

The Effectiveness of Different Transformer Maintenance Strategies

by **Thomas Kessler**

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While the failure rates are low, the potential consequences of major transformer can be severe, like regulatory information and guardianship, criminal liability, utility legitimation in question /1/, all beside other depending on the financial damage and impact. The goal of this paper is to well balance the failure rates, consequences of failures and preventive measures.

Challenges of the Transformer Lifecycle Management

Power transformers are known to be very reliable assets. Average Global failure rates of 0.53% p.a. for substation transformers and 0.95% p.a. for Generator Step-Up transformers have been reported /x/. While the failure rates are low, the potential consequences of major transformer can be severe, like regulatory information and guardianship, criminal liability, utility legitimation in question /1/, all beside other depending on the financial damage and impact. The goal of this paper is to well balance the failure rates, consequences of failures and preventive measures.

Addressing the Main Business Levers and Performance Areas of Assets

/2/ provides a starting point for the above-mentioned balancing. These are the main business levers that are shown in table 1: Safety, financial, quality of service, reliability, environmental.

These business values and performance areas are used in the following for the balancing described under III. We start with the estimate of the transformer risk exposure monetizing as financial damage and impact in case of a major transformer failure.



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Example of business values & performance areas	Description
Safety	The company values safety of employees and 3 rd parties. The business value „safety” contains performance elements like Lost Time Incidents, etc.
Financial	The company values a sound financial position and system. The business value „Finance” contains financial performance elements.
Quality of Service, Reliability	The company values a good quality of service. The business value „quality of service” contains performance elements like Customer Minutes Lost, etc.
Environment	The company values the environment. The business value contains performance elements like cost of environmental damage, etc.

Table 1: Examples of the main business levers and performance areas of assets

Transparent Transformer Risk Assessment

Transparent transformer risk assessments to estimate the financial impact and consequences of major transformer failures. They monetize in case of failure as unplanned CAPEX and OPEX spendings.

Table 2 provides a guideline to estimate the risk exposure of transformers.

It needs to be said that thinking the most unlikely to happen and considering all relevant aspects is essential to assess the transformer risk exposure fully and transparently as some practical examples show.

In the U.S. a major utility went bankrupt because long-neglected

distribution grids have caused huge wildfires resulting in billion damages and fatalities of people. Aged and poorly maintained distribution transformers in easily flammable areas have been a key factor as cause of fire.

Also, failures of industrial transformers have been reported where the fire and resulting disintegration caused major damages of neighboring transformers, consequentially resulting in a full shutdown of entire production lines. The neighboring transformers have not been sufficiently protected against external impacts.

In the next step measures are being discussed and evaluated that allow the mitigation and reduction of the transformer risk exposure.

Due to its importance the application and benefits of different kind of DGA sensors needs to be discussed. As picture 2 shows the application of H₂ + H₂O sensors is sufficient for the early identification of evolving transformer failures. The detection of all additional combustible and diagnostic gases provides further information about the failure mode but do not provide additional benefits from the risk mitigation perspective /5/.

Finally, the achievable risk mitigation needs to be well balanced with the available CAPEX and OPEX budgets as well as with the remaining risk as explained in the following.

Benefit and Discounted Cash Flow (DCF) Consideration

Picture 3 explains the principle of risk mitigation: Maximum 70% of the over risk related to evolving major transformer failures can be identified in advance, as described under VI. This is the risk mitigation potential. To monetize this risk mitigation potential an invest into preventive measures like diagnostics, online monitoring and maintenance is required. The delta is the benefit or profit. If it is positive the applied risk mitigation is financially feasible for the end-user.

The benefits of risk mitigation are calculated as described in the following. The annual benefit of risk mitigation is calculated as follows:

$$\text{Benefit} = \text{Risk Mitigation potential} - \text{Costs of Risk Mitigation by prevention} [1]$$

The Discounted Cash Flow (DCF) generated by the benefits after a period of n years is

$$\text{DCF} = \text{Benefit}/(1+r) + \text{Benefit}/(1+r)^2 + \dots + \text{Benefit}/(1+r)^n, [2]$$

where r is the annual rate of interest and n the number of years.

Maintenance Strategies and Achievable Risk Mitigation for Power Transformers

Picture 4 shows the different maintenance strategies investigated in this paper. In the following these are declared as maintenance strategies.

Environmental, e.g.	<ul style="list-style-type: none"> • Oil volume • Availability of oil collector • Cost for potential oil contamination of ground, water • CO₂ footprint
Network-related, e.g.	<ul style="list-style-type: none"> • „n-1“ principle applied • „n-1“ principle not applied • EMC protection e.g. against harmonics of frequency converters
CAPEX, e.g.	<ul style="list-style-type: none"> • Replacement costs • Installation & Commissioning of new transformer
OPEX, e.g.	<ul style="list-style-type: none"> • Repair costs • Installation & Commissioning of repaired transformer • Removal costs • Costs-of-Energy-not-Supplied, CoENS • Penalties • Consequential damages • Re-Dispatching • Availability of spare units
Safety, e.g.	<ul style="list-style-type: none"> • Costs of injuries • Costs of fatalities • Legal costs

Table 2: Guideline to assess the risk exposure of transformers.

Goals and Approach

It is assumed that the appropriate maintenance strategy for power transformers shall reduce the risk of major failures /x/ as good as possible. Key for the effective risk mitigation is the early identification of evolving major transformer failures. Picture1 explains the basics of risk mitigation /3/. Essential is the early identification of evolving failures. As shown in picture 1 and further explained in /3/ maximum 30% of evolving failures can be identified in advance by applying onsite diagnostics and manual condition assessments.

Additional maximum 40% of all evolving failures can be early identified by applying different methods of transformer online monitoring as also shown in picture 1.

The diagnostics or online monitoring provide information about the conditional status of the power transformer (Step 1). In this case preventive or improving action needs to be initiated (Step 2). As shown in /x/ the is always a remaining risk of approximately 30% of major failures that cannot be identified in advance. Effective emergency processes are highly recommended (Step 3).

Service Level A:

Minimum or no maintenance, replacement of the transformer after 25 years by a new asset

Service Level B:

Annual Condition Assessments, OLTC maintenance every 7 years, preventive bushing exchange, oil regeneration and drying indicated by conditions after minimum 25 years in operation.

Service Level C:

See Service Level B, plus DGA monitoring (Single gas + H₂O or 5 gas). Please keep in mind that DGA multigas does not provide further benefits considering the risk mitigation perspective.

Service Level D:

See Service Level C, plus bushing monitoring.

Service Level E:

See Service Level D, full scope online monitoring system including OLTC monitoring.

Further, it is assumed that all online monitoring components must be exchanged after 17 years in operation, as the lifecycle of electronics is significantly shorter than the achievable lifetime of power transformers, which is supposed to be 50 years /1/.

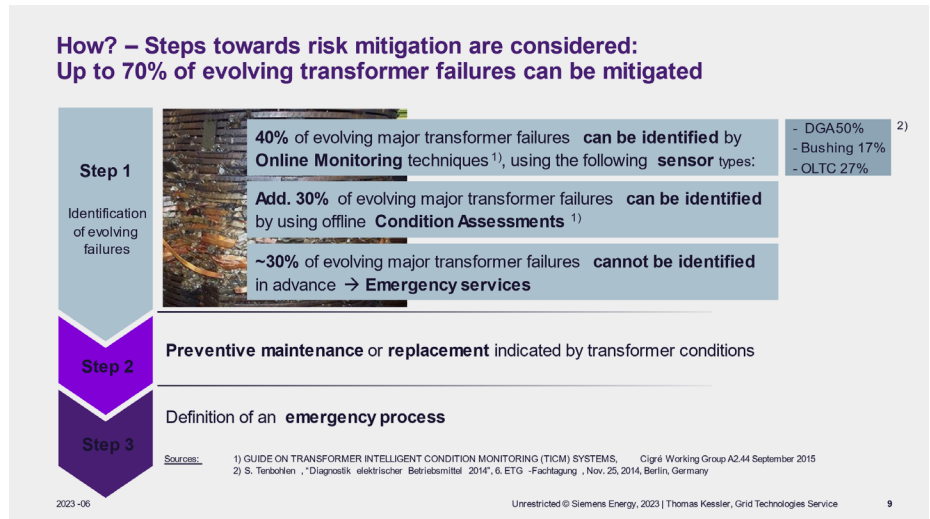
Picture 5 shows the achievable risk mitigation potentials of the described Service Levels A to E, considering the risk mitigation potentials shown in picture 1.

General Assumptions

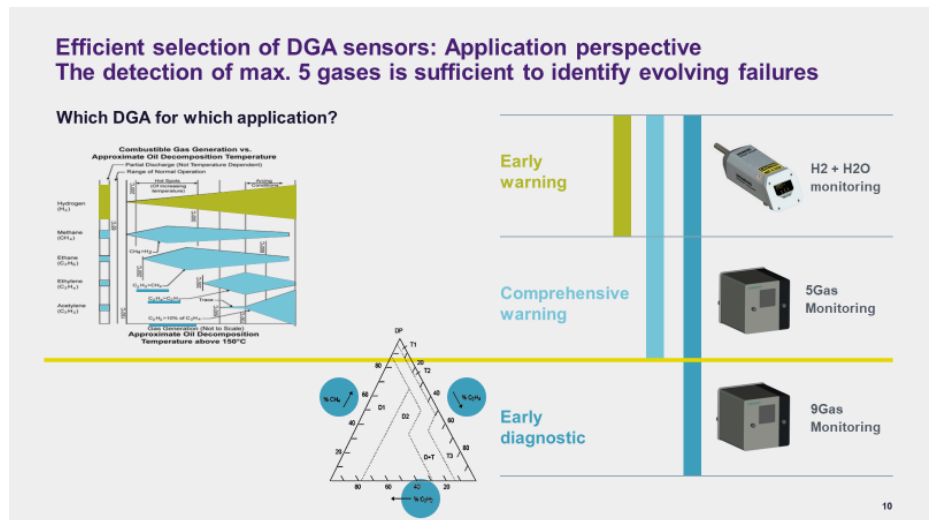
October 2022 is the reference month for all financial figures including the rates for the generation and transmission of electricity, pricing for transformers and services: Oil regeneration and drying, preventive bushing exchange, diagnostics, online monitoring equipment, onload tap changer (OLTC) maintenance.

Discussion of Maintenance Strategies for Transmission Transformers

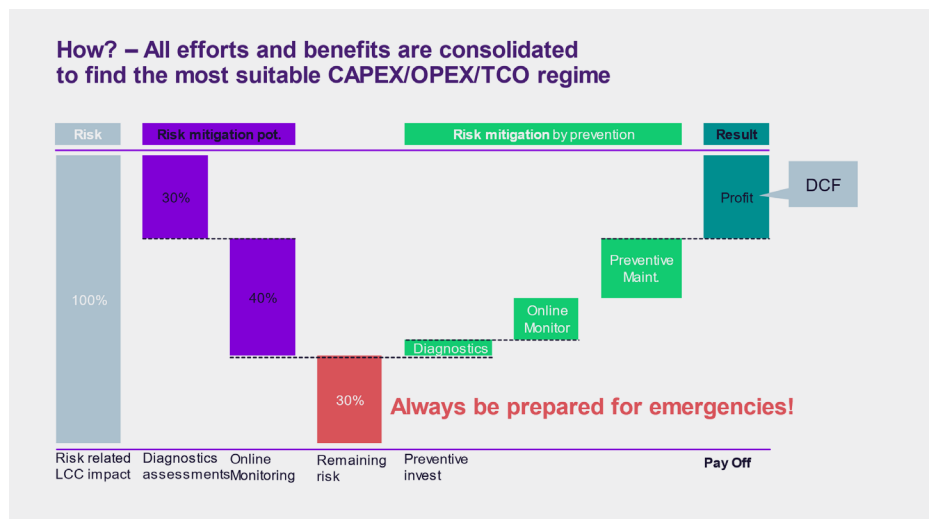
It is assumed that transmission companies are mostly regulated companies. The Return-on-Invest (RoI) on the Regulated-Asset-Base



Picture 1: Principle of risk mitigation for evolving major power transformer failures /3/, /4/.

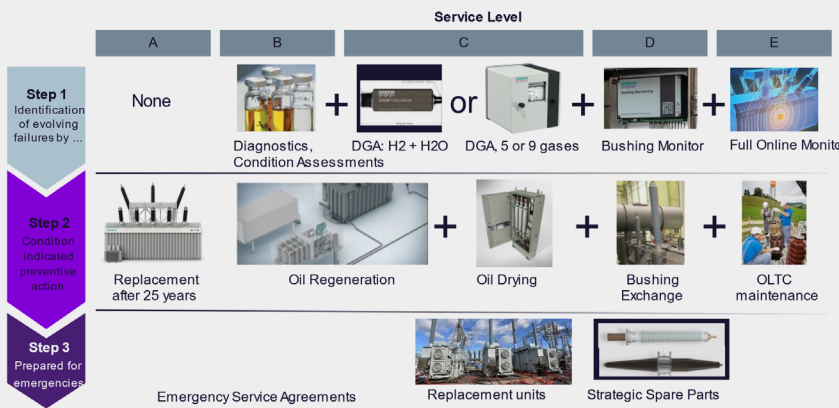


Picture 2: Application of different kinds of DGA sensors /5/



Picture 3: Principle of risk mitigation, showing the risk mitigation potential, preventive efforts and profit.

What? – We offer appropriate levels of risk mitigation and fast emergency services

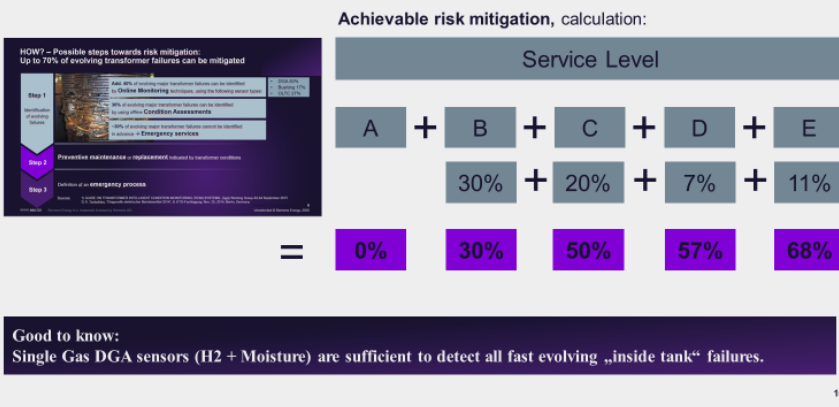


Picture 4: Overview of Service Levels A to E

(RAB) is their most important source of profits. The average Global failure rate for transmission transformers is 0,53% p.a. /1/, reaching from nearly 0 in the first 25 years to almost 1% in the later life cycle /1/.

The „n-1 principle“ is fully applied. This means that no power losses and Costs-of-Energy-not-Supplied (CoENS) in case of transformer failure are considered. In result the risk exposure is limited to the direct damage of the transformer. However additional costs for the necessary re-routing of energy and re-dispatching in case of failure need to be taken into account during the risk assessment. The same applies for the impact of incentive and malus payments due to the applicable regulatory scheme or customer contracts.

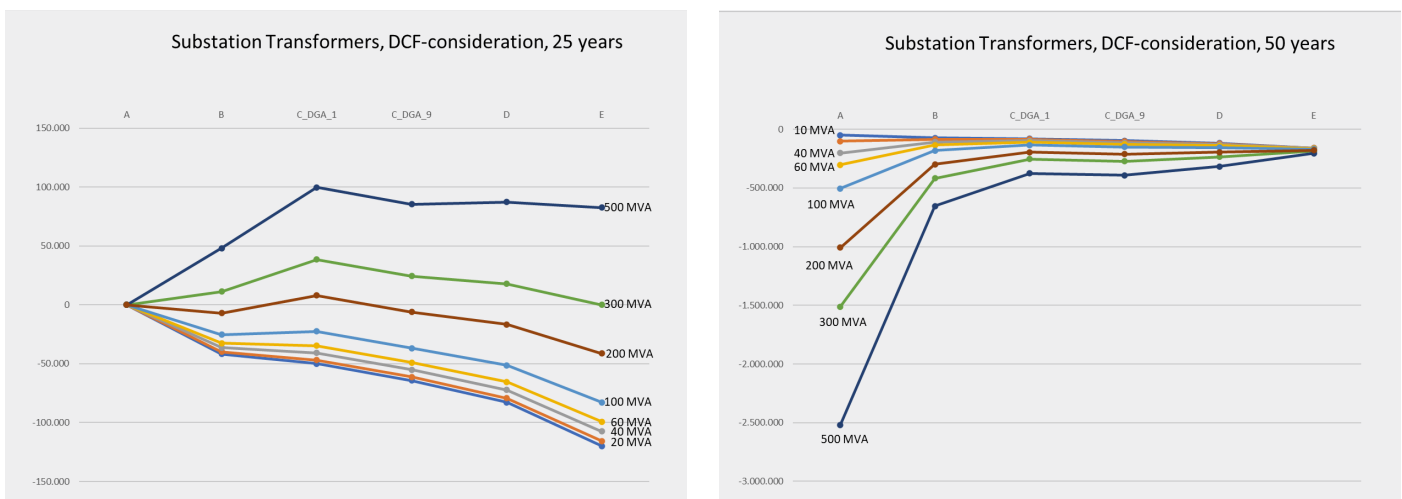
What? – Max. 68% of the risk exposure can be mitigated by applying our service levels, A to E



Picture 5: Achievable risk mitigation potentials for Service levels A to E (figures in purple shadowed fields)

The benefits and resulting DCF of transformer maintenance strategies (A) to E) have been computed for various types of substation transformers. The following diagrams display the benefits for redundant substation transformers. DCF evaluation periods of 25 years and 50 years (see picture 6) have been computed.

The modelling for 25 years shows that applying preventive measures may only pay off for bigger substation transformers with ratings of > 100 MVA. In these cases, the accumulated costs for risk mitigation are less than the corresponding risk exposure.



Picture 6: Benefits (DCF, EUR) for various kind of redundant substation transformers for maintenance strategies A) to E), DCF evaluation period of 25 years (Left), 50 years (Right)

For smaller ones the risk mitigation costs are higher than the risk exposure.

The modelling for 50 years changes the picture completely. Although the generated DCF is always negative Service Level A is the less beneficial for all kinds of substation transformers except very small ones due to the replacement costs of the existing transformer after 25 years. The DCF generated by Service Levels B to E are impacted by significant maintenance costs e.g. for preventive bushing exchange, oil regeneration and drying.

In summary the most feasible maintenance strategy depends on the considered time frame and size of the substation transformer (see picture 7).

Transmission: Financial evaluation, iscounted Cash Flow/DCF Impact of more and less beneficial service levels

Financial evaluation of service levels for transmission transformers: DCF/EUR

Power Rating	Time frame	25 years: Risk exp. 4% of new asset		50 years: Risk exp. 37% of new asset	
		Best/DCF	Worst/DCF	Best/DCF	Worst/DCF
10 MVA	A	0	-119.845	-50.374	-159.905
20 MVA		0	-115.715	-85.240	-160.825
40 MVA		0	-112.705	-97.328	-201.495
60 MVA		0	-107.455	-109.416	-302.243
100 MVA	C	0	-82.674	-133.593	-503.739
200 MVA		8.034	-41.371	-177.381	-1.007.477
300 MVA		38.583	-69	-186.579	-1.511.216
500 MVA		99.581	0	-209.974	-2.518.693

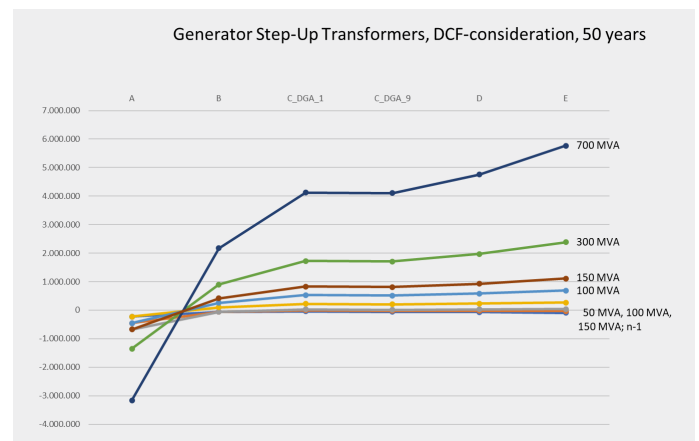
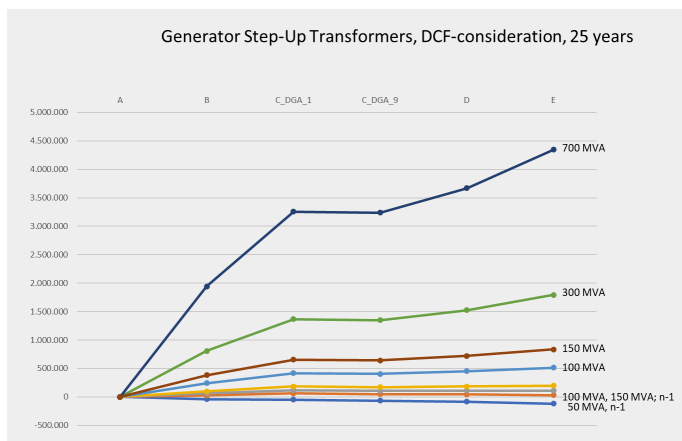
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Picture 7: Financially more and less beneficial Service Levels for substation transformers, 25 years and 50 years evaluation

The main financial benefit is that potentially high unplanned OPEX are shifted to the planned OPEX budgets.



Picture 8: Benefits (DCF, EUR) for various kind of redundant GSU transformers for maintenance strategies A) to E), DCF evaluation period of 25 years (Left) and 50 years (Right)

For 25 years and smaller transformers on distribution level preventive measure may stay at the minimum (Service Level A). For bigger ones Service Level C is appropriate.

For a period of 50 years Service Level C makes also sense for smaller substation transformers. For the big one's full-scale online monitoring system make sense.

Due to the remaining risk of failure (see VI. and VIII.) effective emergency processes are key to further reduce the risk exposure of the transformers.

The main financial benefit is that potentially high unplanned OPEX are shifted to the planned OPEX budgets. This is an "insurance-like" approach.

This is an 'insurance-like' approach.

Generation: Financial evaluation, Discounted Cash Flow/DCF Full scale Online Monitoring mostly makes sense

Financial evaluation of service levels for GSU transformers:

Rating	Time frame	25 years: Risk exp. 34,5%/142% of new		50 years: Risk exp. 34,5%/142% of new	
		Best/DCF	Worst/DCF	Best/DCF	Worst/DCF
n-1	50 MVA	4.658	-45.937	-37.952	-225.545
	100 MVA	62.379	0	-2.753	-451.090
	150 MVA	120.100	0	37.020	-676.636
w/o n-1	50 MVA	195.460	0	264.393	-225.545
	100 MVA	514.896	0	687.771	-451.090
	150 MVA	834.331	0	1.111.149	-676.636
	300 MVA	1.792.639	0	2.381.284	-1.353.271
700 MVA	4.348.124	0	5.768.309	-3.157.632	

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Picture 9: Financially more and less beneficial Service Levels for GSU transformers, 25 years and 50 years evaluation

Discussion of Maintenance Strategies for Generator-Step-Up-Transformers

It is assumed that power generation companies are mostly non-regulated companies. Energy sales are their most important source of profits. The average Global failure rate for Generator Step-Up transformers (GSU) is 0,95% p.a. /1/, along the entire cycle /1/.

The „n-1 principle“ is rarely applied only to smaller GSU in the area of renewable energy applications. The Costs-of-Energy-not-Supplied (CoENS) is the dominating risk in case of GSU failure. Also the doubling of the major failure rate in comparison to substation transformers is a risk driver. Further additional costs for the necessary re-routing of energy and re-dispatching in case of failure need to be taken into account during the risk assessment. The same applies for the impact of incentive and malus payments due to the applicable customer contracts.

As result the risk exposure of GSU's is significantly higher than for comparable network transformers. The benefits and resulting DCF of transformer maintenance strategies (A) to E) have been computed for various types of GSU transformers. The following diagrams display the benefits for GSU transformers. DCF evaluation periods of 25 years and 50 years (see picture 8) have been computed.

The modelling shows that applying preventive measures pay for almost all kind of GSU transformers with the exception of very small and redundant assets. Mostly, the accumulated costs for risk mitigation are far less than the corresponding risk exposure. The modelling for 50 years shows a similar picture. The generated DCF is mostly positive for Service Levels C to E (see picture 9).

The background for both mainly is the mitigation of the CoENS-related risk. The risk mitigation efforts are somehow neglectable in comparison with the CoENS-related risk exposure in most cases.

In summary the Service Level C appears as the most feasible maintenance strategy for smaller GSU's. For GSU's of 100 MVA and bigger Service Level E including full scale online monitoring is feasible (see picture 9).

Due to the remaining risk of failure (see VI. and VIII.) effective emergency processes are key to further reduce the risk exposure also of the GSU transformers.

The main financial benefit is the increase of energy sales. These are enabled by the higher GSU availability as result of the preventive and risk mitigating measures.

Output Oriented Maintenance Strategies

In the following it is described how the Service Levels A to E (see VIII) can be applied to well known maintenance strategies described in /2/ and entire power transformer fleets.

Reliability Centered Maintenance, RCAM

The goal is the maximum availability of the transformers, e. g. in the safety critical industries like the chemical industry or transformers of high relevance, e.g., GSU. There is a high-risk exposure of individual assets. Service Level E appears as the most suitable approach to maximize the transformer availability and risk mitigation.

Risk Based Maintenance, RBM

The focus is to achieve an acceptable performance and risk exposure of a group or fleet of assets. For this the acceptable fleet risk exposure needs to be assessed. The appropriate Service Levels needs to be defined per asset. This is an iterative process, starting with the most critical assets.

Condition Based Maintenance, CBM

Service Levels B to E can be considered as CBM for individual assets.

Time Based Maintenance, TBM

Services in fixed time intervals according e. g. to OEM or end user standards.





A holistic view on the transformer is key, instead of a view on individual components like OLTC or bushings only.

Corrective Maintenance

Reactive service in case of failure. This is similar to Service Level A (Emergency Services).

Typically, CBM, TBM and Corrective Maintenance are subsets of RCAM and RCM

Summary

Power Transformers are very reliable assets. However, the potential damage in case of major failures is very high. Benefits of and efforts for risk mitigation need to be well balanced. 5 graded Service Levels have been modeled to find the most suitable CAPEX/OPEX/TCO regime by addressing the main business drivers: Safety, Financial, Quality of Service, Reliability, Environment and how to embed them into an overall asset management strategy. A holistic view on the transformer is key, instead of a view on individual components like OLTC or bushings only.

The unavoidable remaining risks requires clearly defined emergency procedures, e. g. emergency agreement with the OEM, to minimize the impact of unavoidable remaining risks.

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