INTEGRATED TRANSFORMER FLEET MANAGEMENT (ITFM) SYSTEM

Audrius ILGEVICIUS
Maschinenfabrik Reinhausen GmbH,
a.ilgevicius@reinhausen.com

Alexei BABIZKI
Maschinenfabrik Reinhausen GmbH
a.babizki@reinhausen.com

ABSTRACT

The implementation of decision support for asset replacement and the maintenance of transformer fleet management is based on a technical risk score (Health Index) and criticality.

This paper describes the application of measurements obtained from online monitoring and regular diagnostic methods for identification of suspect transformers based on the Health Index (HI). The computer software system supports risk-based maintenance and replacement prioritization compliant with PAS 55(Publicly Available Specification for the optimal management of physical assets) and DIN VDE 0109. Initial field test results demonstrate the feasibility of this approach, and its application for asset managers to prioritize replacement decisions and improve maintenance programs. Data integration based on IEC 61970 (CIM) enables the number of APIs (application programming interface) between the software systems of different vendors to be reduced to a minimum.

The parameters obtained from online and diagnostic measurements are arranged into physical subgroups before calculating the overall HI of transformers.

INTRODUCTION

The management of transformer fleets with heterogeneous structures of different age, physical condition and importance requires a modern software system to assess the impact of the individual transformer on the performance of the whole fleet.

It is therefore important to detect irregularities and anomalies of equipment, by updating the HI with online monitoring data before failures occur. The following condition-based approach for transformer condition assessment is proposed [1, 2]:

- **Level 1:** online monitoring and online diagnostic (no outage required);
- **Level 2:** routine off-line diagnostic measurements (short outage required);
- **Level 3:** advanced off-line measurements (a longer outage required).

In order to make assessment of the transformers' condition economically viable data should be readily available via the software package In Level 1 the pre-processed data are based on both online monitoring and time-based online diagnostic data, such as oil temperature, load, DGA, oil condition, furan analysis, visual inspection or historical condition data. In Level 2 the condition based off-line electrical and dialectical measurements are applied. Finally, in Level 3 the advanced off-line measurements, like FRA, SFRA, PDC/FDS or vibroacoustics, are applied.

Depending on the HI-score, recommendations for the maintenance level are issued (see Table 1).

CONCEPT OF ITFM SYSTEM

The choice of the IT platform for the fleet management system is based on the following requirements:

- Ability to integrate different types of data: from online monitoring, offline diagnosis or historical data from different databases
- Ability to implement algorithms and models for statistical and reliability analysis
- Scalable database to handle large numbers of assets
- Capacity for display, visualisation and trending analysis of historical and online information
- Ability to meet IT cyber security requirements from the utility side

The main concept of the ITFM (Fig. 1) system is based on the integration of online data, continuous data from different sensors (e.g. DGA, OLTC, bushing, moisture) via Integrated Smart Module (ISM®), a transformer monitoring device, and the correlation of this information with the historical and offline data. This requires the implementation of some statistical algorithms and trending analysis to identify the condition of the physical parameters. Next, the database must allow the storage of data from online sensors, CSV or XML files with offline measurements or the manual input of information from visual inspection data.

The data model for the database must contain IEC 61970/61968 CIM-based structure [3]. The integration of online monitoring data considers IEC 61850 Ed.2 data objects for monitoring and supervision of equipment.

Finally, the results must be converted into meaningful information, (for the asset manager or maintenance engineer), such as the HI and risk index (RI) based on the colour-coding and numerical scheme

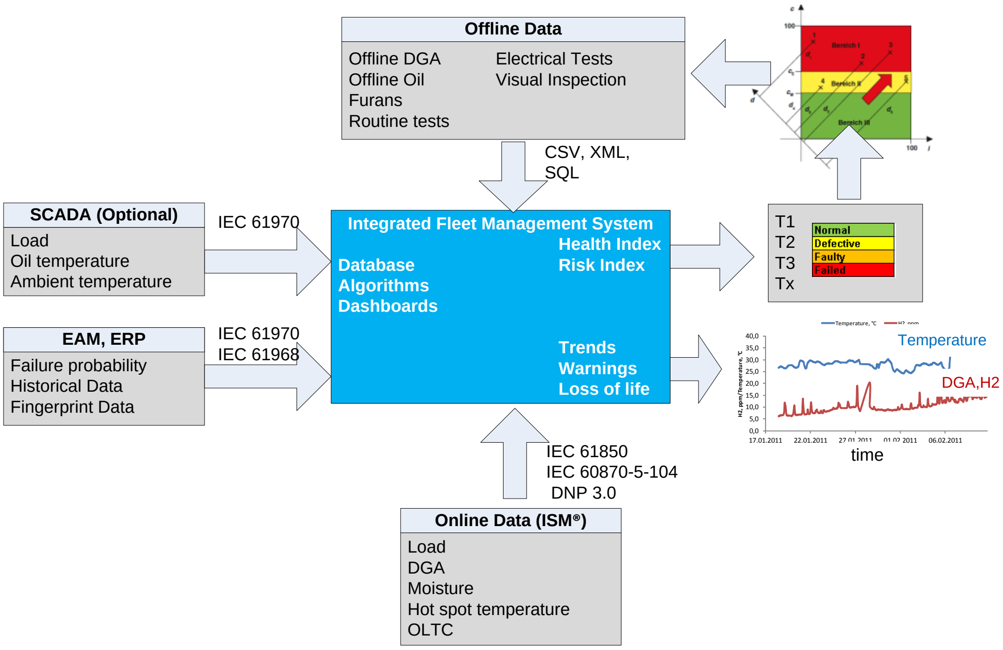

Fig. 1 Concept of ITFM System

DYNAMIC CONDITION ASSESSMENT OF TRANSFORMER FLEET

The main challenge in assessing the transformer's condition is estimating the HI based on the online monitoring data and the regular diagnosis data from oil analysis and electrical measurements. Furthermore, the HI must be related to probability of equipment failure. Figure 2 shows the main steps in the transformer condition assessment. In steps 4 and 5 the required interface for the input of ISM®, offline diagnosis and further simulations should be considered.

Transformer failure modes

In the first step the statistical information on historical failure modes is collected. The examples of such failure modes are:

- Mechanical
- Thermal
- Dielectric
- Tap changers
- Bushings
- Accessories

The advantage of such a structured condition assessment approach is that it allows for better tuning of individual failure modes to the probability of failure using weighting factors. The information about the failure rates and how they are distributed between the transformer components can be obtained, for example, from [4].

Failure indicators and condition parameters (online and offline parameters)

The second step is identifying which failure indicators and condition parameters, indicate the failure modes. In the ITFM Tool there are more than 100 condition parameters together with the transformer design, maintenance and operation, location of installation and accessories. The following online monitoring data can be used in the algorithm:

1. *Active part:*
   - DGA
   - Moisture in oil,
   - Moisture in paper,
   - Hot spot temperature,
   - Aging rate
   - Oil level
2. *Bushing*
   - Leakage current,
   - Capacitance,
3. *Tap Changer*
   - Temperature,
   - Motor torque,
   - Contact wear
   - Vibroacoustic

Condition parameters (CP)

Condition parameters like DGA, Oil tests or historical data are converted to a score of dimensionless unit (Fig.3). By comparing the physical parameters with the thresholds from international and national standards and

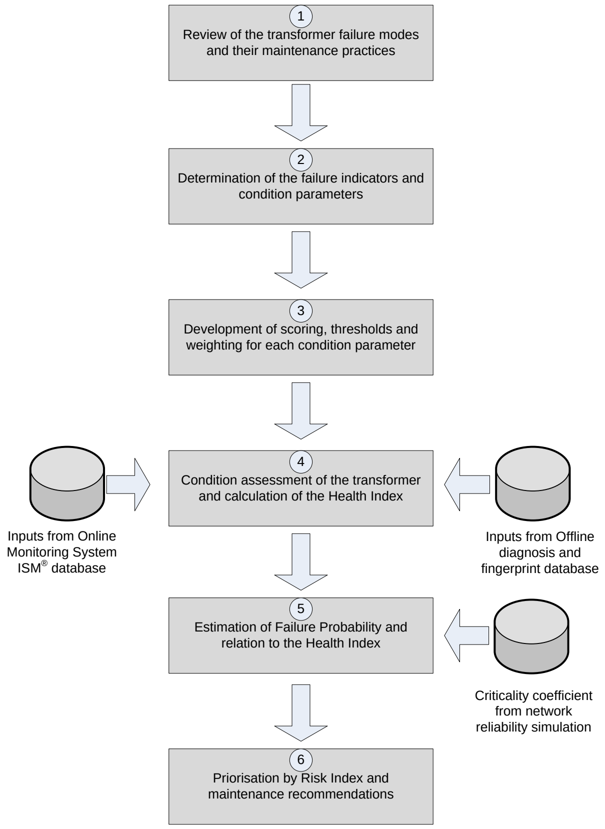

Fig. 2 Main steps of transformer condition assessment

field experience, the scoring values are obtained. The score of individual results is discreet and coded using classification system from 0 to 3 (where 0 is normal condition and 3 is a faulty condition: see Fig. 3).

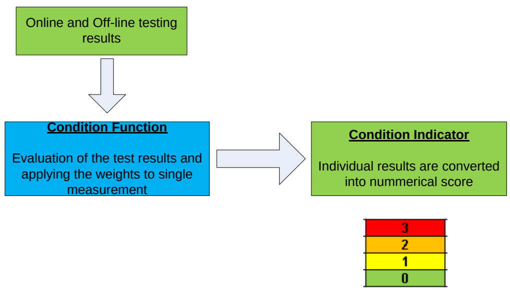

Fig. 3 Conversion of test results into numerical score

Calculation of the Health index for a Transformer

After the first evaluation of the individual condition parameters, they are classified into the following risk groups (Fig 4):

1. Mechanical condition including active part and windings
2. Thermal or solid insulation condition (aging of insulation)
3. Dielectric condition (Oil and DGA results)
4. OLTC condition
5. Bushing condition
6. Cooling System condition
7. Tank and accessories condition
8. Historical Reliability

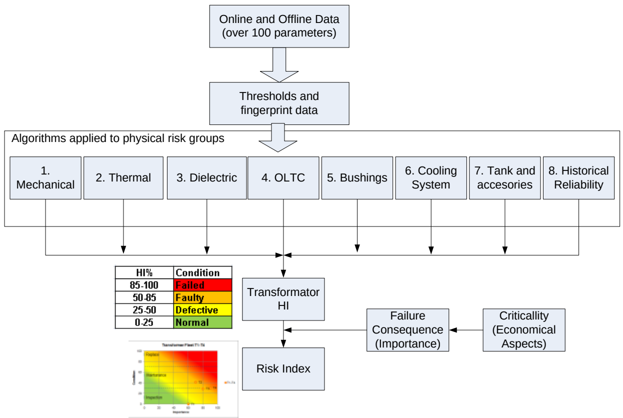

Fig. 4 Structure of transformer failure risk assessment

As mentioned above, the risk groups are based on the transformer failure modes. In each of the risk groups, weighted individual condition parameter scores are averaged to the risk group parameter score (RPS).

The RPS is calculated according to the following equation [5]:

$$RPS = \frac{\sum\limits_{n=1} (WCP_n \cdot CP_n)}{\sum\limits_{n=1} (WCP \cdot CP_{\max})} \qquad (1)$$

Finally, the HI is then calculated according the following equation:

$$HI = \frac{\sum\limits_{m=1} (WRPS_m \cdot RPS_m)}{\sum\limits_{m=1} (WRPS_m \cdot RPS_{m,\max})} \cdot 100\% \qquad (2)$$

Here the *WCP* and *WRPS* in the Eq 1 and 2 denotes weighting coefficients of CP and RPS respectively.
The Health index is normalized between a score of 0 (new) and 100 % (failed) or from 0 to 1 on a linear scale. The condition value can be any number in between.
In case of the HI score >30%, the linear Pearson's correlation between the single condition parameters and

risk groups is made:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)\sigma_x \sigma_y} \qquad (3)$$

Based on the correlation coefficient r the maintenance recommendations are made.

When aggregating the individual parameters to the risk group score (RPS) and further to transformer HI, it is important that the failure of one critical parameter should lead to the total HI approaching 100% (failed). This is achieved using the non-linear approach, where the weighting of the condition parameters of a specific risk group depends on the score of a particular condition parameter. However, not all the condition parameters lead to transformer failure. In order to model the criticality or impact of the condition parameter to the overall transformer condition a probability method must be applied. One of the possible approaches is the application of the Bayesian conditional probability rule [5]. Based on the transformer fault three, a complex Bayesian Network representing all input variables can be built and the aggregation of the condition parameters to HI according to Bayesian formula is made.

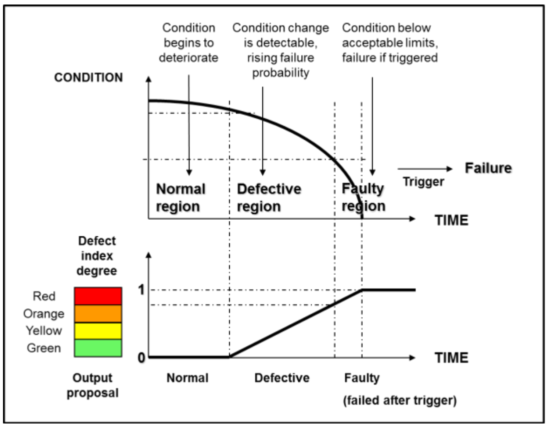

Fig. 5 Condition development in time (top) and condition coding (bottom)

Table 1

Health index	Colour	Condition	Recommendation
85 < HI < 100		Failed	Emergency replacement
70 < HI < 85		Faulty	Replacement on short term
50 < HI < 70		Defective	Increased diagnostic testing / repair action required / Level 2,3
30 < HI < 50		As good as new	Normal maintenance / Level 2
0 < HI < 30		New	Normal maintenance / Level 1

The interpretation of the HI is presented in the Fig. 5 and Table 1, recommended by Cigre Working Group A2.44 (D10) [6], can be referred to the condition (probability of failure) or to the maintenance action required . However, the link between maintenance action and the condition is very specific and depends on respective company policy.

Estimation of failure probability and relation to the Health index

Once the HI of the transformer is determined, its effective age can be determined from the relationship between the probability of failure and its HI. The relationship between the health index and the fault rate is shown by the probability of failure curve in Fig. 6. The coefficients A, B and C are calculated in the equation (4) from the failure rates of the equipment components [7].

$$\lambda(HI) = A \cdot \exp(B \cdot HI) + C \qquad (4)$$

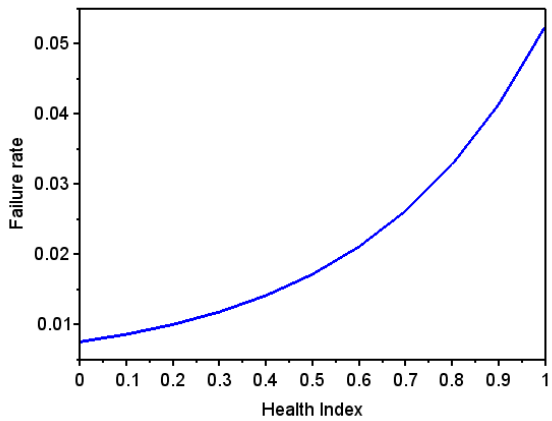

Fig. 6 Health index relative to probability of failure

Prioritization by risk index and maintenance recommendations

The risk score or index can be formulated as follows:

$$Risk\ Index = \lambda \cdot CC \qquad (5)$$

where: CC – criticality coefficient

In the formulation (5) above the term λ probability of failure denotes the technical condition of an asset, also identified as HI from 0 (normal) to 100 % (failed), while the criticality coefficient *CC* from 0 (unimportant) to 100 % (high importance) includes economic factors related to the loss of power delivery, systems stability, repair or penalties.
From the risk score, a risk matrix with the maintenance strategy can be created including the prioritization of maintenance activities.

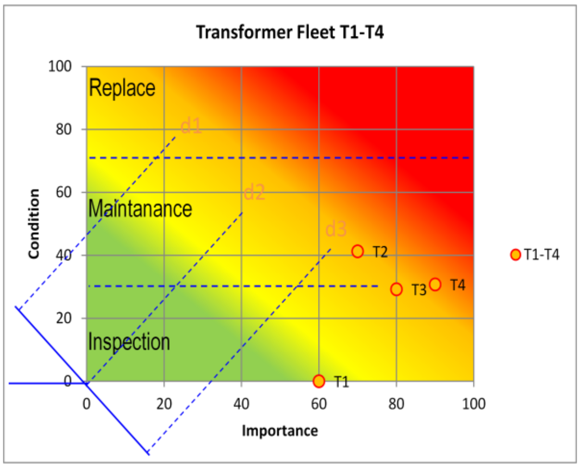

Fig.7 Transformer fleet maintenance prioritization

The maintenance prioritization order in Fig. 7 can be calculated from the distances d1-d3, considering 45°C shift of the d axis with respect to the ordinate. The following order of transformer maintenance is calculated: T4, T2, T3 and T1.

RESULTS FROM THE FIELD

The example for the evaluation of transformer fleet of 4 transformers (220/66 kV, 100 MVA from different manufacturers and of different age, from 8 to 40 years) and its components is shown in the Fig. 8.

The algorithm was applied to calculate the condition of each transformer node (risk of failure) and the total HI of each transformer. It can be seen that transformer 2 has the worst HI value due to load history (overload), which possibly lead to the overheating of the solid insulation (ratio of CO2/CO > 11). The same applies to the transformer 3, where the ratio of CO2/CO > 18. Here, the correlation between the loading, top oil temperature and DGA results was applied. The transformer 4 was benchmarked with the HI of 31% due to old age (over 40 years) while transformer T1 is the newest with the age of 8 years and was benchmarked with the best condition.

	Dielectric and thermal	Mechanical condition	Thermal condition/solid	Accessories 1 condition	Accessories 2 condition	Design/Reliability/Load	Total HI:
Trafo 1	0%	0%	0%	0%	0%	0%	0%
Trafo 2	19%	0%	43%	0%	0%	50%	41%
Trafo 3	10%	0%	43%	0%	0%	33%	29%
Trafo 4	0%	0%	0%	0%	0%	50%	31%

Fig. 8 Overview of transformer fleet evaluation

CONCLUSIONS

The paper presents an IT-based tool for transformer fleet management considering online monitoring data and off-line data. The advantage of this approach is that the monitoring system based on ISM® technology enables any anomalies in the transformer fleet to be detected before the components become defective. The HI is related to the probability of failure where different properties of the transformer (mechanical, dielectric, thermal, OLTC, bushing, cooling system and accessories) are considered separately as risk groups.

Linear correlation between individual condition parameters and between risk groups is applied in case the HI or failure risk indicates defective condition (>30%).

The most challenging issue is the Health index aggregation, where non-linear or Bayes probability methods must be applied in order to accurately calculate the effect of individual condition parameter on the HI.

Finally, the IT and data security issues must be considered when integrating the tool in the utility IT or asset management environment. Much of the input data of the tool comes from online sensors and is of confidential nature. Therefore, integration of monitoring data into IT environment must comply with utilities IT and data security policies.

REFERENCES

[1] W. Fleischmann, T. Krüger, A. Ilgevicius, Maschinenfabrik Reinhausen GmbH, 3rd International Colloquium Transformer Research and Asset Management, Split, Croatia, October 15-17, 2014

[2] CIGRE Working Group 2.34 – Guide for Transformer Maintenance

[3] CIGRE Technical Brochure 227: "Life management techniques for power transformer", WG A2.18, Paris, 2003

[4] S. Tenbohlen, et.al, XVII International Symposium on High Voltage Engineering, Hannover, Germany, August 22-26, 2011)

[5] CIGRE Technical Brochure 248: "Guide on economics of transformer management" Working Group A2.20, Paris, 2004

[6] R.E. Brown, Failure rate modelling using equipment inspection data, IEEE Trans.Power Systems, Vol.2, May 2000, pp.782-787

[7] CIGRE Technical Brochure: "Guide on transformer intelligent condition monitoring system" Working Group A2.44. Draft 10, 2014