Meet the challenges of tomorrow: 
Increase the power of your transformer in record time

Authors:
Dr José-Carlos Mendes  
ABB  
Guarulhos, Brazil  
jose-carlos.mendes@br.abb.com
Lars Eklund  
ABB  
Guarulhos, Brazil  
lars.i.eklund@br.abb.com
Paolo Capuano  
ABB  
Vittuone, Italy  
paolo.capuano@it.abb.com
1. Abstract

With the increased demand of electrical power the utilities invest in new generation and new transmission and distribution systems to satisfy the demand. However in some cases already installed equipment may be upgraded to handle more power than it originally was designed for. Such upgrade may be possible thanks do the development of new technologies and new material that allow the equipment to operate at a higher load still within safe design margins.

One factor that may limit the opportunities for upgrade of already installed electrical equipment is the requirement of very high availability of the power network. Therefore it is important to develop efficient and reliable processes to minimize the time until upgraded equipment can be put back to service.

This paper present solutions for upgrading of power transformers by applying new technologies and environmental friendly materials in the design and manufacturing of transformers but also new processes now available to reduce the required time of the upgrade and the time until the units may be recommissioned.

The new design uses a recently developed material, BIOTEMP® which is a vegetable insulation oil developed by ABB and NOMEX®, a synthetic paper and pressboard insulating material developed by DuPont. ABB has now developed technology using these two superior materials also for high voltage power transformer. This paper will describe the technology used and also recently performed real upgrade project where the rating of the transformer could be increased by more than 60%.

To considerably reduce the time of unavailability of transformers during repair and upgrade ABB has developed a site repair process. This process makes it possible to get the transformer back in service in much shorter time than shipping the transformer to
transformer factory. This site repair process, TrafoSiteRepair™ is globally available and is also applicable for upgrades using the new technologies described above. The paper presents the features of TrafoSiteRepair™ process, but also recently performed projects including projects in the Middle East region.

2. Upgrade of power transformers using new technology

2.1 BIOTEMP®: A Superior vegetable oil

BIOTEMP® is an advanced biodegradable electrical insulating fluid from high oleic vegetable oil renewable natural agricultural sources developed by ABB to be friendly to the environment.

The fluid has excellent dielectric characteristics with high temperature stability and superior flash and fire resistance: 330°C and 360°C respectively while mineral oil has flash and fire temperatures of 145°C and 160°C. BIOTEMP® has excellent compatibility with solid insulating materials and is 97% biodegradable in 21 days. It is an inhibited oil approved in an Oxidation Stability Test according to Test Method ASTM D2440 (72h at 110°C) for mineral insulating oil type II acc. ASTM D3487 [7].

Table 1 shows some BIOTEMP® properties in comparison with others insulating fluids.

<table>
<thead>
<tr>
<th>TYPICAL PROPERTIES OF INSULATING FLUIDS</th>
<th>BIOTEMP</th>
<th>Mineral Oil</th>
<th>H.T.H.</th>
<th>Silicone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric Strength, kV (ASTM D877)</td>
<td>45</td>
<td>30</td>
<td>40</td>
<td>43</td>
</tr>
<tr>
<td><strong>Physical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity, cSt. 100°C (ASTM D445)</td>
<td>10</td>
<td>3</td>
<td>11.5</td>
<td>16</td>
</tr>
<tr>
<td>Flash pt. °C (ASTM D92)</td>
<td>230</td>
<td>146</td>
<td>298</td>
<td>300</td>
</tr>
<tr>
<td>Fire pt. °C (ASTM D93)</td>
<td>350</td>
<td>169</td>
<td>309</td>
<td>330</td>
</tr>
<tr>
<td>Specific Heat (cal/g°C) (ASTM D2766)</td>
<td>0.47</td>
<td>0.43</td>
<td>0.45</td>
<td>0.36</td>
</tr>
<tr>
<td>Coefficient of Expansion, °C (ASTM D1893)</td>
<td>6.88 x 10⁻⁴</td>
<td>7.55 x 10⁻⁴</td>
<td>7.3 x 10⁻⁴</td>
<td>1.04 x 10⁻³</td>
</tr>
<tr>
<td>Pour pt. °C (ASTM D97)</td>
<td>-15 to -25</td>
<td>-40</td>
<td>-24</td>
<td>-55</td>
</tr>
<tr>
<td>Sp. Gravity (ASTM D1208)</td>
<td>0.91</td>
<td>0.91</td>
<td>0.87</td>
<td>0.96</td>
</tr>
<tr>
<td>Color (ASTM D1500)</td>
<td>&gt;0.5</td>
<td>0.5</td>
<td>0.5, -2.0</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodegradation Rate (%) 21 - 60°C - 1°C</td>
<td>97.0</td>
<td>25.2</td>
<td>27.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Remark:
HTH = High Temperature Hydrocarbons fluid (ASTM D5222)
Figure 1 show a comparison of flash and fire temperatures of mineral and BIOTEMP® vegetable oils.

![Figure 1 - Flash and Fire Points Temperatures Insulating Mineral and BIOTEMP® Vegetable Oils](image)

BIOTEMP® vegetable oil can absorb water thus greatly increasing the life of the insulation paper immersed in it. In fact a study based on tensile strength and degree of polymerization measurements has shown that kraft paper immersed in BIOTEMP® lasts twice as long as paper in transformer oil derived from petroleum sources. This property combined with BIOTEMP®’s superior thermal properties means a transformer can support higher hot spot temperature in its windings.

Further advantages of the BIOTEMP® application in power transformers are related to the transformer installation requirements:

- Eliminate requirement to build fire walls in the substation bay;
- Reduced fire liability and insurance costs;
- Optimization of requirements on fire extinction systems in the substation bay;
- Reduction of distances clearances between the transformer and adjacent equipments and/or buildings in the installation place; and
- Possible future optimized requirements to build expensive oil basin containment, narrow channels, etc.
2.2 The NOMEX® Thermal protective technology

The NOMEX® Thermal protective technology, rated class 220 °C, is a family of synthetic paper and pressboard insulation materials that provide high levels of electrical, mechanical and chemical integrity. In power transformers these materials can be used to protect the insulation system in the hottest parts of the winding, to selectively replace cellulose with and capitalize on its thermal strength in the design.

For end-users who need to boost the power of their existing units, there is the possibility of rewinding the coils with NOMEX® high temperature insulation material. As a result significant improvements in lifetime and reliability are achieved. Besides the cost advantages for the unit, side benefits worth consideration include: lower environmental impact than scrapping, no construction needed to prepare the site (the footprint remains identical) and a lower weight compared to a conventional unit.

3. Refurbishment and uprating of a power transformer

A transformer originally rated 138/13.8kV, 10/15MVA, ONAN/ONAF and delivered by ASEA Brazil in 1974, has been refurbished and uprated to 20/25MVA, ONAN/ONAF by ABB Brazil in 2006 to CEMIG - Companhia Energética de Minas Gerais - one of the largest Brazilian electric power utilities, in a joint development project.

The refurbished transformer delivered by ABB to CEMIG includes the following advanced characteristics:

- Up-to-date ABB TrafoStar™ technology;
- Extreme high overload capability, up to 70% above rated power, without loss of useful life;
- Advanced ABB TEC transformer electronic control and on-line monitoring system;
- Low voltage on-load regulation using ABB UZ type on-load tap changer filled with superior performance ABB BIOTEMP® vegetable oil;
High voltage ABB GOB type bushings filled with superior performance ABB BIOTEMP® vegetable oil; and Reduced maintenance requirements.

The benefits provided by such transformer as seen by CEMIG include:
- High transformer reliability;
- High transformer availability due to reduced maintenance needs;
- Reduced installation costs; and
- The risk of a transformer explosion and the consequent ground and underground waters contamination is significantly reduced when compared to a mineral oil filled transformer. Even if an explosion would occur, the vegetable oil will generate much less hazardous non-toxics by-products.

Figure 2 shows location of Minas Gerais state in Brazil and its capital, Belo Horizonte, a city 3 million inhabitants.
**Engineering and manufacturing**

Table 2 shows the transformer main data before and after complete refurbishment and uprated.

Table 2 - Transformer Data

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Refurbished</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial Number</td>
<td>54381</td>
<td></td>
</tr>
<tr>
<td>Manufacture</td>
<td>ASEA</td>
<td>ABB</td>
</tr>
<tr>
<td>Year</td>
<td>1974</td>
<td>2006</td>
</tr>
<tr>
<td>Frequency, Hz</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Phases</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Voltages</td>
<td>138 ± 2 x 2.5% / 13.8 ± 16 x 0.625 kV</td>
<td></td>
</tr>
<tr>
<td>Rated Power, MVA</td>
<td>15 (ONAF2)</td>
<td>25 (ONAF2)</td>
</tr>
<tr>
<td>Overload, MVA</td>
<td>-</td>
<td>37.5 (6h, 150%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42 (4h, 170%)</td>
</tr>
<tr>
<td>OLTC</td>
<td>UZERN 250</td>
<td>UZF 250</td>
</tr>
<tr>
<td>Insulation</td>
<td>Cellulose</td>
<td>Hybrid (Nomex+Cellulose)</td>
</tr>
<tr>
<td>Oil Type</td>
<td>Mineral</td>
<td>BIOTEMP®</td>
</tr>
</tbody>
</table>

The transformer electrical and mechanical design has been fully developed by ABB Brazil. Engineering efforts have been dedicated specially to:

- Winding insulation dimensioning having Nomex® as paper and board insulation. In fact ABB Brazil has also long time experience in Nomex® application as a transformer solid insulation. Several industrial and network transformers have been designed, tested and are under reliable operation using this technology, including a large size 3phase, 300MVA, 245kV transformer;
- Winding insulation dimensioning as Nomex® impregnated with insulating vegetable oil has a dielectric permissibility value different than the standard cellulose paper impregnated with insulating mineral oil. In consequence, electric potential distribution will get a specific distribution in the winding mix insulation;
- Internal windings connection leads electrical and thermal dimensioning for overload conditions; and
- External cooling system dimensioning and temperature rises evaluations, taking into account differences in the viscosity of the vegetable and mineral oils and the extreme high overload requirement.
Figure 3 shows the transformer in HV Laboratory ready for test.

Figure 3 - Regulating Transformer 25MVA, 145kV
Filled with BIOTEMP® Vegetable Oil

The transformer has been manufactured in the ABB Brazil medium and large power transformer plant. The manufacturing process has been in accordance with the well-established TrafoStar™ manufacturing process. The final oil filling process has been specially adapted to meet the requirements established for the vegetable oil filling:

- Completely separate temporary oil system;
- Dedicated oil processing machines (thermo-vacuum plant, filters, heaters, hoses, etc);
- Specifics before filling oil conditioning, vacuum time, oil filling under vacuum process, oil circulation time and final standing time period before tests have been defined and applied to this case; and
- Specific oil quality controls, with several tests in all processing steps have been established in order to assure the insulating vegetable oil filled transformer overall quality.
The quality controls of all manufacturing processes have been recorded according to internal ABB Six-Sigma procedures certified in compliance with ISO 9001 and ISO14001 standards.

**Final test of the complete transformer**

The complete assembled vegetable oil filled transformer has been fully tested. All standard [8; 9] routine tests as well as a set of special and type tests have been performed in this unit, including dielectric, thermal and operational tests as:

- Lightning (full and chopped waves) and switching impulse tests in all windings terminals;
- Short duration AC applied tests;
- Long duration induced voltage tests, before and after heat run and overload thermal tests, including measurement of Partial Discharges;
- No-load and load sound level measurements tests, including octave-band noise spectrum measurement;
- Complete heat run test with oil and winding temperature rises measurements;
- Long duration overload test (initial load 100% or 25MVA and peak load of 170% or 42MVA over 4 hours) with oil temperature measurement;
- Power frequency long duration over-excitation tests; and
- Frequency response (FRA) test.

All dielectric and thermal tests have been monitored by oil dissolved gas analysis (DGA). The transformer has been successfully approved in all electrical and thermal tests. The oil DGA tests results has not shown any significant variation in gases concentrations before and after electrical and thermal tests, given a very good as demonstration of the transformer superior and reliable test performance, [10].
Commissioning and performance

After being approved in all acceptance tests, the transformer has been shipped by road for about 550km from ABB factory to CEMIG Cidade Industrial Substation located nearby Belo Horizonte downtown.

While under shipment, the transformer tank was kept filled with BIOTEMP® vegetable oil, means a further advantage and cost reduction associated to transportation and related licenses. In case of mineral oil instead, the oil should be shipped in a separate container.

After site erection, oil processing and commissioning, the transformer entered into commercial operation in July, 31st-2006. Figure 4 shows an overall view of the transformer at substation bay after energization and loading.

Figure 4 - BIOTEMP® Vegetable Oil Filled Transformer in Operation at Substation Bay

Since then, the transformer is operating properly and reliable, taking peak overload up to 42MVA (170%) almost every weekday. As an example, figure 7 shows a heavy duty loading cycle supplied by this transformer with peak load above 35MVA.
Transformer operation is being monitored by ABB TEC on-line monitoring system as well as by conventional oil tests, oil and windings temperatures monitoring and periodic infrared scan. The aim is to close follow performance of the transformer and of the BIOTEMP® vegetable oil. Updated monitoring results are shown that the transformer performance is operating with reliability even under severe overload conditions.

4. Repair, refurbishment or retrofit of transformers at site
Last year at the Power-Gen conference here in Bahrain ABB presented the concept for repair power transformers at site. The concept developed by ABB based on many years experience and now combined with state-of-the-art technology makes it possible to save time when a transformer has failed and have to be repaired but the same technology may be used also for refurbishment and retrofit of transformers. This technology, as marketed by ABB as TrafoSiteRepair™, is a well suitable solution for upgrading of power transformers using new material and new technology, as been presented in the first part of this report, when the distance to a transformer factory is long or the option to transport a heavy transformer is limited by other reasons.
Figure 6 - Active part of a large transformer being re-tanked after repair at site

**The TrafoSiteRepair™ process**

To achieve the same quality of repair at site as repair in factory the guideline for the ABB TrafoSiteRepair™ concept is: “We bring the factory to site”.

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 repair of a transformer at site, the same capabilities have to be set up at site to meet the individual circumstances of each case. The ABB TrafoSiteRepair™ concept includes:

- Manufacturing of windings and other components to be replaced is performed in one of the ABB transformer factories. The windings and insulation components are also dried and impregnated at the factory and then shipped in dry atmosphere
or oil in closed containers to site. During the repair process the windings and repair components are kept dry until the final drying is performed at site.

Figure 7 - Assembly of an active part at site

- As a TrafoSiteRepair™ 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 possesses a maintenance area which 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.

- 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.

Figure 8 - High voltage testing performed of a power transformer after site repair. The temporary workshop can be seen in the background.

Globalizing the TrafoSiteRepair™ technology

From being developed mainly through three forerunners, ABB in Brazil, Italy and Spain the TrafoSiteRepair™ processes for repair, refurbishment and retrofit of transformers are now being made available to meet customers’ needs worldwide.

Today ABB has completed more than 200 transformer repairs at site in total 25 different countries in South America, Europe, Africa and Asia and the concept is spread to new countries every year.

In the Middle East two projects were completed 2007, one in Egypt and one in Bahrain. The Bahrain project is presented below.
5. Transformer refurbished at site in Bahrain using the ABB TrafoSiteRepair™ technology

Alba, Aluminum Bahrain B.S.C, is one of the largest modern aluminum smelter in the world, with an annual production capacity of more than 850,000 tones. To ensure maximum efficiency, Alba utilizes cutting edge technology at every stage of its production process. Alba does not only have its own reduction lines and cast houses, the company also has a 600,000 tones per annum coke calcining plant, a water desalination plant and a 2000 MW power plant ensuring power for the energy intensive process of producing aluminum. The electrolytic process for aluminum production takes place 365 days a year. Direct current is continuously applied to the pot-lines through the rectifier transformers. To avoid any loss of production, the reliability of the generator step-up transformers feeding the rectifiers is crucial.

Beginning of March 2007 a fault was detected in a 105 MVA – 141/10.5 kV generator step-up transformer manufactured by ABB in 1991. The transformer was immediately taken out of service.

Alba immediately requested transformer manufacturers to supply a new transformer with a very fast delivery. With new transformer delivery time reaching 12-18 months, ABB responded to Alba’s request by proposing not only a new unit but also the option to repair the transformer on-site including the replacement of all the three winding blocks. The work would be done using ABB’s TrafoSiteRepair™ technology, a service product bringing together ABB’s 100 year transformer know-how with more than 15 years of experience in repairing power and industrial transformers at site.

Now the pace greatly accelerated – Alba’s request for quotation for repairing the transformer was sent on March 16, the quotation was submitted on March 23 and the order was placed on March 29. Alba quickly recognized the value of the site repair, reducing the loss of production by more than 4 months and awarded the
TrafoSiteRepair™ order to ABB Italy with the extremely short delivery time of 6.5 months, compared to a normal repair time of 9-12 months.

The decisive factor enabling ABB’s fast response to Alba’s problem was the internal cooperation, where ABB in Bahrain, Sweden, Germany and Italy worked together with the global TrafoSiteRepair™ product team to determine the scope and resources needed globally to deliver the project on time. With raw material being long-lead items, ABB in March ordered the material needed for the new windings, after checking old design, and in April activities for dismantling the unit were carried out at site in Bahrain. In May a joint inspection was performed by ABB Italy and Sweden to collect information necessary to assess the condition of the other generator step-up units in service at Alba.

Design of winding was reviewed and improved on the basis of above inspection with the use of thermally upgraded paper and different cooling criteria on LV windings exit bundles.

Windings were received in Bahrain before end of July, thanks also to fast air transportation provided by the Customer.

The activities started immediately, so that in one month, at the end of August, the transformer was ready for the active part inspection before tanking, crucial check point foreseen in ABB Quality system procedure. This inspection was carried out by a joint team of experts, from technical, production and test department, of ABB Italy Service center strictly following the same procedure applied in the manufacturing of new units in the Factory.
After that the final activities was carried out as per ABB procedure and in the fastest way: active part tanked, oil treatment process, retightening, transportation and final assembly on the bay.

The transformer was ready for HV test 29 weeks after order received, even before the Contractual agreement.

High voltage test was then performed with partial discharge measurement confirming the quality of the repair job done.

This order from one of ABB’s most important customers in the region is a break-thru for the TrafoSiteRepair™ solution in the Middle East.

6. Conclusion
The power transformer technology and industry may sometimes be considered as mature. The basic concept is still the same as 100 years ago. However, even based on the same basic concept, the development of the technology and the materials used has taken significant steps and the power transformers manufactured today are using inventions in design, advanced new materials and advanced computer technology to improve efficiency and reliability and now also to make the transformers more safe and environmentally friendly.

This paper presents how advanced new material can be used to upgrade old transformer to increased rating, improved safety, less maintenance and increased product lifetime. Cooperation between manufacturer and plant owner, in this case ABB and the Brazilian utility CEMIG, created conditions for implementing a package of innovative technologies creating financial, technical and environmental benefits for the utility. This is also a significant contribution to the industry and to the society as a whole.

The paper also presents how such a refurbishment or upgrade of a transformer can be performed at site. The transformer can remain on site and does not need to be transported to a transformer factory. Instead the new windings, processed at the factory will be transported to the site where the assembly, final drying and testing will be performed.
The TrafoSiteRepair™ concept is based on a proven process that allows to reduce repair time by several weeks or even months while ensuring a highly reliable repair. The key success factor is a strong project management combined with state-of-the-art technology and strict quality control. The article presents the recent repair of a power transformer at site in the Middle East and highlights the benefits for the transformer owner. The distance and time needed to transport power transformers to a factory able to perform a repair being significant, the TrafoSiteRepair™ concept is well suited to be applied in the Middle East region and may help utilities and industries to restore the network or power supply in a much shorter time.

7. References