Increase transformer reliability and availability: From condition assessment to On-Site Repair.
1. Abstract
Over the last decade there has been a renewed and increased interest in transformer life evaluation and monitoring. The main reason is that a large number of the transformers world population is approaching its expected end-of-life and the need increases for better methods to see whether the transformers are still fit for use or need to be retrofitted or replaced.
In this article we describe a methodology for evaluating transformers. It is an adaptable three-step evaluation approach. Each step addresses different size of population, business needs and ambition levels defined by the asset owners.
Output of such a condition assessment survey is a ranking of the population with priorities for investment and recommended maintenance actions plan for each unit.
Such advanced diagnosis of the transformer condition is used to identify defects before even untanking the transformer and therefore is from great support in order to speed up repair time especially in the case of On-Site Repair.

Normal maintenance and retrofit of a power transformer not requiring winding replacement or other major step of action is normally performed at site. However, when a major repair is required, the failed unit is normally transported to a transformer factory where the required space and equipment is available.
For a large transformer and when the distance to the transformer factory is long the transportation time will have a major influence on when the transformer can be put back in service and the capacity can be restored. Also the cost and risk of such a heavy transport has to be considered.

Since some years ago ABB started to develop processes to perform also major repair, including replacement of windings and repair the core at site. In total some 200 units including utility, industrial and HVDC transformers and reactors have been repaired until to today. In may cases together with an upgrade of the unit to an increased rating.

By introduction of state-of-the-art technology in combination with extensive experience On-Site Repair can today offer even greater speed, minimizing the outage time of the transformer, unavailability of the power supply and the loss of revenues for the owner.
2. Introduction

How to keep aged assets up running at a minimum Total Cost of Ownership while ensuring a requested reliability?

This question is the challenge that each and every asset manager face in his daily work. Transformers are a large part of the asset cost structure of the power system. With increasing financial pressure on utilities, the trend is to use existing units as long and hard as possible without putting the reliability of the system at risk. For critical transformers, the consequential cost of a failure can easily exceed the value of the transformer itself by one or two orders of magnitude.

In this perspective, assets managers are exposed to solving a complex equation that involves both technical and economical criterions. The capability to make a correct condition assessment of the equipment is essential to meet the goals of maximizing return on investment, reducing costs associated to possible loss of production [1] and lowering total Life Cycle Costs.

Transformer asset management, which relies mainly on condition assessment study outputs combined with financial evaluations, will then be the main decision driver in future planning and budgeting either for maintenance strategy, retrofit or replacement purpose.

To fully gain the advantages of the condition assessment of the assets any measures required should be performed in as short period of time as possible. The development of processes to perform also advanced repair and retrofit at the site has made it possible to now reduce the down time in such cases considerably.

3. Understand the status of the assets: Condition Assessment

A statistical approach based on international figures about transformer reliability is useful in a first step to setup rough maintenance and investment budgets. However, ABB’s experience shows that each unit should be considered as a specific case once the user need to decide about precise maintenance actions or wants to take solid decisions to relocate, retrofit or replace the unit by a new one.

The method presented here is a modular approach to meet different levels of expectation defined by the end-user in term of population’s size, level of information requested and budget available.

The strategy we have taken for the evaluation is to identify the most critical transformers and use a fast screening to reduce the number of concerned units to be studied closer. The
ambition level will then judge how deep the investigation should go. Our evaluation approach has been to make the evaluation in steps [2]. It is not necessary to spend efforts on units that are very well suited for their purpose or which looks to be in a very good shape. The steps are normally linked together in order to reuse the information gained in an earlier step. The assessment methodology is then based on the three steps described below:

- **Step 1: Fleet screening**
  This is a quick scanning of a large population (20 – 200 units) using easily accessible data such as name plate data from the units, oil and dissolved gas in oil data, load profile and history of the unit (maintenance, operation and events).
  One idea with this step is to reduce the number of units, which could be of interest for further deeper studies. All units that look normal do not need to be treated further. This also means that the ambition level is reduced.
  Only factors available fast and easily, are used at this step, however the evaluation methodology is based on our transformer engineering expertise and previous cases performed. One does not use the extra information, which could be extracted from the relations between the factors. They are treated as separate and independent factors.
  The evaluation is directed towards a relative comparison (ranking) among several transformers. Units are ranked according their strategic importance in the network (cost of energy not delivered, cost of repair / replacement, consequential damages) versus their assessed condition.
  This first step provides higher-level management and asset managers with a cockpit view of their assets as shown on Fig. 1. It gives relevant inputs for maintenance or investment budget strategy. It is also used to select units that must be further investigated either because they are strategic units or because they are in a critical status.

Fig. 1: Example of a transformer population ranking

*Energy 21C*
*Sydney, 2007*
Step 2: Normal evaluation

The experts here focus on a smaller number of units (10 to 20 units) identified during step 1. The normal evaluation step needs more information. It uses the results from the screening evaluation, but adds some calculations, site inspections and measurements. Experts use modern design rules and tools to evaluate the original design. Advanced diagnosis tests [3] are performed (DGA, Furanes, Frequency Response Analysis, Dielectric Response, Partial Discharge) to assess each of the main properties of the transformer in a structured way: mechanical status, thermal status and ageing of the insulation, electrical status of the active part as well as the condition of the accessories such as tap changer(s), bushings, over-pressure valves, air-dryer system, pumps and relays.

In terms of serviceability the end user gets richer information since a ranking is done on different criteria for each of the key properties. For example a transformer could be suitable to withstand overload but not short circuit.

Taking into account the results of this detailed assessment, the experts elaborate for each unit an action plan to improve each key properties and as a result their overall reliability.

Assets, maintenance and operation managers take full benefits of this second part of the survey. Valuable inputs (see Fig. 2) - such as a list of spare parts to be kept in stock, a list of maintenance actions to be done at site with clear priorities, proposals to relocate or de-load units, to repair or change for new - will help them strengthening their daily decisions with solid understanding and explanations.

<table>
<thead>
<tr>
<th>Unit #</th>
<th>Mechanical</th>
<th>Electrical</th>
<th>Thermal</th>
<th>Accessories</th>
<th>Overall</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFO 2</td>
<td>Winding</td>
<td>Arcing</td>
<td>Heating</td>
<td></td>
<td>95</td>
<td>Visual Inspection and repair in factory / rewinding</td>
</tr>
<tr>
<td>TFO 5</td>
<td>Tank</td>
<td></td>
<td>OLTC heating</td>
<td></td>
<td>80</td>
<td>Repair on site and OLTC overhaul</td>
</tr>
<tr>
<td>TFO 1</td>
<td></td>
<td>Aged oil</td>
<td></td>
<td>Bushing</td>
<td>70</td>
<td>Oil regeneration / filtration and advanced diagnosis / change HV bushing</td>
</tr>
<tr>
<td>TFO 6</td>
<td></td>
<td>Arcing</td>
<td></td>
<td>Thermometer</td>
<td>50</td>
<td>Exchange TopOil - thermometer / on line monitoring of DGA</td>
</tr>
<tr>
<td>TFO 3</td>
<td></td>
<td></td>
<td></td>
<td>Silicagel</td>
<td>40</td>
<td>Exchange Silicagel</td>
</tr>
<tr>
<td>TFO 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>Standard maintenance actions and controls</td>
</tr>
<tr>
<td>TFO 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>Standard maintenance actions and controls / 10 % overload capabilities</td>
</tr>
<tr>
<td>TFO 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>Standard maintenance actions and controls / 15 % overload capabilities</td>
</tr>
</tbody>
</table>

Fig.2: Result of a condition assessment survey step 2 (Normal evaluation) on eight transformers
• Step 3: Expertise

This last step uses the data from step 2 but adds some more data and extra analysis (Fig. 3). The number of units to be further analyzed is usually limited to two or three out of a population of 100 units. International experts are involved using state of the art simulation tools to perform thermal simulations such as hot spot and ageing, mechanical calculations such as short-circuit withstand and electro-magnetic field computations.

![Chart illustrating the organization of the advanced and expert step also using the influence between the factors.](chart)

The goal is then to define weak points of the units that need to be improved in order to meet defined serviceability constraints.

The assessment is here very detailed and provides a deep evaluation of each main properties including remaining life time and risks in operation.

This third module within the assessment process provide accurate information to the end-user’s engineering manager that want to overload a transformer, upgrade a unit to increase its nominal power [4] or voltage rating, or extend its life time. It could also be used to understand root causes after failures and support decisions related to the possibility of a workshop or an On-Site Repair [5].
4. On-Site Repair of Power Transformers

As discussed above the increased age of the installed base of transformers has increased the interest for assessment of the condition of the transformers. The above described program for condition assessment will assist the owner of the transformers to take early measures to prevent failures that may require an extensive repair or a replacement of the transformer. However with the aging stock of transformers also the failure rate of transformers will increase and create an increased demand for repair or replacement of units. The result of the condition assessment and a required increase of production or transmission of power may also lead to decision to upgrade the rating of transformers. Such an upgrade will normally include replacement of the windings and insulation and also an upgrade of the cooling system.

A repair or of a power transformer not requiring winding replacement or another major action is normally performed at site. However, when a major repair or upgrade has been required in the past the transformer has been transported to a transformer factory where the required space and equipment were available.

For a large transformer the transportation will have a major influence on the time until the transformer can be put back in service and the capacity be restored. Such heavy transportation may also be very risky. In some cases it may not even be possible to get the transformer to a transformer workshop due to changes of the infrastructure that not any longer support the transportation of the heavy loads of large power transformers.

To reduce the outage time of a failed transformer and to solve the difficult cases when transportation is not possible, On-Site Repair offers a solution. It will save time and avoid risks of transportation damages. However, a repair of a large power transformer is a demanding process, requiring clean environment, highly qualified workmanship, an advanced drying process and verifying high voltage dielectric tests. Would all this be possible to fulfill at remote site far away from the well organized transformer factory?

In the middle of the ‘80-ties this was a challenge taken by ABB and some utilities for the first time. Since then the On-Site Repair concept has been developed to be an important alternative to increase the availability of transformers, power generation plants and substations.
Until a few years ago On-Site Repair was mainly performed by ABB in three countries, Brazil, Italy and Spain. Today it is a concept being developed to be applied globally. Since the successful first projects were performed some 20 years ago, more than 200 transformers have been repaired successfully on-site in 20 different countries.

4.1 The On-Site Repair processes
Power transformer factories and workshop are characterized by their orderliness, cleanliness and well controlled atmospheres which are conditions required for manufacturing and repair of high voltage equipment. They also possess heavy lifting equipment, special tools and fixtures, high voltage test laboratories and experienced and well trained operators for each step of the process.

To perform an On-Site Repair of a transformer, the same capabilities have to be set up at site to meet the individual circumstances of each case. The ABB On-Site Repair concept will include:

- As an On-Site Repair should be performed in a controlled environment it should be performed indoors, in a facility where the required levels of cleanliness and orderliness may achieved. The facility should as far as possible, allow for the performance of all critical steps of the repair inside the facility. If the customer does not have a repair area a temporary workshop will be set up.
- Heavy lifting equipment will be brought to the site. The largest transformers may require a capacity of up to 400 metric tons for untanking and tanking of the active part. If the customer possess a maintenance area the may be used for the repair an overhead crane may be available.
- The same type of tools and equipment as used in a factory are brought to the site and used for the repair.
- Maintaining the dryness of the insulation of highest importance for the result of the repair. Windings are manufactured at transformer factory and insulation components are vapor-phased prior to shipment. They are then specially packed to maintain the dryness and shipped for assembly at site.
- Following the complete assembly of active part it is tanked and prepared for final drying. The On-Site Drying process will reduce the moisture level to below 1 %. There are several methods available for On-Site Drying. To further save time of the repair a special method for On-Site Drying has been developed by ABB.
• High voltage test of the assembled transformer is carried out on-site according to the agreed test schedule. To meet the requirement of portability and flexibility an On-Site High Voltage test system has been developed together with a test equipment supplier.

4.2 Facilities for On-Site Repair

Temporary workshops

Based on the experience gained within the ABB Service centers that have performed On-Site Repair projects a maintenance shop owned by the customer is available for approximately 50% of the repair projects. Those may also be equipped with an overhead crane for lifting of active parts and winding blocks. For the remaining 50% of the projects it is necessary to set up a temporary facility. When a permanent facility is available at site to be used for the transformer repair should be separated from the rest of the facility to maintain the cleanliness required.

A temporary workshop may be set up based on a steel structure with a cladding of corrugated sheets of steel or aluminum. This type of building is primarily used when more that one transformer will be repaired at the same site or when there is a desire to keep the building for any future repair or maintenance.

Figure 4: A steel building used as temporary workshop by ABB in Brazil for On-Site Repair
Another very flexible solution is to use a large tent consisting of a steel structure and claddings of flexible sheet material such as PVC giving a tight facility where it is possible to keep an excellent environment for the work on the active part of the transformer. These types of tents may be set up in very short time, normally less than a week. They are also designed to withstand heavy wind severe weather conditions such strong winds and snow load.

![Figure 5: Typical tent structure that may be used as temporary workshop for On-Site Repair](image)

**Heavy lifting at site**

The major heavy lifting during repair of a core type transformer is the lifting of the active part for untanking and tanking of the transformer. The active part of the largest transformers may weigh up to 400 metric tons. To handle this weight, mobile compact lifting systems are available from global suppliers. For smaller transformers the lifting of the active part may be performed with mobile cranes which are also used for lifting of windings and other components for disassembly and reassembly of the active part and the transformer.

![Figure 6: Tanking of large power transformer using mobile lifting equipment](image)
4.3 The factory is brought to site

For achieving the same quality of repair at site as repair in factory the guideline for the ABB On-Site Repair concept is: “We bring the factory to site”.

That means that the repair should be performed in the same way at site as in the factory. The same processes, tools, fixtures and equipment shall be used as far as possible. For tools and fixtures this rule can normally be followed to 100%. When the factory processes or equipment may not be used and an alternative has to be applied, the same criteria for successfully performed process should be applied as in the factory.

One process used in factory which not is used at site is the drying of the active part using the vapor-phase process. However based on the experience and detailed investigations of the result from a large number of projects the drying result of the alternative processes used is fulfilling the required maximum level of moisture content. These alternative processes are described below.

4.4 On-Site Drying

Initially, all new winding blocks and the remaining insulating components internal to the transformer are submitted, while in factory, to Vapor Phase drying and oil impregnation processes. The oil impregnation is a protection against moisture intake when handling the parts. In addition all parts are specially packed or transported with special containers that are filled with dry oil or dry air. On site the new parts and the transformer are stored under controlled climatic conditions. Air drying units guarantee the best possible condition to prevent moisture ingress during the repair.

Once the repair is finished, an on site drying process is initiated after the assembly and tanking of the transformer’s active part. The on site drying includes a heating of the whole transformer succeeded by vacuum cycles.

Typical processes used:

- Hot oil circulation: Hot oil is circulated through the transformer and once the desired temperature is reached the oil is emptied into a tank and vacuum is applied. As the transformer will cool down during the vacuum phase several cycles are needed. Also the maximum allowed oil temperature may limit the maximum drying temperature.

- Hot oil spray: Spray nozzles are installed at the available flanges and hot oil is sprayed over the active part at the same time as vacuum is applied. This allows limiting the temperature reduction during the vacuum cycles. But due to design of the core type transformers with press plates and shieldings, it might be difficult to heat up
the whole transformer uniformly. For shell type transformer this method is more often used as the main insulation can be easily reached by the hot oil spray.

- Low frequency current heating (LFH) in combination with hot oil spray: In order to heat up both low and high voltage windings, a frequency of approx. 1 Hz is applied to the transformer. With the combination of LFH drying and the conventional hot oil spray method, the whole transformer can be heated very uniform. The LFH system is heating the windings from the inside and the hot oil spray supports the heating process by heating outer parts of the insulation system.

The LFH process combined with hot oil spray allows to reduce the drying time essentially. It is possible to reach the same low levels of moisture in the whole insulation as with a factory repair within approx. 1 week. Compared to “conventional” systems like oil circulation or hot oil spray, this is a time reduction by approximately a factor of 4.

Using the most advanced techniques, the repair process including On-Site Drying, ensures low final moisture and high-quality insulation of the transformer, compatible with advanced on-factory drying processes.

Figure 7: Plant concept for a mobile LFH drying process in combination with hot oil spray.

4.5 On-Site High Voltage testing

For most of On-Site Repair projects that have been performed by ABB the quality of the repair has been verified by high voltage tests including applied voltage test and induced voltage test with measurement of partial discharge in addition to all other type of quality control identical or exceeding what is performed when manufacturing new transformers or repairing transformers in a factory.

The performance record after performed On-Site Repairs is excellent. None of the transformers repaired have failed and in total it represents some 700 transformer years of operation without a single failure in operation after site repair. This confirms that the quality
of the On-Site process as such is very high and that the performed verifying high voltage tests have been appropriate.

On-Site high voltage test may except for verifying the quality of an On-Site Repair or refurbishment also be applied for:

- As a part of a diagnostic procedure to confirm that the insulation still is free from defects or for provide reference values for future tests or to confirm results from earlier test
- As a commissioning test to demonstrate the condition after shipment and the installation at site

To perform On-Site high voltage tests one need a test system that is easily transported and set up and prepared for test in short time. The test system should also be flexible to easily be set up for test of transformers with different characteristics. So far mobile high voltage test equipment has been built based on motor generators set completed with adaptation transformers, components for reactive compensation and measurement and recording equipment. To improve the portability and flexibility of such equipment ABB has together with a test system supplier developed a new concept for On-Site high voltage test based on high power electronics as a variable frequency power source.

The new Mobile High voltage system that recently has been commissioned is equipped for performance Applied Voltage test and Induced voltage test with measurement of Partial discharge. In addition measurement of No-Load losses may be performed, for large transformers requiring somewhat more reactive compensation. The test system is designed for test of transformers with a rating up to at least 500 MVA.

For performing Applied voltage test a resonance circuit is set up between the capacitance of the test object and the resonance reactor supplied with the test set up. The resonance circuit is fed by the frequency converter through the adaptation transformer. The block diagram below show schematically the test set up for Applied voltage test.
For performing Induced voltage test the advantage of the variable frequency converter is used to find the self compensation of the test object. The self compensation frequency of a power transformer is normally between 50 and 150 Hz. By performing the test at the self compensation frequency the power compensation of the test circuit will be limited. The adaptation transformer is designed to match the normal voltage range applied for tertiary voltage windings of power transformers. The block diagram below show schematically the test set up for Induced voltage test.

The Mobile High Voltage Test System is built in to a 40’ container for easy transportation by truck, by sea or by air. The picture below shows the test system delivered to a substation for test of a transformer.
4.6 Project references

In total ABB has repaired more than 200 transformers on-site. The largest units have been rated 750 MVA, 800 kV ac. More than 60 transformers above 200 MVA but also a number of HVDC transformers for up to 600 kV dc have been repaired on-site. As regards to transportation the largest transformers are naturally the units for which the most time may be saved by On-Site Repair. Time savings of 2-3 months or more compared to factory repair are common for the large units, in some cases even more. However the reference list also contains some 100 of transformers on or below 50 MVA. In one case some 30 transformers of 30 - 40 MVA were upgraded and refurbished in the same temporary workshop set up close to the location of the customer’s substations.

5. Conclusions

The electrical market in most of the countries, not to say all, value more and more the quality of the energy supplied to the end-users. One of the important challenges for utilities is therefore to ensure no interruption in the delivery which means a high availability and reliability of the different equipments installed in the networks.
Transformers being a key component among the electrical assets, ABB developed dedicated solutions to help utilities and especially power producers managing their fleet of equipment in a more efficient way. After several years of experience in many countries ABB sees lots of value to combine condition assessment survey and On-Site Repair to help transformer owners reducing the downtime of their equipment.

Condition Assessment provide relevant information to support informed decisions needed to implement condition based maintenance and reduce repair time by better planning the repair tasks and ordering of material.

On-Site Repair based on a proven process and strong project management combined with state-of-the-art technology and strict quality control allows reducing repair time by several weeks or even months while ensuring a highly reliable repair.

Condition Assessment and On-Site Repair helps utilities keeping a high standard of energy delivery through improved availability of transformers.
References:


