Power transformers diagnostic

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Abstract
This paper presents main ideas of power transformers diagnostic. Talking about diagnostic we must understand that fault diagnosis and finding of fault location are affined fields. The fault diagnosis is based on electrical measurements, oil chemical analysis and certainly dissolved gas analysis evaluation.

Keywords
Power transformer, diagnostic, determination of technical condition, useful lifetime, fault location, fault diagnosis.

Introduction
Power transformers are required throughout modern interconnected power system. The size of these transformers ranges from as low as a few kVA to over a few hundred MVA, depending on system loading. Its average existing age could be varying between 20 and 40 years. However, the in-service failure of a transformer is potentially dangerous to utility personal through explosions and fire, potentially damaging to the environment through oil leakage, is costly to repair or replace and may result in significant loss of revenue.

The electric transmission and distribution challenge are nowadays affected industry. Concepts of power transformer life extension, increasing loading and reduced maintenance costs are often discussed. These ideas at first appearance are contradictory, but all strive for the same results – to reduce operating costs and improve reliability in the delivery of electricity to consumer.

Power transformers are the single largest capital item in substations, comprising almost 55 percent of the total belonged equipment investment. The utility expenditures associated with this investment in acquisition, installation, operation and maintenance typically do not reflect the relevance of this investment. The cost of premature and unexpected failure of one of these assets can be several times more than the initial cost of the power transformer.

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Is important to take into account that the technical condition of power transformer base in the time of slow rates of reestablishing and replacement of out-of-resource power transformer can become a source of threat for power safety of the region and of country overall.

The useful lifetime extension of power transformers is prior moment in the maintenance. It can be done basis on diagnostics results, modernization effectiveness and using of new technical condition prognosis methods. Certainly, the decision of extension useful lifetime is accepted for each power transformer separately. The conclusion about the extension of power transformer resource should be accepted on the basis of careful inspection of technical condition, estimation of insulation aging, detection and elimination of failures.

1 Main technical condition principles

The most appropriate life assessment should concentrate on factors, which directly influence the life of the transformer – insulation life. A relative comparison of the transformers is an alternative to remaining life determination, which involves many uncertain assumptions.

Power transformer useful life involves several mechanisms of degradations. The life of a transformer may be introduced as the change of its condition with time under impact of thermal, electric, dielectric, chemical, electromagnetic and electrodynamics stresses, as well as under the impact of various contamination and aging processes. Technical life of a transformer maybe thought as of several components:

- “Dielectric Life”- life span up to critical reduction of dielectric margin of insulation.
- “Thermal Life”-time up to critical decomposition of winding conductors insulation, e.g. DP ≤ 250
- “Mechanical life”-up to critical mechanical weakness and deformation of windings under cumulative stresses of through faults, in-rush currents, vibrations.
- “Life of accessories”, especially bushings and LTC, which sometimes can be shorter than complex life of active part of a transformer.
Service experiences give motives to conclude that many failures occur just due to aging phenomena. However statistics available has not exhibited yet correlation between number of failures and transformer years [4]. Average age of failed transformer is still between 20-22 years. Contribution of generation “more than 25” is becoming more weighty, however there has been experienced also a number of failures of new equipment. There is still little information available about the units that have failed primarily due to thermal degradation of insulation material.

In fact “Dielectric life” is shorter than “Thermal life” due to critical effect of oil aging products resulting in reduction of dielectric withstands strength of oil and degradation of surface strength. The quality of insulation oil has impact on power transformer reliability. It affect on power transformer withstand in maintenance. For new power transformer, its useful lifetime and quality of construction are expected like is shown in Fig. 1. The withstand stress of a power transformer decreases with time as the insulation system ages. The aging of the insulation system reduces both the mechanical and dielectric withstand of the power transformer. Unfortunately the applied stress tends to increase with added load or reduced protection over time [2].

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**Fig. 1. Power transformer normal expected useful lifetime**

Fig. 1 shows the normal useful lifetime of a power transformer which has been able to withstand the periodic accidental faults on the system. Load has grown gradually and withstand decreased due to normal aging. Finally, at the end of lifetime, the power transformer hasn’t withstand operating or fault stress, which in many cases is greatly higher than the original designed for stress (real stress zone).

### 2 Investigation of technical condition

First of all, each specialist must be with a good experience in diagnostic, fault prognosis and schedule of energy system should be able for analyzing and technical data storage. There must be clear difference between real existent situation and theoretic power transformers operating possibilities. The end of lifetime is presented as 95% of accumulated life loss and 5% as remaining design life left [3].

Power transformer age and end of life has a poor correlation. There is example of one power transformers producing year group, which were under diagnostic during maintenance, see Table 1. In Table 1 diagnostic results (measurements) for 3 different transformers (results in each column from top to bottom) are given.

**Table 1. Power insulation diagnostic results**

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<tbody>
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<td>Rabs tg δ</td>
<td>1.66 0.33</td>
<td>1.68 0.46</td>
<td>2.0 0.32</td>
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<tr>
<td>2.17 0.45</td>
<td>2.0 0.53</td>
<td>2.98 0.29</td>
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<tr>
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<td>1.19 0.20</td>
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<td>1.13 0.21</td>
<td>1.31 0.24</td>
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<td>1.23 0.22</td>
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<td>1.06 0.23</td>
<td>1.59 0.49</td>
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<tr>
<td>1.81 0.52</td>
<td>1.88 0.58</td>
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Dielectric losses (loss tangent) and insulation measurements are shown in Table 1. It is necessary to detect correlation rate between both technical condition regulated values. For our investigation we took measuring results of power transformer produced in 1981. There are measuring results for main scheme i.e. high voltage winding.
Fig. 2. is constructed for visual imaging of insulation absorption rate and dielectric loses during maintenance. It is good visible example of correlation checking.

**Fig. 2. Insulation absorption rate (Rabs) and dielectric loses**

The second measuring point from the beginning has done after power transformer tackle and switching on to energy system.

For checking on practice, in engineering, of correlation theory between two factors we built the Fig. 3.

**Fig. 3. Correlation between Rabs and \( \tan \delta \)**

Increased dielectric loses follows with decreased absorption rate of solid insulation and it is the maintenance theoretical rule. It means that between them negative linear correlation has place to be. In our case we have linear positive correlation both those two factors to maintenance time period, and between itself. The last one explains by improvement and modernization works in maintenance of power transformer.

**Correlation rate is** \( r = 0.904053 \), which indicates that between marks exist intent positive linear relevance. The relevance and density of those technical condition’s factors for each power transformer can be different.

The replacement of each power transformer is calculated individually, not chaotically. It is very easy to replace the existing transformer for the new one (the same rated power), but during replacement we must take into account the customers’ possible marketable power in the service area of the concrete transformer substations. Example of replaced high power transformers of some energy transmission company is shown in Fig. 4.

**Fig. 4. Replaced HV transformers quantity**

### 3 Power transformers problems and faults

Power transformer faults can occur as a result of different causes and conditions. In most cases the transformers faults defined as [5, 6]:

- any forced outage due to transformer damage in service (winding damage, tap-changer fault);
- problems that requires removal of the transformer for return to a repair facility, or which requires extensive field repair (excessive gas production, high moisture levels).

Transformer failures can be broadly categorized as electrical, mechanical or thermal. Transformer faults can be internal and external, as mentioned in Table 2. In addition to failures in the main tank, failures can also occur in the bushings, in the tap changers or in the transformer accessories. In addition to normal aging, a transformer may develop a fault that results in faster than normal aging, resulting in a higher probability of failure.

Power transformers have proven to be reliable in normal operation with a global failure rate of 1-2 percent per year. The end of life of power transformer is typically defined as the loss of mechanical strength of the solid insulation in the windings.

A survey reports that the main causes, it is 51% of transformer failures in a five year period, were due to the following problems [7]:

- moisture, contamination and aging which caused the transformer’s internal dielectric strength to decrease,
- damage to the winding or decompression of the winding under short circuit forces,
- damage to the transformer bushings caused by loss of dielectric strength of the internal insulation.

**Table 2. Causes of transformers faults**

<table>
<thead>
<tr>
<th>Internal</th>
<th>External</th>
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<tbody>
<tr>
<td>Insulation deterioration</td>
<td>Lightning strikes</td>
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<tr>
<td>Loss of winding clamping</td>
<td>System switching operations</td>
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<tr>
<td>Overheating</td>
<td>System overload</td>
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<tr>
<td>Oxygen</td>
<td>Systems faults (short circuits)</td>
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<tr>
<td>Moisture</td>
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<tr>
<td>Sludge/solid contamination in the oil</td>
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<tr>
<td>Partial discharge</td>
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<tr>
<td>Design/manufacture defects</td>
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<tr>
<td>Winding resonance</td>
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</table>

Another survey done by CIGRE working group on failures in large power transformers [5] found that about 41% of failures were due to on-load tap changers (OLTC) and about 19% were due to the windings. The failure origins were 53% mechanical and 31% dielectric.

On transformers without on-load tap changers 26.6% of failures were due to the windings, 6.4% were due to the magnetic circuit, 33.3% were due to terminals, 17.4% were due to the tank and dielectric fluid, 11% were due to other accessories and 4.6% were due to the tap changers.

Fault investigation is a major issue of power transformer maintenance. The results are the basis of a trade-off decision to continue operation, re-energize the protection-tripped transformer after treatment, partly/fully repair or replace the failed transformer. For instance, the fault could be an unintentional core ground that can be eliminated using the “sledge hammer” method, or a through-fault (fault occurs outside the transformer but induces very large currents through the transformer windings) that may or may not harm the transformer too much. Fault location can help identifying these kinds of fault by discriminating between “core fault” and “winding fault”, thus provide the decision-making support for maintenance engineers.

### 4 Diagnostic and condition evaluation

A condition evaluation program should include the following levels:

- Level 1- Transformer Engineering Analysis
- Level 2- Internal and External Field Inspections
- Level 3- Testing and Diagnostics

Each of these steps has several elements, which facilitate the benchmarking process. These elements can also identify defects or deficiencies, some of which may be reversible and possible lead to transformer life extension or improved load capacity. It is important to understand that some assumptions will need to be made about design elements, sizes, materials and condition of components in the Level 1 analysis. The purpose of level 2 and 3 is not only to perform the required inspection and tests, but verification of the prior assumptions must be made at that time.

**Fig. 5. Technical condition evaluation**

The level 1 consists of four main subgroups: design, operating environment, usage, historical tests and diagnostics. The level 2 consists of two main subgroups: internal and external examination. The level 3 consists of two examination groups:

1. Dissolved Gas Analysis (DGA), moisture in oil, power factor (Dissipation Factor), magnetizing current, winding resistance, frequency response analysis (FRA), discharge detection and location, furan is a colorless toxic flammable liquid or gas used in the synthesis of nylon (predicted DP);
2. Leakage reactance/impedance, turns ratio, insulation resistance, moisture level in paper insulation, degree of polymerization, vibration, location of sensor, infrared scan, return voltage method (RVM).

The quantity of electrical measurements for full diagnostic is determined depending on testing laboratory conclusions.
Conclusions

All this, before mentioned in paper information, has influence on choosing of accurate maintenance strategy and technical conclusion making. But it is not enough to make decision for remaining lifetime prognosis and extension of useful lifetime. For that reason, technical staff must estimate each power transformer separately, in view of performed modernization works. Technical information and history should be stored. Determination methods of power transformers’ technical conditions are normally applied.

The diagnostics specialists and engineering personal is needed to realize main idea: to extend power transformers useful lifetime with minimum/rational resource involvement and recheck substations rated power needs, in case of necessity.

There is no single scientific method available to determine the condition or end-of-life of an operating power transformer. Experienced engineers, chemists and technician are required to conduct analysis, test, inspections and review historical data to help form the decision. The combination of analytical, inspection and testing methods, when used together help form a complete picture of the condition of a specific unit or groups of units in service. The results of the proposed condition evaluation benchmarking program will help significantly in directing future condition-based maintenance and possible dynamic loading of these transmission and distribution assets.

References