FIELD DIAGNOSTIC TESTING OF POWER GENERATORS AND TRANSFORMERS USING MODERN TECHNIQUES

Edgar Robles

Instituto de Investigaciones Eléctricas
Av. Reforma 113, Temixco, Morelos, México
erp@iie.org.mx

Abstract

It is of great importance to define the operating conditions of the main power electrical equipment. On-line and off-line partial discharge measurements are a powerful tool to achieve this goal. Some experiences on the evaluation of high voltage generators are described in this paper, where discharge patterns can define the type of deterioration mechanisms. The actions taken after some critical generator evaluation are also discussed.

Acoustic partial discharge has been recorded on power transformers, the technique is briefly described and some results associated with the deterioration mechanisms are presented. The application of some off-line techniques to find transformer adverse conditions are also presented.

1. Introduction

The Electrical Equipment Department of the *Instituto de Investigaciones Eléctricas* (Electrical Research Institute) has concentrated its efforts on field testing of power equipment. It has been implementing testing techniques to support the maintenance engineers to define deterioration mechanisms and take corrective actions.

The work has been done for the *Comisión Federal de Electricidad*, CFE (the Mexican Electrical Utility) and for PEMEX (the Mexican Oil Industry). CFE operates hydroelectric generators from 30 to 350 MW, and steam power generators from 30 to 600 MW. The power electrical network operates at 230 and 400 kV.

PEMEX generates its own electrical energy on each main working center, oil refineries or petrochemical plants. They generate at 13.8 kV on units from 30 to 50 MW. They have also a 115 kV feeder from CFE to attend emergency conditions.

This article presents some of the results on field-testing and techniques used to determine the conditions of power generators and transformers.

2. Generator Field Diagnosis

The reliability of power generators is of prime importance to the electrical utilities. It is essential to define the working conditions of an electrical generator operating under service stresses, with special reference to the insulation of the windings. A series of testing techniques has been developed to assess a generator at standstill. The Electra Review /1/ published a summary of the most common procedures for diagnostic testing.

Modern instrumentation, mainly digital partial discharge detectors, allows performing on-line diagnostic testing of power generators. This has the advantage to have the normal electrical stress distribution and the influence of mechanical and thermal stresses on the stator windings.

The insulation system that has been used in the stator windings is mica with a bonding compound. In the early years asphalt was used as a bonding material with mica flakes. In the fifties the binder changed to polyester resin. Modern materials use mica powder with an epoxy binder.

The main insulation is applied to a pre-shaped stranded conductor. Mica tape is half-lapped in layers around the conductor strands to achieve the required insulation thickness. Two types of insulation tapes can be used depending on the manufacturing process. If vacuum impregnation is available, then the mica tape used is made on glass cloth with a small amount of adhesive. Once the tape is applied, the bar is subjected to a vacuum to remove moisture and volatile materials contained in the mica tape layers. The bar is then impregnated with an epoxy resin and pressurized to allow the resin to permeate into all the small interstices. The resin-impregnated bar is shaped as required and heated for curing.

If a vacuum impregnation process is not available, then the insulation tapes consist of a mica tape fully impregnated with epoxy resin. The resin content is about 46% of the total weight. Woven glass cloth is normally used as the supporting fabric. The tape is applied either manually or with an automatic taping machine. The bar is then consolidated under heat and mechanical pressure to obtain the final dimensions and shape. During manufacture, the resin is taken to the `B' stage resulting in a flexible material with a volatile content of less than 1.0%. The resin flows under low consolidation pressures at elevated temperatures. This characteristic is particularly important when good consolidation of stator coil end-windings insulation is required and only low external pressure can be applied.

3. Resonant transformer for AC testing

Typical capacitances of turbogenerators are between 0.1 μF and 0.3 μF per phase, for 30 MW to 300 MW generators respectively. The capacitance of a 400 MW hydro-electrical generator can be as high as 1.2 μF per phase. A resonant transformer is required to excite a generator winding with an AC voltage. There are two advantages when a resonant transformer is used. As the inductor is tuned to be in resonance with the capacitance of the winding, the required input power of the transformer and voltage regulator are significantly reduced. As a consequence, the size and weight of the equipment diminish significantly. The equipment provides a noise free output voltage with greatly reduced harmonics, mainly when a series resonance circuit is implemented.

A variable frequency resonant transformer was especially designed and built for stator winding testing. The fixed high voltage reactor is made of two coils encapsulated in epoxy resin. The coils can be connected in series or in parallel, depending on the type of generator under test. An output voltage of 30 kV can be obtained with both windings in series on a turbogenerator winding (300 nF load). An output voltage of 15 kV can be supplied to a load of 2 μF (large hydrogenerator).

The variable frequency supply was made of a three-phase rectifier with a filter and a single-phase inverter. The output frequency can vary from 40 to 120 Hz. The output voltage is controlled with the width of the pulse of the variable frequency electronic source. This is an advantageous feature because it reduces considerably the weight and size of the resonant transformer. The variable frequency resonant transformer is shown in Fig. 1.

Fig. 1 Variable frequency resonant transformer

4. Stator PD measurements

Partial discharge measurements and detection are difficult to carry out in the field due to the high noise level normally present. All kinds of precautions to avoid noise should be taken into consideration when performing this test. When the generator uses hydrogen as a cooling gas, measurements at different pressures should be performed to clarify whether the discharges are internal or external. When the partial discharge test is performed, the inception and extinction voltage should be recorded at the circuit sensitivity.

PD detection is a powerful tool to identify many of the deterioration mechanisms of electrical generators /2/. The oscilloscope display should be carefully studied to determine the type of discharge occurring in the sample. For example, if there is an asymmetry between the discharges in the positive and the negative half cycle, then it is likely that slot discharges might be occurring. The slot discharges are very harmful to the machine insulation. It has been observed during field testing that the possibility of slot corona discharges can be detected at test voltages close to the inception voltages. At voltage above the inception the phenomenon tends to be overridden by discharges at other sites.

A contaminated stator winding can be identified through partial discharge measurements. Contaminated generators produce external discharge activity at the endwindings. Contamination deposits affect the electrical field distribution of the silicon carbide coating. The discharges produce ozone that attacks the insulation and in the long term loosens the winding. This problem occurred in air-cooled generators operating in oil refineries and petrochemical plants and on vertical hydroelectric generators that are affected with residues from the brakes.

Direct cooled hydrogen generators use a resistor to keep the cooling ducts at the same potential than the main conductor. A failure of this resistor can induced external discharges that can generate a catastrophic failure /3/. On-line and off-line partial discharge measurements can detect defective resisitors and prevent this failure mechanism to occur.

Damaged stator cores by abnormal operating conditions give rise to hot spots that affect the insulation and induced internal discharges. On-line and off-line partial discharge measurements can detect this type of defect.

Fig. 2 Digital slot discharge meter with storage capabilities

The use of a discharge probe to locate specific defective areas is very efficient during off-line inspection. Typical defects on the stator windings can be (i) internal discharges within the insulation, (ii) external discharges at the endwindings produced by improper stress- relief at the endwindings or (iii) slot discharges due to the loss of the conductive paint.

A discharge probe with digital storage capability was designed to ease the recording of the discharge level of each slot. The equipment stores the discharge level of three generator positions, (the exciter side, the turbine side and one in the middle area of the stator. Data is unloaded to a personal computer trough a serial port. A view of this instrument is shown in Fig. 2.

5. Power Transformer Field Diagnosis

Oil impregnated paper, the insulation system of the power transformers, is quite susceptible to partial discharge activity. The discharge level that is allowed in a transformer during the induced voltage test is limited to 250 pC. The induced voltage test is performed at two times the rated voltage. There is no doubt that the power transformers are properly tested in the laboratory, but it is necessary to take into account that the transformer might be damaged during transportation and commissioning. The oil has to be drained out from the tank and the bushings and accessories are dismantled to move the transformer to the field. It is possible that some malfunctions may occur due to inadequate transportation.

Power transformers are under intense electromechanical stresses in abnormal operating conditions. If there is a failure in the transmission line or other substation equipment, the transformer windings can be mechanically deformed and induced partial discharge activity. Power plant step up transformers can be stressed during accidental out of phase synchronization.

Another source of partial discharge activity on power transformers is caused by the deterioration and aging of the components. The wear and tear of the oil pumps can introduce metallic particles within the transformer that might be trapped in an intense electrical field zone and induced partial discharge activity. Tracking of the insulating structure of the tap changer can also be a source of partial discharge activity.

Partial discharges can be detected with either electrical or acoustical methods. Electrical methods are more sensitive than the acoustical, but it is not easy to achieve a good sensitivity due to corona discharges and other noise sources. Acoustical methods are less sensitive; they can detect mainly arcing processes within the transformer. But it is easy to apply the technique and to correlate the type of damage that might be occurring within the transformer. A good knowledge of the construction of the transformer is required to correlate the results with the deterioration mechanism.

6. PD Acoustic technique fundamentals

Partial discharge activity within the transformer generates a pressure wave that propagates from the source to the tank walls. The ultrasonic sensors, externally clamped can register them. The mechanical signals are converted into electrical signals that are amplified and plotted. The signals are proportional to the energy contained in the shock wave. In general, two types of wave shapes are obtained. The *"arrow head shape"* and the *"egg shape"* envelops. The type of envelope depends on the attenuation of the signal due to the propagation path /4/.

The signal, with an *"arrow head"* envelope, shown in Fig. 1, is obtained when there is a minimal attenuation; the propagation path is mainly insulating oil. The *"egg shaped"* envelope, shown in Fig. 2, is obtained when the ultrasonic signal is propagated through different layers of solid materials (iron, copper, insulation, etc.) The analysis of the obtained wave shape permits to determine the location and type of PD generating source.

PD ultrasonic signals have a duration between 50µs and 2 ms, a frequency bandwidth from 100 kHz to 200 kHz and characteristic frequency of 160 kHz. The voltage amplitude depends on the distance between the source and the sensor; the path and the discharge intensity.

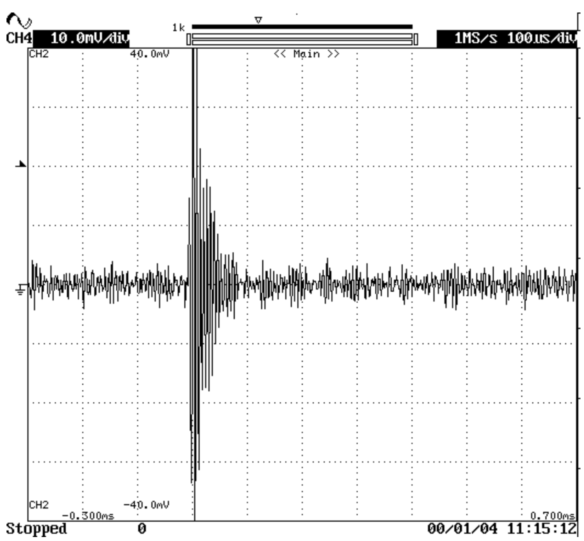

Fig. 3 "Arrow head" acoustic PD type of signal.

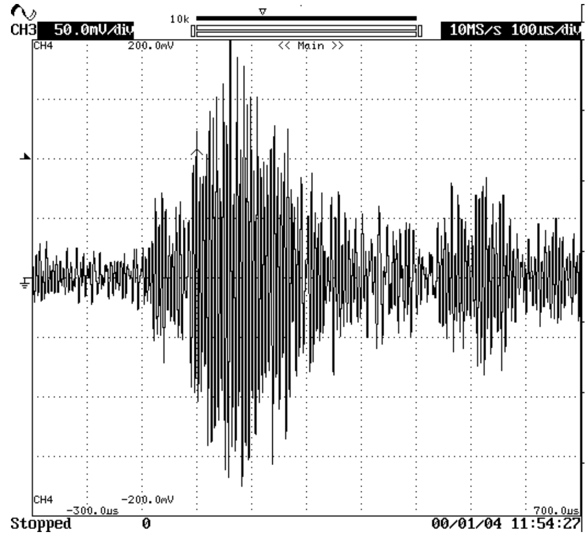

Fig. 4 "Egg shaped" acoustic PD type of signal.

The PD acoustic measuring system is made of ultrasonic sensors with internal pre-amplifiers, a signal conditioning and an amplifier, a digital oscilloscope with printer and the connecting wires. The sensor is a piezo electric transducer with an operation frequency range (for longitudinal waves) from 70 to 200 kHz and a resonant frequency (maximum sensitivity) of 150 kHz. The sensor's pre-amplifier gain is 40 dB and matching impedance of 50 Ω.

The conditioning stage has eight data acquisition inputs that are protected against electromagnetic interference. All the system is interconnected by double shielded cable with characteristic impedance of 50 Ω. The maximum length of the connecting cables is 30 m. A view of the instrumentation is shown in Fig. 3.

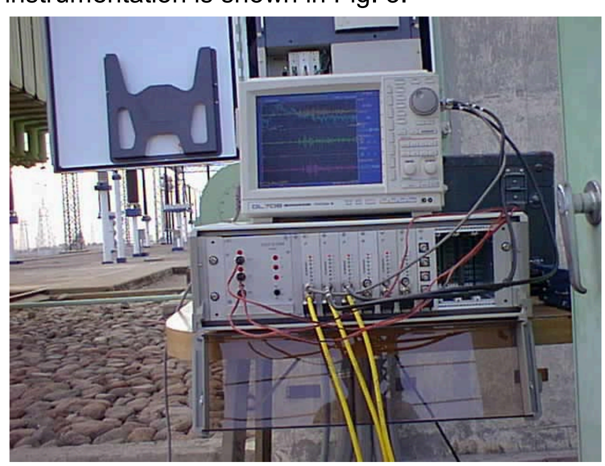

Fig. 5 PD acoustic equipment set up.

The sensors are placed on each wall of the transformer tank and PD acoustic activity is registered on each wall. The signal with the shortest arriving time and greater amplitude will consequently have a shorter distance to the point of the partial discharge source.

After locating the point of failure, it is necessary to analyze the design drawings of the transformer to define the severity of the problem. This information permits to take appropriate actions or carry out additional tests or even to make an internal inspection of the transformer.

7. Field test results

Many transformers from the 400 kV Mexican Electrical Grid had been assessed with the PD acoustic technique. Floating core transformers were found; high contact resistance in the low voltage side of the step up unit transformers were corrected after being diagnosed; transformers with deteriorated tap changers were found and properly maintained. Some relevant results are presented to show the benefits of the PD acoustic technique.

CASE 1. One of the transformers of a 75 MVA 400/115 kV bank, shell type, had a 2000 ppm hydrogen concentration. Ultrasonic detection was carried out and found that heavy arcing was occurring inside the transformer, typical displays of the obtained signals are shown in Fig. 6. It was decided to take the transformer out of service, then the oil was drained to make an internal inspection.

A large amount of conducting particles (bronze) were found inside the transformer. The particles came from worn down oil pump bearings. These particles were concentrated in high electric field areas of the transformer and produced heavy arcing that was detected trough the PD ultrasonic emission technique.

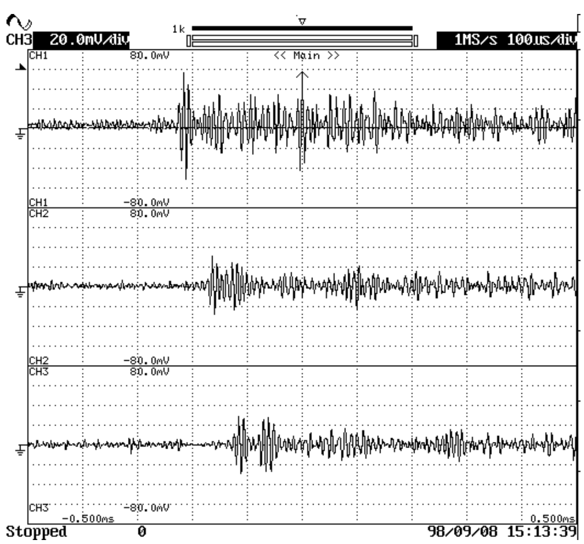

Fig. 6 Typical display obtained on the bronze particles contaminated transformer.

CASE 2. It was programmed an ultrasonic test on a single-phase 100/125 MVA, 400/230/13.8 kV autotransformer, as part of the maintenance program. High ultrasonic activity was detected on the wall of the main tank adjacent to the "On-Load Tap Changer (OLTC). Typical signals are shown in Fig. 5. The PD activity came mainly from the region of the OLTC diverter switch tank. As an additional test, DGA was performed to the diverter switch oil. Results indicated slightly abnormal values, considering the reduced number of operations made.

The OLTC was disassembled for inspection and the pressboard insulated structure that supports the diverter switch mechanism was found very deteriorated with carbon tracking. The degradation was originated in the neutral connector. Fig. 8 shows one of the deteriorated insulated supports where tracking can be observed.

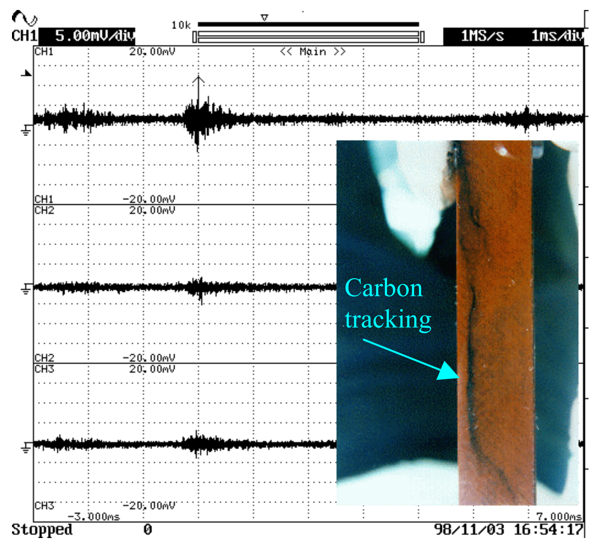

Fig. 7 Oscillograms from a deteriorated diverter switch. Damaged insulated support is also shown.

CASE 3. A failure occurred in a step up unit transformers of a 107 MVA, 20/230 kV. It was decided to inspect the other three transformers including the spare one of the bank. The transformers are of a core type. Ultrasonic activity was detected on the wall adjacent to the high voltage bushing. The registered ultrasonic signals are shown in Fig. 6.

It was concluded that the PD activity came from the high voltage lead of the bushing. The unit was taken out of service for an internal inspection. A mechanical problem between the high voltage lead and the equipotential ring was found. The discharges were occurring between the HV lead and the stress relief ring.

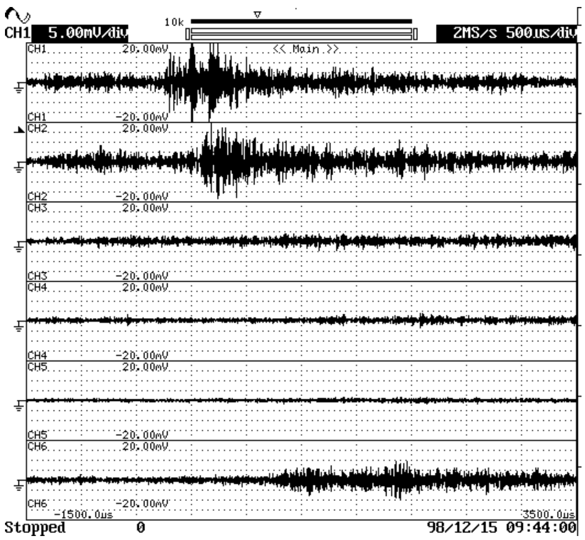

Fig. 8 Signals from a transformer between the HV lead and the stress relief ring.

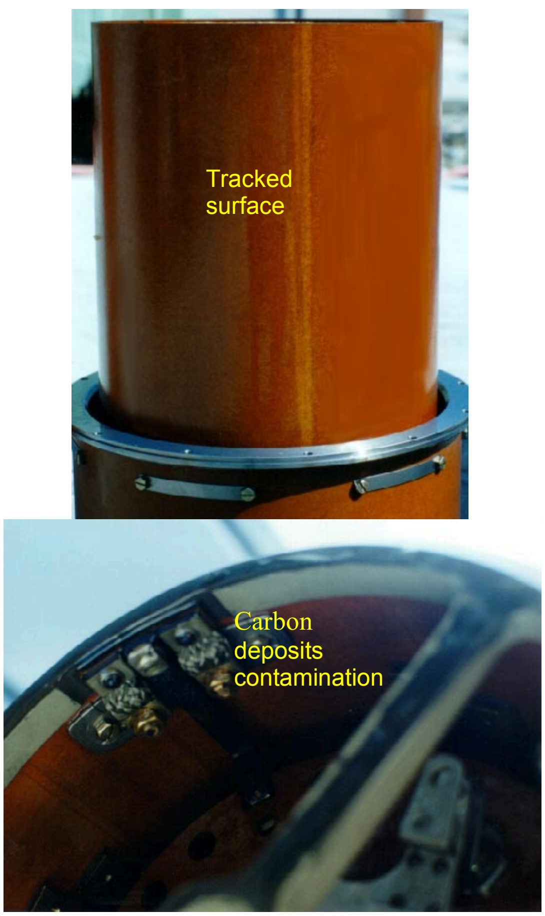

Fig. 9 Damaged insulation support of the OLTC and carbon deposits contamination

CASE 4. During the commissioning of a 230/138/13.8 kV, 25 MVA, single-phase autotransformer, an audible noise coming from inside the transformer was detected. The commissioning was temporarily suspended to determine the noise source. A DGA analysis was made in oil samples from the main tank, the OLTC tank and the Buchholz relay deposit. The results showed an abnormal amount of CO in the OLTC, indicating a process of burned cellulose. PD acoustic discharges were also recorded.

The autotransformer was energized through the 13.8 kV tertiary winding with a distribution transformer. Heavy arcing from the OLTC tank was noticed. When the internal inspection was carried out, a large amount of accumulated carbon was found, mainly on the diverter switch resistance compartment (on the fixed contact area and on the connector of the diverter switch lower ring). The OLTC insulated cylinder was also tracked. Both defects are shown on Fig. 7.

8. Conclusions

Field testing of power equipment can be very helpful to avoid catastrophic failures and the loss of critical equipment. Techniques that were reserved for laboratory environments can be now successfully applied in the field. On-line testing is particularly attractive to identify deteriorated equipment as it is under combined stresses.

References

/1/ Schuller, R. H. Report on diagnosis and monitoring for evaluating the conditions of windings of rotating electrical machines. Electra Review, International Conference on Large High Voltage Systems N° 112, 9-16, May 1987.

/2/ Robles E. García A. Reyes O. Deterioration mechanisms of electrical generators.

/3/ Robles Medina A, E. López E. Description of a violent failure of a 346 MVA generator. Annual Doble Client Conference, 1995

/4/ IEEE PC57.127/D2*,* Trial use guide for the detection of acoustic emissions from partial discharges in oil-immersed transformers*, 1989.*