replacement of damaged equipment	Long repair time	Preventive maintenance through electrical tests to check up insulation condition	7	3	2	42
	FFS	A real hazard or malfunction in Firefighting sensors/valves	Power interruption for real hazard, immediate shut down of FFS for malfunction	Short repair time (FFS malfunctioning)	Scheduled maintenance program to check the valves and sensor conditions, pressure of air and water of FF system	2	3	3	18
	HS	Loose connections	Overheating and power losses	Short repair time	Thermal Image	2	4	4	32
	Leakage	Leakage of oil from main tank/SF6 gas from GIS compartment/ air from Circuit breaker	Low level of oil operates buchholz relay/ circuit breaker will be in blocked state for SF6 or air leakage	Long repair time	Periodic visual inspection of pressure gauges	2	4	3	24
	FO	Deposit of dirt on bushings	Arcing and tracking Of bushings	Intermediate repair time	Periodic cleaning of transformer tank and bushings	2	4	4	32
	BW	Wind and rains	Slippage of transformer accessories and protection devices	Intermediate repair time	Checking the outdoor protection wires /cables and clearance distances	4	3	2	24
	A&B	Crossing the magnetic field of the transformer	Phase to phase or phase to ground faults	Intermediate repair time	Caging outdoor visible connections	4	3	2	24
	HM	Wrong switching, intervening actions within transformer magnetic field	Human injury risk, loss of power	Short repair time	Following up a firmly safety rules	7	3	2	42
	NF	No alarm or indication to transformer outage	Overloading risk on nearby parallel transformer	Intermediate repair time for investigating the exact outage reason	Considering the design of protection & alarm system	3	3	4	36
Others	Malfunction of circuit breakers, over flux protection , abnormal sounds of operation, tap changer control, etc.	Loss of power	High repair time	Preventive maintenance of transformer switchgear/accessories	3	5	3	45	

TABLE IV. MAJOR FAILURES FMECA OF TRANSFORMERS

Failure	Outage mode	Possible outage cause	Local effect	Final effect	Compensating provision against failure	S	O	D	RPN
Major	On-load tap changer	Wearing out of selector contact, loose base, loose spring, low insulation of oil	Arcs and partial discharges inside tap. Overheating and excessive pressure	Replacement of tap changer and loss of power	Preventive maintenance based on regular periods or number of tap changer operations. Online oil filtration.	7	4	7	196
	Winding	Continuous Overloading, moisture contents, sludge, oxidation	Thermal and mechanical ageing of winding. Incapability to stand future short circuits	Transformer ageing, and replacement of transformer	Mechanical and Electrical condition assessment (SFRA, DC resistance of winding, turns ratio, Meggar)	9	2	9	162
	Core	Rust deposits, excessive heating or burning of the laminations insulation	Hot spot, high losses as a result of eddy current and flux distortion	Transformer ageing. Replacement of transformer	Condition monitoring through Dissolved gas analysis, oil and furan analysis.	9	2	9	162
	Oil-Filled Bushings	Moisture from leaky gaskets. Gas bubbles from prolonged exposure to extreme electrical, mechanical and environmental conditions.	Conducting tracks that can short out one or more layers of the bushing.	Bushing/gasket replacement	Thermal image and bushing tan delta, capacitance monitoring. Periodic inspection of oil level of the busing window	6	2	7	84
	Tank	Tank rupture as a result of severe short circuit and malfunction in protection system	Transformer replacement	Loss of power	Regular testing of protection systems	9	2	3	54
	Insulation deterioration	Oxidation, high acidity, low breakdown of oil, moisture of windings paper	High arcing, corona, and partial discharge	Oil filtration / oil replacement in site, or reprocessing of insulation condition in factory	Dissolved gas analysis monitoring, Furan test, tan delta of oil, and chemical analysis of oil characteristics	8	4	8	256

IV. CONCLUSIONS

The aim of presenting a FMECA on utility transformers is to provide power utilities a guide of feasible hazards that could interrupt transformers operation and result in financial losses. FMECA risk priority number depends on many factors and varies according to the operating and environmental condition of power utilities. We tried to generalize the severity, occurrence and detection of the 220 kV transformer failures for a better performance in the transmission network.

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