Failure Modes and Effects Analysis (FMEA) for Power Transformers

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***Abstract*—The Failure Modes and Effects Analysis (FMEA) technique has been shown to be an effective way of improving reliability, increasingly using in different fields of power grids. Due to the economic value and importance of the power transformers in a power grid, FMEA technique is proposed and studied for them in this paper. The output of this analysis could be graphical charts and matrices to sort the most critical components, failure modes and causes. This sorting will contribute to identify and take the most effective maintenance actions. Also, another output (this table output is a traditional output in FMEA) which is a worksheet lists common failure modes together with their failure causes, failure effects and a common index used to measure failure seriousness, usually risk priority number (RPN). Also, in this table the corrective actions should be proposed to reduce failures RPN.**

Keywords*—power transformer; FMEA; failure mode; failure cause; failure effect; corrective action; risk priority number (RPN)

I. Introduction

Power transformers in addition to playing an important role in the efficiency and reliability of power transmission networks, are also the most expensive network equipment. It is important to know when the transformer is the most dangerous element because it contains a great quantity of oil in contact with high voltage elements. Thing which favors the risk of fire and explosion in case of abnormal circumstances or technical failures. So, it is necessary to plan and to focus the efforts by set of priorities with a general aim is to improve the reliability of the system, and consequently, to reduce their failure risk.

The first step of a system reliability study is often the Failure Modes and Effects Analysis (FMEA), one of several methods used for risk assessment and management thorough failure analysis [1]. In other words, FMEA is an important procedure to identify and assess consequences or risks associated with potential failure modes. A FMEA is a qualitative analysis and typically includes a listing of failure modes, possible causes for each failure, effects of the failure and their seriousness and corrective actions that might be taken [2].

A review on the past studies shows that FMEA technique is used in some fields of power systems, e.g. wind turbines [3-4], solar modules [5-6], induction machines [7] and motor drives [8]. A similar work is done in the power transformers field in [9]. Authors claim that their work is called FMEA, but it is more similar to the Fault Tee Analysis (FTA) rather than FMEA. FTA is a deductive, top-down method aimed at analyzing the effects of initiating faults and events on a complex system. However, it is not good at finding all possible initiating faults. While, FMEA is an inductive, bottom-up analysis method aimed at analyzing the effects of single component or function failures on equipment or subsystems. FMEA is good at exhaustively cataloging initiating faults, and identifying their local effects. In [9] controls including prevention and detection controls, recommended actions and risk measurements are not included, while all of them are studied in this paper.

II. Conventional Failure Modes and Effects Analysis (FMEA)

FMEA was developed in the 1940's to study problems that might arise from malfunctions of US military systems. In general, FMEA is a systematic, proactive method for evaluating a process to identify where and how it might fail and to assess the relative impact of different failures, in order to identify the parts of the process that are most in need of repair and maintenance.

There are many different standards developed for FMEA application in various industries. Some of the most important standards are: SAE-J-1739 [10] (geared for the ground vehicle community), AIAG's FMEA [11] (a reference manual to be used by suppliers to Chrysler LLC, Ford Motor Company, and General Motors Corporation), MIL-STD-1629A [12] (drafted by The United States Department of Defense), IEC 60812 [13] (a guidance to how these techniques may be applied to achieve various reliability program objectives), and BS EN 60812 [14] (the European adoption of the IEC 60812). A typical standard will outlines Severity, Occurrence and Detection rating scales as well as examples of an FMEA spreadsheet layout. Also, a glossary will be included that defines all the terms used in the FMEA. The rating scales and the layout of the data can differ between standards, but the processes and definitions remain similar.

FMEA assigns a numerical value to each risk associated with a causing failure, using severity, occurrence and detection by calculating the risk priority numbers (RPN) for each failure cause:

$$RPN = (Severity) * (Occurrence) * (Detection)$$

and subsequently prioritizes the actions needed to counteract or avoid these failures. By targeting high value RPNs the most critical failure cause can be addressed.

The definitions of terms used herein are in accordance with the definitions in [13] and [15]:

Failure: termination of the ability of an item to perform a required function

Failure mode: manner in which an item fails

Failure cause and/or mechanism: cause or sequence of causes that initiate a process (mechanism) that leads to a failure mode over a certain time. The most likely causes of the failure mode are listed under "Possible failure causes".

Failure effects: consequence of a failure mode in terms of the operation, function or status of the item

Severity: refers to the magnitude of the end effect of a system failure. The more severe the consequence, the higher the value of severity will be assigned to the effect.

Occurrence: refers to the frequency that a root cause is likely to occur, described in a qualitative way. That is not in the form of a period of time but rather in terms such as remote or occasional.

Detection: refers to the likelihood of detecting a root cause before a failure can occur.

Note, in the FMEA, the definitions of failure modes, failure causes and failure effects depend on the level of analysis and system failure criteria. As the analysis progresses, the failure effects identified at the lower level may become failure modes at the higher level. The failure modes at the lower level may become the failure causes at the higher level, and so on.

The most widely used standard is MIL-STD-1629A. With over 30 years usage and development, it has been employed in many different industries for general failure analysis. Due to the complexity and criticality of military systems, it provides a reliable foundation on which to perform FMEAs on a variety of systems. In this paper, MIL-STD-1629A standard is used to scale two Severity and Occurrence factors tabulated in Tables I-II.

TABLE I. SEVERITY CLASSIFICATION FOR POWER TRANSFORMERS

Value	Description	Criteria
1	Category IV(Minor)	primary function can be done but urgent repair is required.
2	Category III(Marginal)	reduction in ability to primary function
3	Category II(Critical)	causes a loss of primary function
4	Category I(Catastrophic)	product becomes inoperative

TABLE II. OCCURRENCE CLASSIFICATION FOR POWER TRANSFORMERS

Value	Description	Criteria
1	Level E(Extremely Unlikely)	a single failure mode probability of occurrence is less than 0.001
2	Level D(Remote)	a single failure mode probability of occurrence is more than 0.001 but less than 0.01
3	Level C(Occasional)	a single failure mode probability of occurrence is more than 0.01 but less than 0.10
4	Level B(Reasonably probable)	a single failure mode probability of occurrence is more than 0.10 but less than 0.20
5	Level A(Frequent)	a single failure mode probability of occurrence is greater than 0.20

Beside, several diagnostic tests may be used to identify &/or detect failures of power transformers. In this paper, CIGRE working group on power transformers [16] is used to scale the Detection factor for diagnostic tests tabulated in Table III.

TABLE III. DETECTION CLASSIFICATION FOR THE DIAGNOSTIC TESTS OF POWER TRANSFORMERS

Value	Description	Criteria
1	Level F	Good identification
2	Level E	Fair identification
3	Level D	Good detection & rough identification
4	Level C	Fair detection
5	Level B	Rough detection
6	Level A	Complementary test

NOTE: Identification indicates that the source or location of a defect or fault has been determined by the test. Detection only indicates that a defect or fault exists.

It can be concluded that the minimum RPN for any Failure Cause is 1 and the maximum is 120.

After scaling three Severity, Occurrence and Detection factors, it is necessary to know an algorithm to create the FMEA. This algorithm is shown in Fig. 1.

For each cause, you can identify the controls that are currently in place to reduce or eliminate the risk associated with the potential cause of failure. There are two controls associated with the cause:

- Prevention Control is intended to reduce the likelihood that the cause, and consequently the failure, will happen
- Detection and Identification Control is intended to increase the likelihood that if the cause does happen, the problem will be detected before it reaches the customer or end user.

After that the controls have been identified, a more accurate assessment can be made of the likelihood that the failure will occur and the likelihood that the failure will be detected before it reaches the end user.

Once all initial RPNs have been determined, you can then prioritize the issues based on risk and give priority to high RPNs. At that point, you can select issues for improvement and define appropriate recommended actions, assign responsible persons, and take actions.

Once actions have been taken to reduce the risk associated with a cause of failure, the RPN rating for the cause will change. So, the revised RPN is defined and calculated by the predicted severity, occurrence, and detection levels.

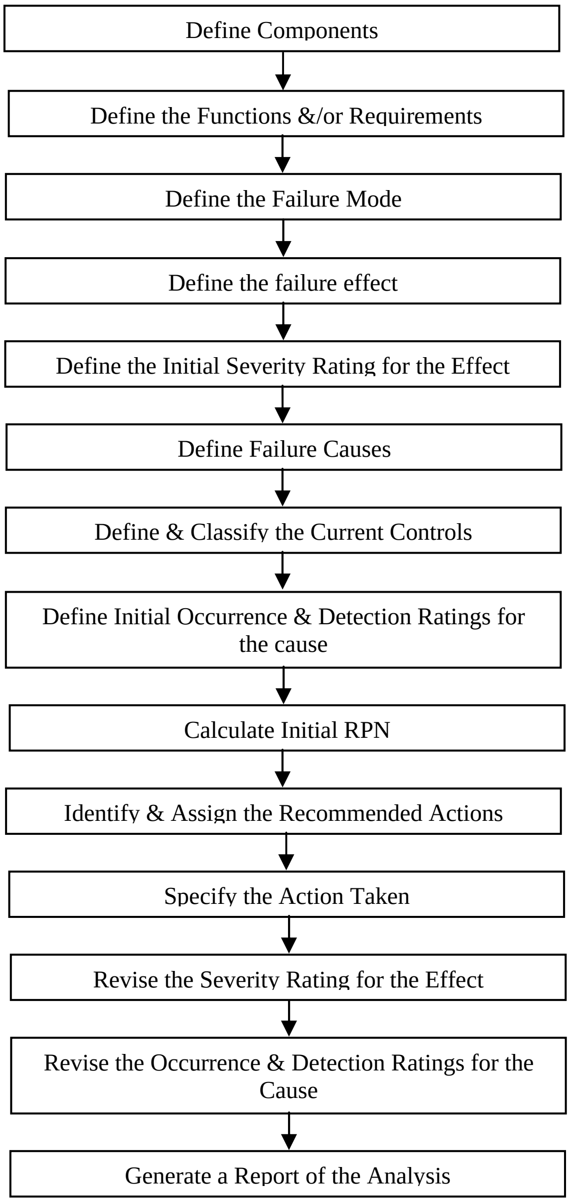

Fig. 1. An algorithm to create a FMEA project

III. Power Transformer Construction Considered in This Paper

To completely analyze failures of a system it should be broken to subsystems, components and parts. In this paper, oil immersed power transformers are considered to study under FMEA technique. Different components of an oil immersed power transformer are:

A. Active part

Core and windings are considered to belong to the so-called active part of the transformer, i.e. where the actual transformation takes place.

1) Core

The function of the core is to concentrate the magnetic flux.

2) Windings

The function of the windings is to carry current. In addition to dielectric stresses and thermal requirements the windings have to withstand mechanical forces that may cause windings replacement.

B. Insulation system

The insulation system in a transformer consists of two parts, a solid part (cellulose) and a liquid part (transformer oil), and where the liquid part has a double function.

1) Solid insulation

The solid insulation in a transformer is cellulose based products such as press board and paper. Its main function is to isolate the windings.

2) Transformer oil

The oil serves as both cooling medium and as part of the insulation system. The quality of the oil greatly affects the insulation and cooling properties of the transformer.

C. Accessories

Also, following transformer components are defined as "accessories".

1) Bushings

A bushing is a component that insulates a high voltage conductor passing through a metal enclosure, i.e. a current path through the tank wall. The inside of the bushing may contain paper insulation and the bushing is often filled with oil to provide additional insulation.

2) Tap changer

The On-Load Tap-Changer (OLTC) is the most complex component of the transformer and its function is to regulate the voltage level by adding or subtracting turns from the transformer windings. The OLTC is built in two separate sections; the diverter switch and the tap selector. Due to the fact an interrupting of the supply is unacceptable for a power transformer, these are fitted with a complex mechanism that change turns ratio without interrupting the load current. To obtain a non interrupted flow current the tap change procedure is performed in two steps [18].

1. The next tap is preselected by the tap selector at no load
2. The diverter switch transfers the load current from preselected tap.

The tap selector makes the new tap connection before releasing the old, and avoids the high current from the short-circuited turns by temporarily placing a large diverter resistor in series with the short-circuited turns before breaking the original tap connection. To avoid contamination of the transformer oil, the diverter switch has its own oil filled housing separate from the rest of the transformer.

3) Cooling system

Power transformers are equipped with cooling fans, oil pumps or water-cooled heat exchangers designed to remove the heat caused by copper and iron losses.

4) Tank

The tank is primarily the container for the oil and a physical protection for the active part. It also serves as support structure for accessories and control equipment. The tank has to withstand environmental stresses, such as corrosive atmosphere, high humidity and sun radiation [17].

5) Mechanical structure

Mechanical structure includes clamping, coil blocking and lead support. Their Function is to support the active part of transformer firmly in its place, and withstand against mechanical stresses.

Winding Connections

Winding connections are between windings, tap leads, and to bushings. Their Function is to provide required electrical connection between these elements.

D. Protection

The primary objective of the transformer protection is to detect internal faults in the transformer with a high degree of sensitivity and cause subsequent de-energisation and, at the same time be immune to faults external to the transformer i.e. through faults.

Protection systems include the Buchholz protection, pressure relief valve circuitry, surge protection, and tap changer pressure relief and surge protection.

IV. POWER TRANSFORMER FMEA

Transformer failure can occur as a result of different causes and conditions. Generally, transformer failures can be defined as follows [19-20]:

- Any forced outage due to transformer damage in service (e.g. winding damage, OLTC failure)
- Trouble that requires removal of the transformer for return to a repair facility, or which requires extensive field repair (e.g. excessive gas production, high moisture levels)

Several surveys were done on transformer reliability. Failure location, failure cause and failure mode classification were based on predetermined classifiers provided in [16]. This methodology enabled the detailed analysis and classification of more than 200 failures in ± 10,000 unit-years, for variously rated transformers, over the period 1996 to 2006 [21].

Figure 2 shows a typical failure locations distribution for transmission transformers based on failure data existed in [21].

It is observable that failures originating in the transformer protection are the largest contributors, followed by the tap-changers and bushings, as shown in Fig. 2.

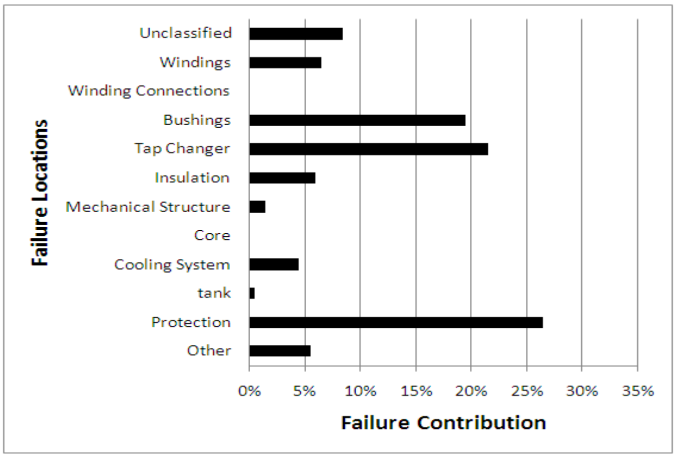

Fig. 2. Failure locations in transmission transformers

After subdividing a transformer to its components and defining their functions and/or requirements, failure modes related to each component should be generated. Totally, a transformer can fail from any combination of dielectric, electrical, physical chemistry, mechanical, and thermal factors. In following it is shown that theses failure modes often involve which

Dielectric mode failures involve insulation breakdown leading to flashovers between windings, near the exit leads, and core to ground insulation.

Electrical mode failures were mainly due to inherited deficiencies such as improper repair, improper site and factory assembly resulting in poor contact or short circuits in the on load tap changer selector, bushings and windings. Typical causes are due to Open circuit, Short circuit, Poor joint, Poor contact, Ground deterioration and Floating potential.

Physical chemistry failure modes are a result of corrosion and contamination with particles (Cellulose fibres, iron, aluminum, copper and other particles), gas or moisture eventually leading to dielectric flashovers in the oil insulation, winding to ground insulation and minor insulation.

Mechanical failure modes involve distortion and loosening or displacement of windings occurring in one of two ways: shipping or movement damage, or electromechanical forces under the impact of through faults. Manufacturing deficiencies with the effect of electromagnetic forces within the transformer have resulted in tearing of the turn-to-turn insulation.

Thermal failure modes are often developed as localized hotspots in winding exit leads and winding turn insulation due to inadequate design. Thermal degradation results in the loss of physical strength of the insulation that, over time, will weaken the paper to the point where it can no longer withstand the mechanical duty imposed on it by the vibration and mechanical movement inside of a transformer.

Figure 3 shows failure modes distribution for failure data taken by [21].

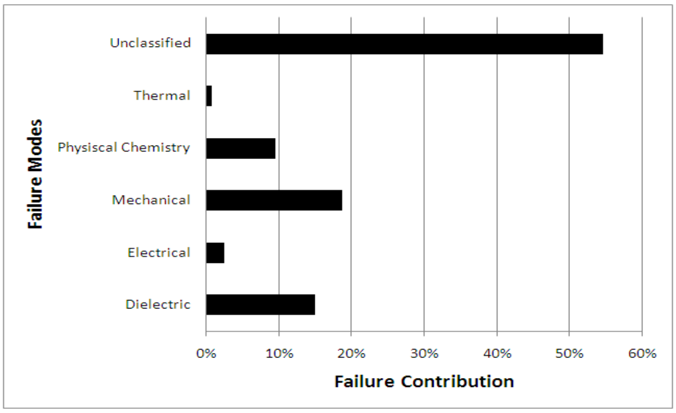

Fig. 3. Failure mode distribution for transmission transformers

Failure causes are categorized to 7 category including Inherent deficiency (involve Inadequate specification and Inadequate design), Inherited deficiency (involve Inherent material defect, Improper factory assembly, Improper site assembly, Improper maintenance, Improper repair, Improper adjustment), Improper application, System event (involve Overload, Load removal, Over-voltage, Resonance and Short circuit), External event (involve Vandalism and Impact of external object), Environmental Lightning (High ambient, Low ambient, Rain, Water ingress, Wind, Seismic and Geomagnetic) and Abnormal deterioration. Figure 4 shows failure causes distribution for failure data taken by [21].

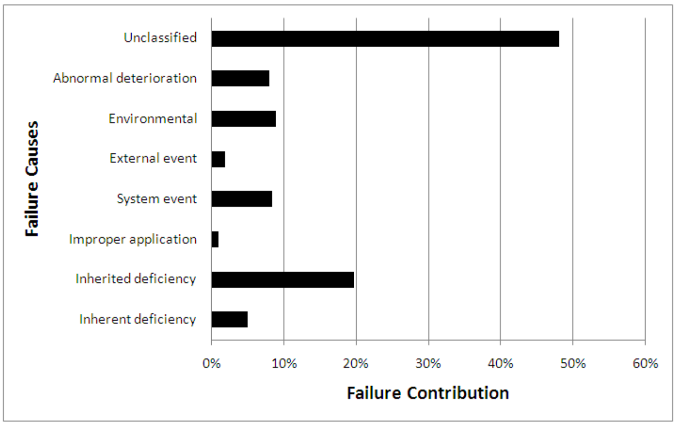

Fig. 4. Failure cause distribution for transmission transformers

Note the occurrence probability of causes may be different from a transformer to another transformer and from an environment to another environment. In this paper, we use a typical occurrence probability for any cause which merely has a study aspect. It means in all power transformers these values and orders are surely different.

Beside, as said before, there may be several tests to diagnose failures of power transformers. For example, tests used to diagnose the excessive moisture in solid insulation are shown in table V, together with their class and scale.

TABLE V. EXCESSIVE MOISTURE IN SOLID INSULATION

Detection Control	Detection Class	Detection Scale
Moisture in oil	Level D	3
Power factor/tan delta	Level E	2
Water heat run	Level C	4
Moisture level in paper	Level A	6
Estimate through Power factor/tan delta vs t^{o}C	Level B	5
RVM	Level D	3

FMEA also should provide a complete array of plots and charts for graphical presentation of analysis. As a typical, a column plot is observable in Fig. 5 showing failure causes vs initial and revised RPN values.

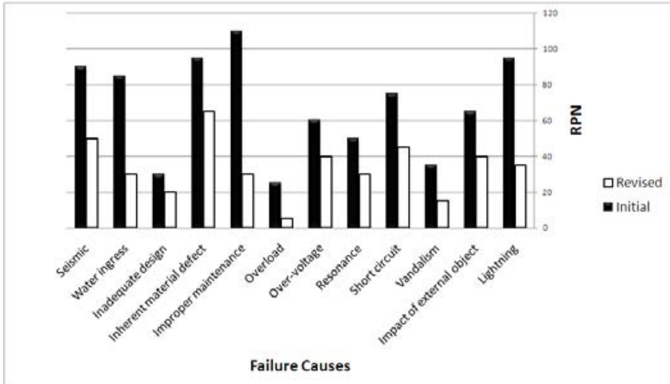

Fig. 5. Failure causes vs initial and revised RPN values

Also, another output of a FMEA may be Occurrence/Severity Matrix. The Occurrence/Severity Matrix displays the severity ratings on the X-axis and the occurrence ratings on the Y-axis. The matrix displays a point for each cause in the data set, at the location where the severity and occurrence ratings intersect.

The matrix also includes two priority lines that are intended to differentiate the high, medium and low priority causes, based on severity and occurrence ratings. The coordinates for these lines are set by the user.

A typical Occurrence/Severity Matrix is shown in Fig. 6. For this example, the following selections were made:

High Occurrence = 5.5

Low Occurrence = 3

High Severity = 3.5

Low Severity = 2

In Fig. 6, you will see that there are six causes in the high priority area, four in the medium priority area and one in the low priority area.

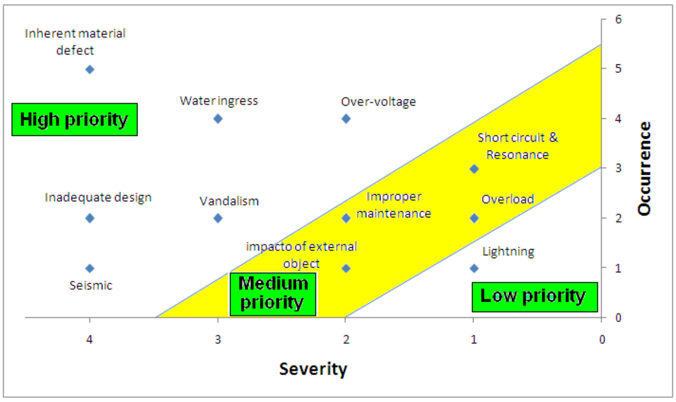

Fig. 6. Occurrence/Severity Matrix

Also, the status of recommended actions should be provided as Fig. 7, to better understand and that how many actions are completed, due and overdue.

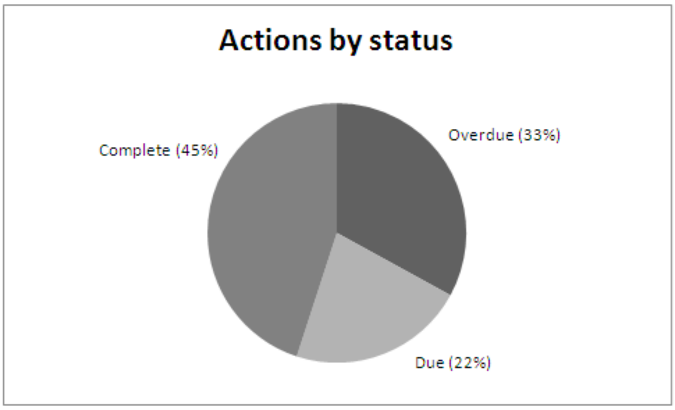

Fig. 7. The status of recommended actions

However, worksheet view is the oldest and the earliest report taken by the FMEA. The worksheet view, which follows the traditional tabular format that most FMEA practitioners are familiar with, allows you to type directly into the worksheet cells and tab through the analysis as you would in a spreadsheet application, such as Microsoft Excel.

V. Conclusion

In this paper, one of the representative qualitative assessment methods, FMEA, was used to analyze the failure modes, causes and effects in the power transformers. This is an encouraging result which demonstrates that the FMEA could be developed further for this purpose.

Once FMEA data is produced, it should be ranked in component order by RPN giving a clear picture of the unreliability of components. Also, graphical charts and matrices could be complementary tools to reach the needed more effective actions. The overall, FMEA could be a useful tool for designers to identify weak points in the transformer design & for O&M designers to give the most of considerations in the transformer maintenance.

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ID	Components	Function(s)	Failure Mode(s)	Failure Cause(s)	Failure Effect(s)		Control(s)		Risk Rating				Recommended Action(s)	Revised Risk			
					Local Effect(s)	End Effect(s)	Prevention Control(s)	Detection/ Identification Control(s)	OCC	SEV	DET	RPN		OCC	SEV	DET	RPN
1	Solid Insulation	Insulation of the windings	Physical Chemistry	Excessive moisture	reduce the dielectric & mechanical strength of paper	Mechanical damage & fault in insulation	Prevent oil free transportation, Prevent directly entry of moisture from the air by the proper sealing	Moisture in oil	3	4	3	36	dry out and dehumidifier the transformer, eliminate leaks and re-sealing	1	4	3	6
								Power factor/tan delta	3	4	2	24		1	4	2	4
2	Oil insulation	Isolate and cool active part of transformer	Physical Chemistry	Particle contamination	Reduce the electrical strength & Breakdown voltage; increase the dielectric loss of oil	Overheating & short circuit in the transformer	Pump bearing monitor, correct oil sampling procedures	Particle count	3	4	2	24	Oil filtering. Oil replacement	1	4	2	8
								Breakdown voltage	3	4	3	36		1	4	3	12
3	Windings	Conduct current	Mechanical	Loose clamping	Winding deformation	High through current faults, high inrush currents, protective relay tripping	Use of higher density insulation and higher clamping pressures during manufacturing. Use of spring dashpot assemblies on the coil clamping structure.	Leakage reactance	2	3	5	30	Reclamping/ repacking	1	3	5	15
								Capacitance change	2	3	1	6		1	3	1	3
4	Tank	Enclose oil/ protect the active part	Chemical/Physical	Insufficient maintenance	Corrosion	Leakage	Monitoring of the inhibitor content according to IEC 60666. external examination for oil leaks	Visual	2	3	3	18	Add synthetic oxidation inhibitors, repair	1	3	3	9
5	Bushings	Connect windings with net, isolate between tank and windings	Physical Chemistry	Lack of maintenance	External contamination, Corrosion/make discharge current on the external surface of insulation	Short circuit, personnel safety	Periodic maintenance	Power factor/tan delta (IEC 137)	2	4	6	48	Replacement	1	4	6	24
								Visual	2	4	3	24		1	4	3	12
6	Core	Wear magnetic field	Thermal	Frame to earth circulating currents	Increased core temperature	Loss of efficiency		Furfuraldehyde Analysis (FFA)	2	3	1	6		1	3	1	3
7	Diverter switch	Maintain a coherent current	Electrical	Worn contact	High carbon build-up	possible flash over	contacts replacement after the specified performance number according to the manufacturer suggestions	DGA	2	3	4	24	Oil replacement	1	3	4	12

Note: **Local effect**s: refers to the effects of the failure mode on the system element under consideration.

End effects: refers to the impact of a possible failure on the highest system level.