# INCREASE TRANSFORMER RELIABILITY AND AVAILBILITY: FROM CONDITION ASSESSMENT TO SITE REPAIR


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***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 case of failure the possibility to reduce the outage time is usually important for the transformer end user.

In this paper we will therefore describe Transformer condition assessment methodology - as well as on-site repair solution – as means to increase both the reliability and availability of transformers and therefore the energy efficiency of the network.

The output of such a Transformer condition assessment methodology survey is a ranking of the population with priorities for investment and recommended maintenance actions plan for each unit.

The advanced diagnosis of the transformer condition is used to identify defects even before it is required to un-tank the transformer and therefore it helps to improve repair time especially in the case when a transformer is repaired at site.

If a transformer has to be repaired in a factory, the transportation time from the end-user site to factory and return plays a major influence on the duration of the project and putting transformer back in service to resume power. Also the cost and risks associated with heavy transport must be considered.

To date a total of more than 300 transformers including utility, industrial, HVDC transformers and reactors have been successfully repaired on site. In many cases transformer output power were also upgraded to provide an increased rating using present advanced design tools.



*Index terms* – Transformer reliability, availability, condition assessment, asset management, transport risks, reduced down-time, power upgrade


## I. INTRODUCTION

Transformer asset management mainly relies on the complete condition and life assessment study results. The study helps the End user of the asset to consider and plan for near 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.

## II. UNDERSTAND THE STATUS OF THE ASSETS AND DEFINE RISKS MITIGATION ACTIONS

A statistical approach based on the information available globally about transformer reliability is useful in considering initial maintenance and investment budgets. However, each unit should be considered as a specific case once the end user needs 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 that has been used 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. The 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:

### *II.1. 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.

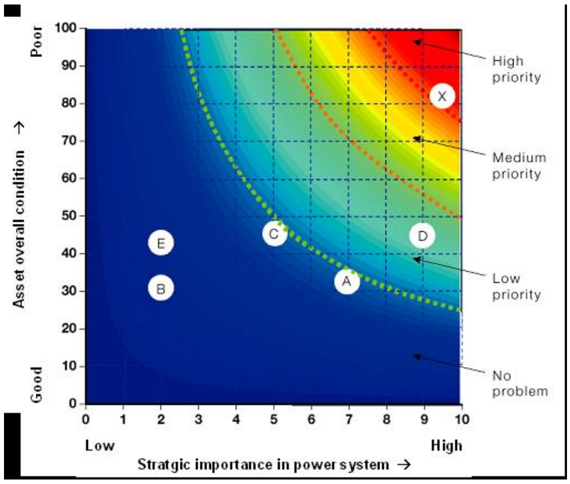


Fig.1 Example of a Fleet Screening survey - level 1

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.

*II.2. Step 2 - Life Assessment*

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.

*III.3. Step 3 - Risk Assessment*

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.

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 site repair [5].

**Plant 1 - Results of condition assessement step 2 and action plan**

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

Fig. 2 Result of a Life Assessment survey on eight transformers

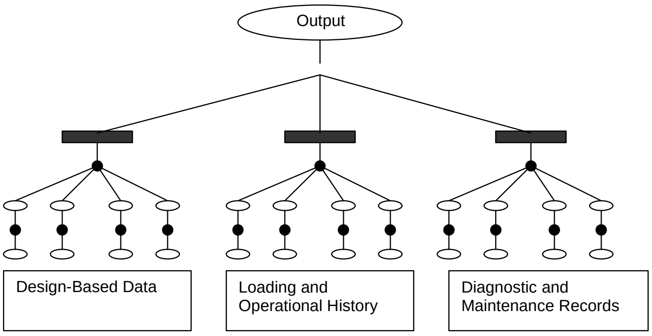


Fig. 3 Chart illustrating the structure of a Risk Assessment survey (step 3) using the influence between the different evaluation criteria

In most of the cases recommendations issued as a result of an assessment survey are followed by the transformer owner. It is therefore difficult to collect feedback on what would happen in case of no actions and therefore to judge if the risk estimated in the survey is real. We notice however that the defects detected with the diagnosis methods used are usually representative of the real condition after internal inspection/dismantling of the transformer. In a few cases we can report that actions recommended in the survey were not completed by the transformer owner and lead to the failure of the unit due to bushing issues, bad contacts on connections, winding displacement/deformations.

A survey performed on a fleet of 128 transformers allowed to reduce the associated yearly maintenance budget by 24%. Also it allowed to prioritize the units according to their condition and importance in order to spend the maintenance budget on the right units. It appears in this case that 54% of the budget was spent on the low risk units and 37% on the medium risk units while only 9% were spent on the most critical units. Based on the survey the maintenance prioritizes were changed in order to spend 25% on the budget on the 11 critical units, 45% on the medium risks units and 30% on the low risks units.

## III. REPAIR OF TRANSFORMERS ON SITE

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

In the past repair or refurbishment of a power transformer that does not requires major winding replacement or another major action was normally performed on site. However major repairs major repairs with winding and insulation replacement were transported to a transformer factory where the required space and equipment were available.

For large transformers, the transportation of the transformer from site to repair factory and back to site has a major influence on the total time required for the transformer to be put back in to service. Such heavy transportation always has risk and costs associated with it.

In some cases it is more challenging and virtually impossible to move a transformer to the repair factory due to the changes in the infrastructure, roads and facilities over the years.

To reduce the outage time of a failed transformer and to minimize the challenges and risk associated with transportation site repair could be a solution.

However, a repair of a large power transformer is a demanding process, requires a 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 the site repair concept has been developed to be an important alternative to increase the availability of transformers, power generation plants and sub-stations.

Until a few years ago site repair was mainly performed in three countries, Brazil, Italy and Spain. Based on the success in these three countries and on a growing interest from transformer owners worldwide, decision was taken to leverage the local expertise in order to provide a global site repair solution available for any country. The process has then been documented with detailed methods provisions and the expertise has been transferred in each continent by training dedicated crews. Today more than 300 transformers of several brands and of any types were successfully repaired on-site in 25 different countries.

### *III.1. On-Site Repair Process*

Power transformer factories and workshops are characterized by their orderliness, cleanliness and well controlled atmospheres which are important conditions required for manufacturing and repair of high voltage equipment. They are also equipped with heavy lifting equipment, special tools and fixtures, high voltage test laboratories and highly skilled operators for each step of the process.

To perform a site repair of a transformer, the same capabilities have to be set up on site in order to meet the individual circumstances of each case. The concept requires the following:

1. In order to perform a site repair a controlled environment facility will be required, where cleanliness and orderliness can be achieved. The facility should meet all the criteria's required to perform the necessary repairs. If the customer does not have a repair area a temporary workshop can be set up on site.
2. Heavy lifting equipment will be required on the site. The largest transformers may require a capacity of up to 400 metric tons and above for un-tanking and tanking of the core and coil assembly.
3. The standard tooling and equipments used in any factory for repairs are made available on site for repairs.

4. Windings and insulation components are manufactured at a transformer factory and are dried and oil impregnated prior to shipment. They are then specially packed to maintain the low moisture content during shipment and are stored on site in a controlled environment.

5. After assembly of core and coils the active part is placed in the transformer tank and prepared for final drying. The On-Site Drying processes used can reduce the moisture levels to below 1 %. There are several methods available for On-Site drying to reduce the total time required for drying a large power transformer.

6. High voltage test of the assembled transformer is carried out on-site according to the agreed test plan. To meet the requirement of portability and flexibility an On-Site High Voltage test system has been developed together with a test equipment supplier.

### *III.2. Facilities For Temporary Workshops*

Based on the experience gained globally within the Service centers that have performed site repair projects it was noted that a maintenance shop owned by the customer is available for approximately 50% of the repair projects completed. The available shop may also be equipped with an overhead crane for lifting of core and coil assembly and winding blocks. For the remaining 50% of the projects it was necessary to set up a temporary facility. When a permanent facility is available at site for transformer repair it 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 (Fig. 4A and 4B). This type of building is primarily used when more than 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 work by the owner.

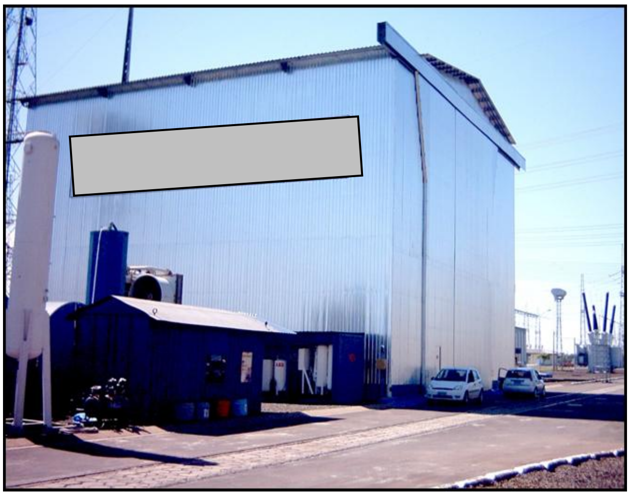

Fig. 4A: A steel building used as temporary workshop in Brazil

Fig. 4B: A steel building used as temporary workshop in Brazil

Another very flexible and economical solution is to use a large tent consisting of a steel structure and claddings (Fig. 5). This structure could achieve and maintain clean and dry environment for the repair work to be performed on the active part of the transformer. These types of tents can be set up in very short time, normally less than a week and are designed to withstand severe weather conditions such strong winds and snow load.

Fig. 5 Typical tent structure that may be used as temporary workshop

*III.3. Heavy Lifting At Site*

One of the major heavy lifting required during repair of a core type transformer is the lifting of the core and coil assembly for un-tanking and tanking of the transformer. The core and coil assembly of the largest transformers may weigh up to 400 metric tons and above. 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

Fig. 6 Tanking of large power transformer using mobile lifting equipment

*III. 4. The Factory Is Brought To Site*

For achieving the same quality standards of repair at site as repair in factory "Bring the factory to site".

That means that the repairs are performed in the same way on site as in the factory. The same processes, tools, fixtures and equipment are applied as far as possible.

One of the processes used in factory which is not presently used on site is the drying of the core and coil assembly 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 on site meets the required maximum level of moisture content. These alternative processes are described below.

*III. 5. On-Site Drying*

Initially, all new windings and insulating components internal to the transformer are dried and impregnated while still in the factory using standard vapor phase drying process. The oil impregnation of the windings and insulation components minimizes the moisture absorption when handling the parts. In addition all parts are then specially packed and transported in special containers that are filled with dry transformer oil or positive dry air pressure. 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 on the core and coil is completed, 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:

1) Hot oil circulation: Hot oil is circulated through the transformer and once the desired temperature is reached the oil is drained into a tank and vacuum is applied to the transformer tank. Based on the kV class of the transformer and moisture content vacuum cycles are maintained till the necessary drying criteria's are met. Also the maximum allowed oil temperature may limit the maximum drying temperature.

2) 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 shielding, it might be difficult to heat up the core and coil assembly uniformly. For shell type transformer this method is more often used as the main insulation can be easily reached by the hot oil spray.

3) 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 approximately 1 Hz is applied to the transformer. With the combination of LFH drying and the conventional hot oil spray method, the active part can be uniformly heated. The LFH system heats 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 reduces the total drying time of the transformer on site. It is also possible to meet the same low levels of moisture in the insulation as compared to factory repair within short period of time. The savings in time compared to conventional hot oil spray method and LFH method could be between 3 to 4 weeks.

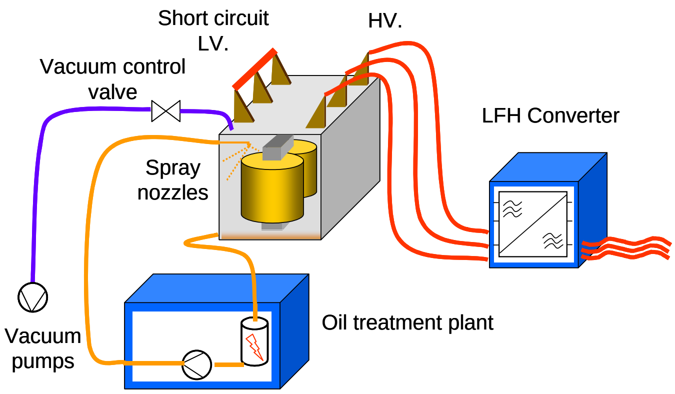


Fig. 7 Plant concept for a mobile LFH drying process in combination with hot oil spray

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.

*III.6. On-Site High Voltage Testing*

For most of the projects the quality and dielectric of the repair has been verified by high voltage tests including applied voltage test and induced voltage test with measurement of partial discharge. These tests are in addition to all other type of quality control tests which are normally performed when manufacturing new transformers or repairing transformers in a factory.

The performance of the projects repaired and tested after site repairs has been excellent. This confirms that the quality of the process performed on site meets the standards of a factory repair.

On-site high voltage testing can also be used for verifying the quality of a refurbishment projects for:

1) As a part of a diagnostic procedure to confirm that the dielectric strength of the main insulation is free from defects and or provide reference values for future tests or to confirm results from earlier test

2) As a commissioning test to confirm the condition of the transformer after shipment and the installation on site

In order to perform on-site high voltage tests, a test system that can be easily transported to any remote site and set up in short time is required. The test system should also be flexible and be able to test at different voltage levels as required for different transformers. So far the mobile high voltage test equipment has been built based on motor generator sets completed with adaptation transformers, components for reactive compensation and measurement and recording equipment. To improve the portability and flexibility of such equipment we have developed a new concept for on-site high voltage test based on high power electronics as a variable frequency power source.

Fig. 8 Mobile High Voltage Test System built on a 40' container arrive to the site for test

The new mobile high voltage system is equipped to perform Applied Voltage test and Induced voltage test with measurement of Partial discharge. In addition, measurement of Load Losses and No-Load losses can be performed at reduced levels. The test system is designed and is capable of testing most of the HV transformers installed globally

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 as shown in Fig. 9. The resonance circuit is fed by the frequency converter through the adaptation transformer. The block diagram below show schematically the test set up for a standard applied voltage test.

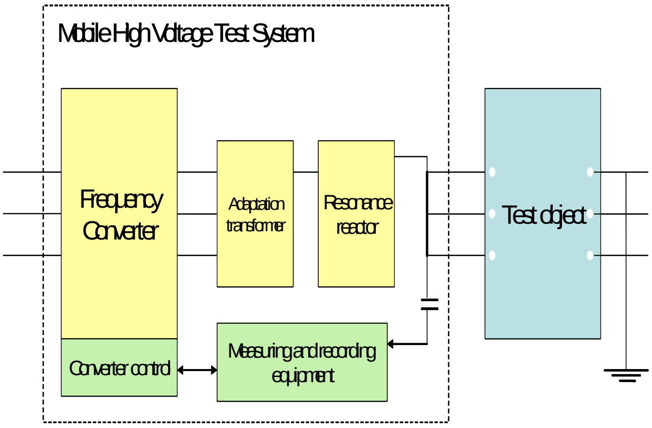


Fig. 9 Mobile High Voltage Test System set up for applied voltage test

For performing an induced voltage test the advantage of the variable frequency converter is used to find the frequency of self compensation of the test object. This frequency of a power transformer is normally between 50 and 150 Hz. By performing the test at the self compensation frequency the power consumption of the test circuit will be limited to the active losses of the transformer and the size of the converter can be reduced. The adaptation transformer is designed to match the normal voltage range applied for tertiary voltage windings of power transformers.

The block diagram Fig. 10 below show schematically the test set up for Induced voltage test.

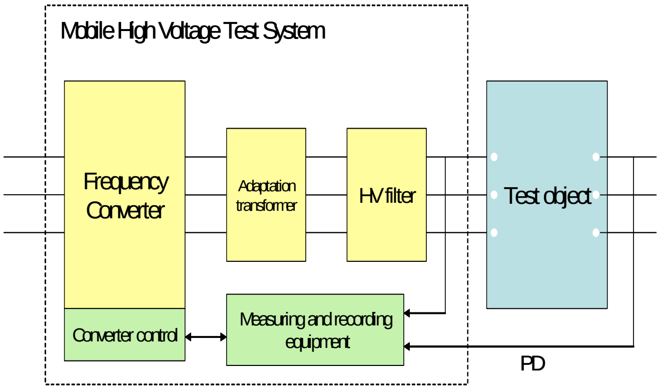


Fig. 10 Mobile High Voltage Test System set up for Induced voltage test

The Mobile High Voltage Test System is designed and built in order to be transported in a standard 40 feet container for easy transportation by truck, by sea or by air. The Fig. 11 shows the test system set up at a substation for test of a large single phase transformer.

Fig. 11 High voltage testing performed of a power transformer after site repair. The temporary workshop can be seen in the background

## IV. TRANSFORMER REPAIRED AT SITE IN PHILIPPINES

A Generator Step Up Transformer (GSU) located in Limay Bataan, Philippines failed in service.

Fig. 12 Transformer on pad, 93 MVA, 240/13.8 kV

The power plant is owned by the National Power Corporation (NPC) in the Philippines and operated by Alstom Power. The power plant did not have any spare transformers and required the quickest option to repair and return the existing GSU to service.

Initial electrical diagnostics testing and oil analysis indicated that the windings of the transformer were damaged and needed to be replaced.

The original transformer design data significantly reduced the design time for the replacement windings.

The manufacturing of the new windings and preassembling of the winding blocks were completed in Thailand, in accordance with the guidelines for new transformers. The winding blocks were dried and assembled in the transportation tank sealed with positive dry air pressure. The winding tanks were shipped to site in Philippines.

Fig. 13 New windings prepared for shipping in container

One of the key and most important challenges was to create factory environment on site. This was achieved by erecting a temporary workshop equipped with an air conditioner and dehumidifier.

Fig. 14 The temporary workshop set up at site

After delivery of the windings from the factory in Thailand to site, the skilled team successfully replaced the windings and repaired the transformer to new condition. After tanking of the core and coil assembly, a vacuum drying process along with hot oil circulation method was applied. The quality of the drying process was monitored by Frequency-Domain-Spectroscopy (FDS) measurements.

One of the most important scope of the project successfully performed was the High voltage testing on site after repair.

A Mobile High Voltage test system was brought to site in order to perform dielectric tests including Applied Voltage test, Induced Voltage test and Partial Discharge measurement. All tests were performed according to the international standards.

Fig. 15 The Mobile High Voltage Test system set up at site for testing of the repaired transformer

After the successful completion of all tests and acceptance by the customer the transformer was successfully put back into service.

## V. PROJECT REFERENCES

In total more than 300 transformers have been repaired on-site. The largest transformer repaired on site is rated at 750 MVA, 800 kV ac. More than 60 transformers above 200 MVA including several HVDC transformers rated up to 600 kV dc have been repaired successfully on-site.

As it relates to transportation costs and risks, the large power transformers are the likely candidates to be considered for on site repair. The total repair time in most of the cases were reduced by 12 to 14 weeks depending on the geographical condition of the transformer and site. However several transformers below 50 MVA and 30 MVA were also repaired or refurbished on site.

## VI. 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 industries and utilities is therefore to ensure no interruption in the delivery which means a high availability and reliability of the different equipment installed in the networks. After several years of experience in many countries the condition assessment survey and on site repair helps transformer owners to reduce 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 help industries and utilities keeping a high standard of energy delivery through improved availability of transformers.

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## VIII. VITA

''Pierre Lorin, M. Sc. Electrical & Mechanical. He graduated in Paris in 1992. From 1992 to 1996 he worked as a research engineer by the Swiss Federal Institute of Technology in Lausanne. He conducted researches for large utilities in Europe and North America on reliability and maintenance strategy for electrical overhead lines. He presented several publications on this topic during international conferences.

From 1996 till today he has been with ABB Power Technologies - Transformers Service. He has been active in Research & Development, mainly involved in transformers reliability, diagnosis methods, on-line monitoring, and active noise control. He is now head of technology for transformers service activities. He is the author or co-author of several publications in this filed."

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