Power Transformer Failures Evaluation Using Failure Mode Effect and Criticality Analysis (FMECA) Method

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ABSTRACT— ***One of the equipment's that has a very important role in electric power transmissions systems is the power transformer. The failures of the power transformer frequently cause interference with the transmissions systems. Therefore the condition and performance of the power transformer should be known, it includes reliability and security. This paper proposes the analysis of risk resources and failure probability of power transformer using Failure Mode Effect and Criticality Analysis (FMECA). An example was taken from 92 power transformer to illustrate the FMECA method. Based on the investigation there are three components having the potential failure modes; winding, OLTC and bushing. In this case, winding has the highest failure probability. The severity and occurrence are divided into 10 levels, while detectability is divided into 5 levels. As a result, the degree of criticality for winding is high, for load-tap-changer (OLTC) and bushing are medium. The maintenance strategy for winding is maintenance immediately, for OLTC and bushing are maintenance priority.***

Keywords— power transformer, risk priority number (RPN), failure mode effect and criticality analysis (FMECA), fault tree analysis.

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1. INTRODUCTION

One of the equipment's that has a very important role in electric power transmissions systems is the power transformer. The failures of the power transformer frequently cause interference with the transmissions systems. Therefore the condition and performance of the power transformer should be known, it includes reliability and security. In one case the failure is endangered for people's security, but for the other ones, the failure is barely influenced. In the meantime, some cases of failure will have more consequences but the probability of failure is smaller. Conversely, the failure has less consequences but the probability of occurrence is greater. Therefore, it is difficult to determine which failures should have more attention since it has more risk and endangered for people's security [1].

This paper proposes the analysis of risk resources and failure probability of power transformer using Failure Mode Effect and Criticality Analysis (FMECA). FMECA consist of two separate analyses, Failure Mode Effect Analysis (FMEA) and Criticality Analysis (CA). The different failure modes and their effects on the system transformer will be analyzed by using FMEA, while the rank of importance based on failure rate and severity of the effect of the failure is classified by CA using historical data. FMECA is a tool to evaluate potential failure modes and their effects in a systematic way, and it will provide information for identifying corrective actions for a given failure. Since FMECA is not a problem solver, then it should be used in combination with the other tools, such as risk analysis [2], fishbone analysis [3], Reliability Centered Maintenance [4].

2. FMECA METHOD

FMECA is the extension of FMEA, designed to identify the failure modes for a process before the failure occurs and to assess the risk. In determining the risk, FMEA has three parameters which are multiple to produce a Risk Priority Number (RPN) or Criticality (C) [4]. The three parameters are; Severity (S) is an assessment of the seriousness of the effect of the potential failure mode to the next component, subsystems, or systems if it occurs, Occurrence (O) is how frequently a specific failure cause is projected to occur, and Detection (D) is the ability to detect the cause of actual or potential failure, and the result is RPN = S x O x D. The rating scale of the three parameters is 1 to 10. For the evaluation, severity is defined as the duration of the outage caused by the failure modes; occurrence is referred to the occurrence of the failure modes, while detection is referred to the ability to detect the failure before it begins for corrective actions [3].

The basic steps in implementing the FMECA are as follows [4];
1) Define the system to be analyzed.
2) Identify failure modes associated with system failures.
3) Identify potential effects of failure modes.
4) Determine and rank how serious each effect is.
5) Determine all potential causes for each failure mode.
6) Identify available detection methods for each cause.
7) Identify recommended actions for each cause in order to reduce the severity of each failure mode.

In this case the value of each parameter was obtained from the accidental and failure statistics data of power transformer.

Since FMECA is assumed as the extension of FMEA, then the usual parameter of FMEA will be used in the FMECA. The evaluation for each parameter is determined by its characterization. Parameter S (Severity) is characterized by the service life to failure, parameter O (Occurrence) is determined by the possible rate of occurrence, and parameter D (Detection) is referred to the level of detectability [4]. The parameter C (Criticality) in FMECA is defined as the risk priority number (RPN). The evaluation for each parameter S (Severity), O (Occurrence), D (Detectability) and C (Criticality) are shown in the following table (Table 1 - 4);

Table 1: Parameter Severity (S)

Service life to failure	Criterion of Severity	Value
> 32 years	Very small	1
28 years < service life ≤ 32 years	Small	2
24 years < service life ≤ 28 years	Very minor	3
20 years < service life ≤ 24 years	Minor	4
16 years < service life ≤ 20 years	Significant	5
12 years < service life ≤ 16 years	Medium	6
8 years < service life ≤ 12 years	Serious	7
4 years < service life ≤ 8 years	Very serious	8
1 year < service life ≤ 4 years	Catastrophic	9
≤ 1 year	Very catastrophic	10

Table 2: Parameter Occurrence (O)

Possible rate of occurrence	Criterion of Occurrence	Value
One every > 18 years	Unlikely	1
One every 16 - 18 years	Unlikely	2
One every 14 - 16 years	Very Low	3
One every 12 - 14 years	Very Low	4
One every 10 - 12 years	Low	5
One every 8 - 10 years	Low	6
One every 6 - 8 years	Medium	7
One every 4 - 6 years	Medium	8
One every 1 - 4 years	High	9
One every year	High	10

Table 3: Parameter Detectability (D)

Level of detectability	Probability	Criterion of detectability	Value
not detectable	0 - 20%	Impossible	9 - 10
difficult to detect	20 - 40%	Very difficult	7 - 9
detecting random	40 - 60%	Occasional	5 - 7
possible detection	60 - 80%	Low	3 - 5
detection at all times	80 - 100%	Immediate	1 - 2

Table 4: FMECA

Degree of Criticality	Value	Risk
Minor	0 - 50	Acceptable
Medium	51 - 100	Tolerable
High	101 - 180	
Very high	181 - 252	Unacceptable
Critical	>252	

3. APPLICATION TO THE POWER TRANSFORMER

According to IEEE (C57.125-1991) the failure of power transformer is defined as *the termination of the stability of transformer to perform its specific function*. Power transformer is consisted of three main parts; 1) primary winding, that produces magnetic flux when it is connected to electrical source, 2) secondary winding, that magnetic flux produced will pass to this secondary winding through the magnetic core link (Fig.1).

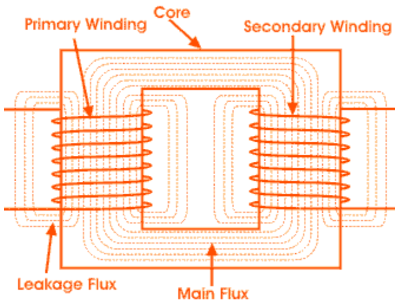

Figure 1: The principle of transformer

3.1 Example

To illustrate the application of FMECA, this paper will examine the failure statistics data of 92 power transformers with electric voltage at 100 kV or above in 2005 to 2013. The system to be analyzed is based on the failure statistical data of 92 power transformers. The result of the analysis has shown that three components; winding, bushing and On-load-tap-changer (OLTC), have the potential failure modes. The failure probability of winding, bushing, and OLTC are 68.48%, 18.47%, and 13.04 %, respectively (Figure 2). Similarly, this is the same as stated by Xie *et al* [1] that winding has the highest percentage of failure probability in transformer.

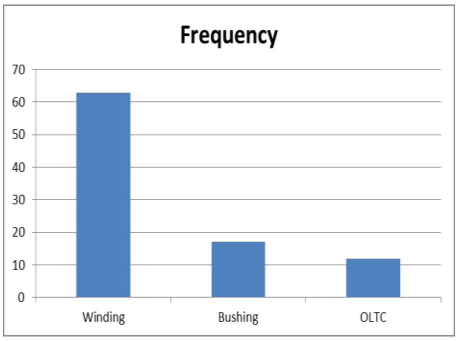

Figure 2. Failure data of 92 power transformer

A fault in windings can occur due to mechanical damage or in insulation material. Windings are arranged as cylindrical shell around the core, and each strand is wrapped with insulation paper. Based on the research investigation the major causes of winding failures are due to mechanical damage. Figure 3 is the fault tree of winding's failure. One of the common fault of winding failure is winding short, this occurs when the insulation on the coil of wire in the primary or secondary breaks down, and current can pass from one winding to the other [5].

Meanwhile, the functions of bushings are to isolate electrical between tank and windings and to connect the windings to the power system outside the transformer. The main failure of bushing in power transformer is short circuit. The major cause of a short circuit is due to mechanical damage or due to material faults in the isolation [6]. Based on statistics, the total number of damages of power transformer is caused by bushing make from 10% to 40% [7].

The tap changer is a voltage regulating device. It changes the ratio of a transformer by adding or subtracting to and turn from either the primary or the secondary winding. On-load-tap-changer (OLTC) generally consists of two switches; the diverter switch and the tap selector. The diverter switch does the entire load making and breaking of currents, while the tap selector preselects the tap to which the diverter switch will transfer the load current. The function of OLTC is failed when it cannot change the voltage level [6].

The major causes of winding and OLTC failures are due to mechanical damage, while the failure of bushing is due to the insulation decrease. This insulation decrease is the most costly faults, since it produces machine outage and electrical supply interruptions. Therefore, a lot of efforts have been done for an early detection of faults in the insulating system of power transformer [8]. The function of oil insulation is cooled the active part of the power transformer, and be the electrical insulation between the different parts. Furthermore, the insulation in cooling system of the transformer is affected by the quality of oil-filled transformer [6]. The major causes of oil deterioration are oxidation of the oil, thermal decomposition, and moisture contamination.

Therefore, the failures of power transformer can be divided into three categories, as follows; 1) winding failures, 2) bushing failures, and 3) load-tap-changer failures. The failure mode of winding is short circuit. By definition failure mode is the way in which a failure is observed, described the way the failure occur, and its impacts on equipment operation [9].

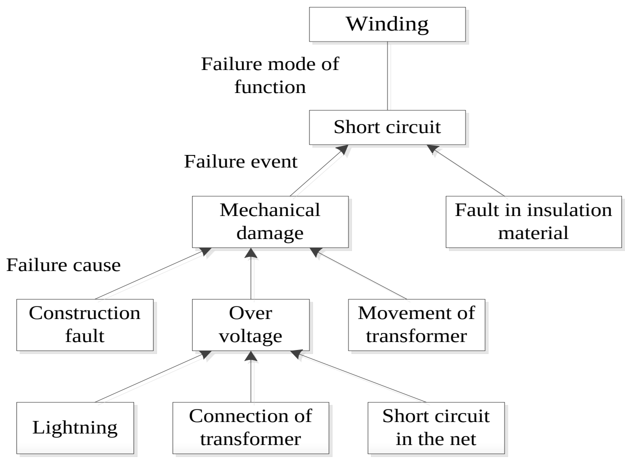

Figure 3. Fault tree for windings (Franzen & Karlsson, 2007).

Based on data of 92 power transformers, the service life until failure of power transformer is presented at Table 5. For example; the number of power transformers that have service life until failure between more than 12 years until exactly 16 years is 19 units.

Table 5. The number of power transformer according to service life until failure

	Service life until failure (year)									
	≤ 1	1<Y≤ 4	4<Y≤ 8	8<Y≤ 12	12<Y≤ 16	16<Y≤ 20	20<Y≤ 24	24<Y≤ 28	28<Y≤ 32	> 32
Number of transformer	5	13	18	6	19	8	4	5	10	5

For category only once failure occurs during the age of power transformer is presented at Table 6. For example; the number of power transformers with only once failure within more than 18 years age is 17 units.

Table 6. The number of power transformer that have only once failure during its life

	Age until failure (year)									
	≤ 1	1<A≤ 4	4<A≤ 6	6<A≤ 8	8<A≤ 10	10<A≤ 12	12<A≤ 14	14<A≤ 16	16<A≤ 18	> 18
Number of transformer	12	14	10	7	5	7	5	11	4	17

The implementation of failure modes effects criticality (FMECA) approach for parts; winding, OLTC and bushing of power transformer is presented at Table 7.

Table 7: Evaluation Sheet of FMECA for Power Transformer

Part	Functions	Potential failure mode	Potential effect of failure	Potential causes of failure	How will potential failure be detected	Criticality				Risk
						S	O	D	C	
Winding	conduct current	short circuit	- mechanical damage - fault in insulation material	- construction fault, - transient overvoltage, - movement transformer, - hotspot, - generating of copper sulfide	detecting all times	medium (6)	high (9)	immediate (2)	high (108)	unaccept able
Load-tap-changer (OLTC)	regulate the voltage level	can not change voltage level	mechanical damage	- wear	difficult to detect	very serious (8)	unlikely (1)	difficult to detect (8)	medium (64)	tolerable
Bushing	- connect windings with net , -isolate between tank and windings	- short circuit	-fault in insulation material, -damage on bushings	- dirt, - water penetration, - careless handling	detecting all times	medium (6)	low (6)	immediate (2)	medium (72)	tolerable

In the FMECA sheet, the RPN of winding, load-tap-changer, and bushing are 108, 64, and 72, respectively. It is shown that winding has the highest value for the degree of criticality with categorize high, while OLTC and bushing have the category of medium. According to the result of analysis using FMECA, there are recommendations for maintenance strategies could be taken. Referring to table FMECA (Table 4), the risk level is determined based on the degree of criticality value. The maintenance strategies are defined for different failures or different risk level, shown in Table 8.

Table 8: Maintenance Strategies

Risk level	Maintenance strategies
Acceptable risk	Maintenance delaying
Tolerable risk	Maintenance priority
Unacceptable risk	Maintenance immediately

Based on the risk level, the maintenance strategies for winding with high risk level is maintenance immediately, for OLTC and bushing with tolerable risk the recommendation are maintenance priority.

4. CONCLUSION

This paper presents the application of FMECA for maintenance management of power transformer. FMECA can be used to identify the failure mode which has a significant effect on the power transformer reliability. Moreover, it provides an objective basis for deciding priorities for maintenance actions. From 92 power transformers are obtained three components having the potential failure modes; winding, OLTC and bushing. The fault tree analysis for the three components has shown the potential failure modes, failure effects and failure causes. The failure severity (S) and failure occurrence (O) are divided into ten grades, while the failure detectability (D) is divided into five grades. Criticality (C) is calculated from the multiplication of severity, occurrence and detectability. The risk assessment is divided into three level; acceptable risk, tolerable risk and unacceptable risk. The maintenance strategies based on risk assessment are categorized in three strategies; maintenance delaying, maintenance priority and maintenance immediately. As a result, the maintenance strategy for winding is maintenance immediately; while for OLTC and bushing is maintenance priority.

5. ACKNOWLEDGEMENT

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