

FAILURE MODE EFFECTS ANALYSIS

An Investigative Tool for Electric Utilities

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An Intro to FMEA

Is a systematic process requires thoughtful consideration for all the potential failure mode associated with a new design or process.

- Risk (R)
- Severity (S)
- Occurrence (O)
- Risk Priority Number (RPN)
- FMEA & FMECA
- Confusion between DFMEA and PFMEA !
- Paper include study on 220kV transformers
- Case Study Review of 33kV VT Failure-in-Service

Risk Management and FMEA

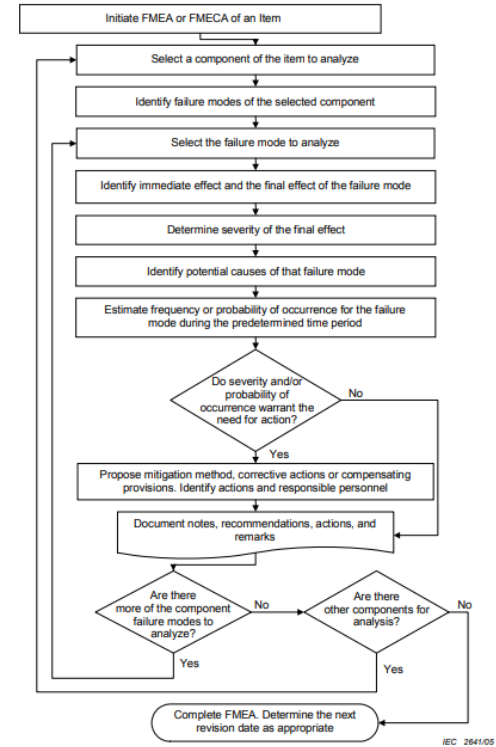
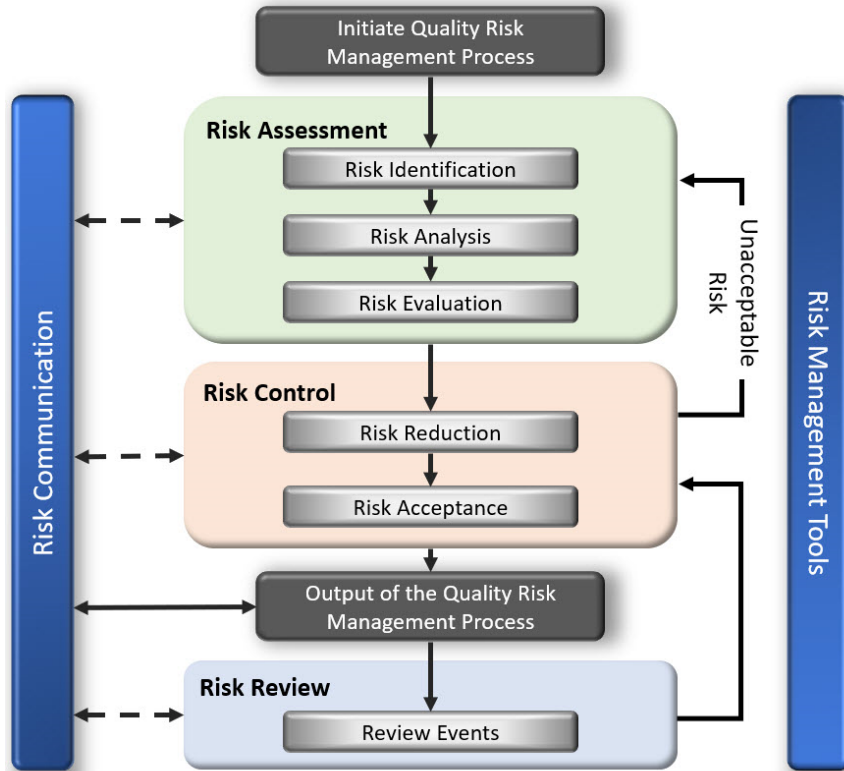


Figure 2 – Analysis flowchart

Our Case Study

Qualitative and Quantitative Failure Mode Effect Criticality Analysis of 220 kV Power Transformers

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Abstract— Power transformers are considered as one of the most significant parts in the electricity network since their replacement and repair process are costly and time consuming. In this respect, a general qualitative FMECA for outage causes of 220 kV power transformers is presented, including the local and final effects, and recommended actions to avoid these outages. Afterwards, quantitative CA is carried out on a case study, using the Egyptian survey of 220 kV power transformers failures during the period 2002-2009 of 252 (average number). The main target of this work is to provide the power utilities a guide, on identifying failure causes of power transformers, through FMECA technique, and the associated risks to achieve better maintenance strategies.

Index Terms—Failure modes; Risk analysis; FMECA; Maintenance activity; Power transformers; Reliability.

I. INTRODUCTION

IEC [1] defines the failure as the termination of the ability of an item to perform a required task. A further definition is introduced by IEEE [2] for power transformers based on the type of outage, whether it is forced or scheduled. The forced outage requires the immediate removal of the transformer from service either automatically or manually as soon as the switching operation can be performed. While scheduled outage is a failure that a transformer is taken out at a selected time based on a planned outage. Decision-makers and utilities managers are giving a lot of attention to forced outages since these outages result in unexpected interruption of power, serious economic and technical consequences [3]. Although the proper protection settings prevent many catastrophic situations, the necessity to understand the root failure causes in the transmission networks remains the ultimate objective for utilities owners.

Transformer failures can be broadly categorized as electrical, mechanical, environmental or thermal. The cause of a failure depends on the outage event, either internal or external [4], [5], [6], and [7]. External factors can be lightning strikes [8], system overload [9], short circuit [10] and internal factors are related to transformer's components such as insulation deterioration [11, 12], winding [13], core [14], and tap changer failures [9]. For an abbreviation in this paper, the term "outage" refers to "forced outage" and the term "transformers" refer to "power transformers".

Transformer failure causes vary according to the voltage level of the electrical network. The selection of 220 kV voltage

level was on purpose, because the 220 kV network is considered one of the oldest transmission networks in many European countries [15-16]. For instance, the generation plants in Germany are linked to the unified Grid through 220 kV level [17]. In Romania and Switzerland, 220 kV system is considered the backbone of transmission network [18-19].

Literature surveys highlighted the outage causes of transformers in numbers of reports and studies in different countries. For instance, CIGRE working group carried out an international survey, aka Bossi survey, on internal failures in large substation utility transformers, the number of transformers, under investigation, with on load tap changer was 15786-unit years and voltage level range 100-300 kV. The total number of failures were 370 during the study period 1968-1978 [20]. Results showed that the on-load tap changers and windings contribute in 41% and 19 % of internal failures respectively. Fig. 1 shows the percentage of the internal failure causes for power transformers with on-load tap changers [20]. Another survey in [21] was done on 50 outages of 500 transformers of power rating 14MVA to 175 MVA. Tap changer, bushing were the dominant over a voltage level range 110 to 150 kV.



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

A more recent CIGRE survey was released in December 2016 [22]. The investigated population of substation transformers was 150075 transformer-years, which was almost four times higher than population in Bossi survey. It shows that the main causes of failures for power transformers were due to winding (40%) and tap changer (27%). While bushings (14%), lead exits (6) and core (4%) were minor contribution. Still, substation transformers had a higher contribution of tap changer related failures than GSU transformers.

In South Africa, a survey is conducted on the failures of utility transformers during the period 1985-1995 in [6], the failure analysis covered 188 outages in the voltage range of 88kV to 765kV and MVA rating from 20 to 800. Considering 100-400MVA transformers, the total number of failures for



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ELECTRICAL TESTS AND FORENSIC EXAMINATION REPORT OF TWO 33KV INDOOR VOLTAGE TRANSFORMERS AT ABC SUBSTATION OF UK

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10 Steps Methodology

1. Define your *System or Process*
 2. Identify Potential *Failure Modes*
 3. Determine Potential *Effects*
 4. Estimate the *Severity*
 5. Determine the potential *Cause*
 6. Estimate the likelihood of *Occurrence*
 7. Determine the *Controls*
 8. Estimate the *Detection Level*
 9. Calculate the *RPN* for each failure mode
 10. Take *Corrective Action*
- } Risk Identification
- } Risk Analysis
- } Risk Evaluation & Control

Set Ground Rules First

- Define the Scales
 - An Acceptable or Unacceptable Risk
- Document the Assumptions
- Communicate

Severity	Occurrence	Detection	Ranking
None	Remote	Almost Certain	1
Very Minor	Low	Very High	2
Minor		High	3
Very Low	Mod.	Mod. High	4
Low		Mod.	5
Mod.		Low	6
High	High	Very Low	7
Very High		Remote	8
Haz with Warning	Very High	Very Remote	9
Haz w/out Warning		Abs. Uncertain	10

TABLE II IEC-60182 CRITERIA FOR OCCURRENCE, SEVERITY, DETECTION

Identify Potential Failure Modes

Failure	Failure Mode	
Minor	Outage category	
	<i>Electrical outage</i>	<ul style="list-style-type: none"> • Buchholz & Pressure relief (B&P) • Over current (OC) • Earth fault (EFP) • Differential (DP) • Outage of incomers (OI) • Bus bar protection (BBP)
	<i>Mechanical outage</i>	<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)
	<i>Environmental outage</i>	<ul style="list-style-type: none"> • Bad weather (BW) • Animal & birds (A&B) • Human mistakes (HM)
	<i>Others outage</i>	<ul style="list-style-type: none"> • No Flags (NF) • Others
Major	<ul style="list-style-type: none"> • <i>Tap changer</i> • <i>Winding</i> • <i>Core</i> • <i>Tank</i> • <i>Bushings</i> • <i>Insulation deterioration</i> 	

Determine the Effects – Qualitative

Failure	Failure mode	Possible outage cause	Local effect	Final effect	Recommendations	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.	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, excitation current, leakage reactance, etc.)	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	Routine tests	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, bushing tan delta, online capacitance and leakage current monitoring. Periodic inspection of oil level of the bushing 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 and transformer removal	Strict routine testing program of protection systems	9	2	3	54
	Insulation deterioration	Oxidation, high acidity, high dissolved gases in oil, low breakdown of oil, moisture of windings paper	High arcing, corona, and partial discharge	Transformer removal	Dissolved gas analysis monitoring, Frequency Domain Spectroscopy, Furan test, and chemical analysis of oil characteristics	8	4	8	256

Determine the Effects - Quantitative

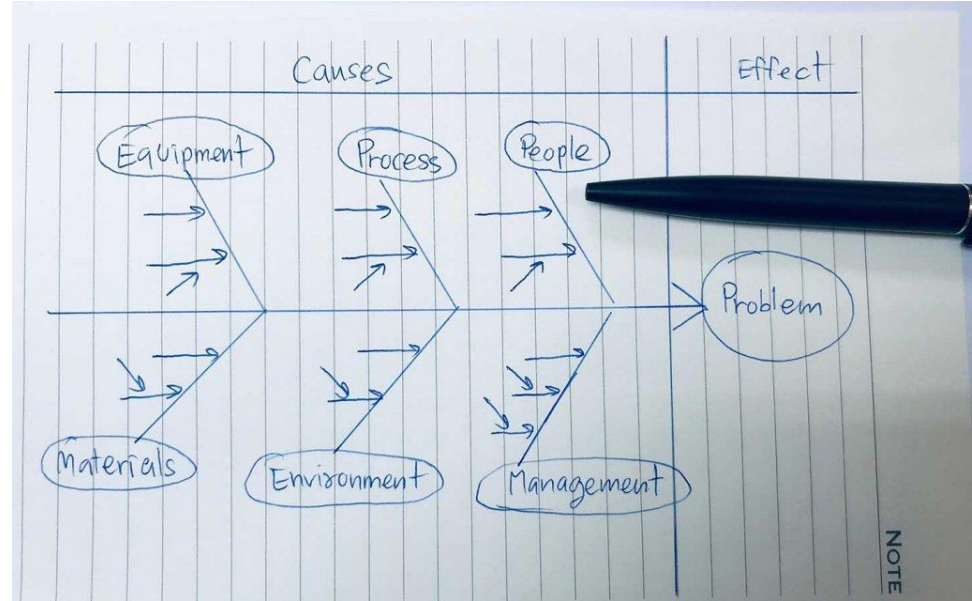
Asset	Related Failure Mode	Outage cause	Failure Effects				S	O	D	RPN
			NF	AIMW	ACID (min)	ART (min)				
220 kV power transformer	Electrical	B & P	52	2.9825	3.49125	950.19	7	5	2	70
		OC	186	21.53	7.48625	133.327875	4	9	2	72
		EFP	78	14.0375	7.56	186.81875	3	5	2	30
		DP	101	15.3945	8.08875	652.06125	5	6	2	60
		OI	39	12.25625	10.6525	846.535	2	3	2	12
		BBP	54	4.495	1.15125	92.055	2	5	2	20
	Mechanical	B & D	76	0	0	74.3225	7	5	2	70
		FFS	30	0.96975	0.73625	496.39	3	3	2	18
		HS	26	0.0675	0.01125	85.605	2	2	3	12
		Leakage	98	17.89375	8.32125	39.74625	4	6	2	48
		FO	20	18.68875	9.19875	136.32125	2	2	3	12
	Environmental	BW	23	2.615	0.48625	110.65	3	2	2	12
		A&B	12	3.4375	1.0625	192.02	4	2	2	16
		HM	50	24.76375	10.6125	46.2425	2	4	3	24
	Others	NF	34	12.24	3.058375	120.3675	3	3	6	54
		Others	136	8.3775	10.06625	418.7425	5	6	2	60

Table V Quantitative CA On Egyptian Transformer Outages (2002-2009)

Determine Potential Causes

8M's of a Failure Mode

- Man
- Machine
- Method
- Materials
- Mother Nature
- Measurement
- Management
- Maintenance



Fishbone (or Ishikawa) Diagram

VTs FMEA – Qualitative Analysis

Possible Causes	Potential Failure Modes	Circulating Currents / localised overheating / Electrical Arcing	Thermal Runaway and Discharge	Follow standard and best practice. Do not use cardboard in core packing material as works mainly during visual inspections (during planned maintenance) for electrical stresses. Do not increase VTs in service.	S	O	D	RPN
Defective insulation material (non-electrical- Best manufacturing process leaving VOIDS in epoxy resin	Thermal / Floating Potential				8	7	8	448
	Dielectric / Mechanical Dielectric				3000	5	2	3000
		IK - 22/0mm HV - O/C						200



Conclusion

- Believe in Reliability Centered Maintenance, use FMEA.
- FMEA gives you a variety and foundation for risk management.
- Thorough understanding of the failure behaviour of a system
- Failure Modes Identification is important.
- Not all FMECAs are done the same way or to the same level of detail.
- The criticality analysis and recommendations shall vary according to operational condition, fleet failure data and implemented maintenance policies

Key Slides / Takeaway



Estimate the Occurrence



- The *Occurrence* ranking is defined as the likelihood or probability that a failure will occur.

Ranking	Qualitative Term	Semi-Quantitative	Quantitative
1	Extremely Unlikely	1	Less than 1 in 1,000,000
2	Remote	2	Between 1 in 1,000,000 & 1 in 100,000
3	Unlikely	3	Between 1 in 100,000 & 1 in 10,000
4	Occasional	4	Between 1 in 10,000 & 1 in 1,000
5	Frequent	5	Between 1 in 1,000 & 1 in 100
6	Often	6	Greater than 1 in 100

Calculate RPN



- RPN is an objective prioritization tool to determine “higher risk” failure modes we should focus on.
- Risk Priority Number (RPN) = $S * O * D$

Failure Mode	Severity	Occurrence	Detection	RPN	Risk
XYZ Happens	8	5	5	200	40

Determine the Controls and Detection



- A *Control* is anything in your process that might prevent or Detect the failure mode being analysed.
- The *Detection* is a reflection of the capability and effectiveness of process control strategy to identify a failure mode, once it has occurred.

Ranking	Qualitative Term	Quantitative
1	Certain	100% Detection
2	Almost Certain	95% Detection
3	High	75% Detection
4	Moderate	50% Detection
5	Low	25% Detection
6	Undetectable	<10% Detection

RPN into Criticality Matrix

Overall Risk Rating Matrix
Likelihood

Almost Certain (5)	Moderate (5)	Significant (10)	Major (15)	Catastrophic (20)	Catastrophic (25)
Likely (4)	Moderate (4)	Significant (8)	Significant (12)	Major (16)	Catastrophic (20)
Good Possibility (3)	Minor (3)	Moderate (6)	Significant (9)	Significant (12)	Major (15)
Possible (2)	Minor (2)	Moderate (4)	Moderate (6)	Significant (8)	Significant (10)
Highly Unlikely (1)	Minor (1)	Minor (2)	Minor (3)	Moderate (4)	Moderate (5)
	Minor (1)	Moderate (2)	Significant (3)	Major (4)	Catastrophic (5)

Impact

■ (20-25) ■ (15-16)	Catastrophic and Major	Risk Treatment Strategies to be implemented by Directors/Executives and, where relevant, action taken to be reported, either directly or via Senior Leadership Team Members, to the Risk and Insurance Manager for inclusion for discussion by the Risk Advisory Committee (RAC) and likely inclusion in the UC Strategic Risk Registrar.
■ (8-12)	Significant	Risk Treatment Strategies to be implemented by Directors/Executives.
■ (4-6) ■ (1-3)	Moderate and Minor	Acceptable – to be managed under normal control procedures.

VTs Failure in Service



VTs FMEA – Qualitative Analysis

Possible Causes	Potential Failure modes	Local effect	Final effect	Recommendations	S	O	D	RPN
Poor manufacturing process leaving VOIDS in epoxy resin	Dielectric	Overheating / Partial discharge, if exposed to low ambient temps and moisture ingress.	Failure in service if fault persisted.	Inspect and test the remaining 100+ VTs in service.	8	5	7	280
Open Circuit	Dielectric	WR – O/C HV Ratio – O/C IR – 229Gohm HV – O/C	Out of Service	Perform offline electrical condition assessment on remaining VTs in service.	8	5	5	200
Moisture Ingress	Dielectric / Mechanical	Corrosion	Accelerated Ageing / Insulation deterioration causing failure	Visual Inspections (during planned outages), check for water traps and dysfunctional heaters.	8	5	9	360
Defective insulation material (non-electrical-grade)	Thermal	Localised overheating / circulating currents	Potential of Fire / Insulation Deterioration	To OEM: do not use toilet paper in core packing material as insulation medium, its hygroscopic and cannot tolerate electrical stresses.	8	7	8	448
Missing Earth Strips	Thermal / Floating Potential	Circulating Currents / localised overheating / Electrical Arcing	Thermal Runaway and Discharge	Follow standard and best practices. Check the installation works quality during commissioning phase.	6	5	5	150

Standards / References

- *IEC 60812 Ed.2 (2006) - Analysis techniques for system reliability Procedure for failure mode and effects analysis (FMEA)*
- *IEC 60076-1, Power Transformers-General, 2nd ed., 1993.*
- *ANSI/IEEE Std C57.117-1986. IEEE Guide for reporting failure data for power transformers and shunt reactors on electric utility power systems, 1988.*



THANK YOU

