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Acoustic Emission Partial Discharge Detection Technique Applied to Fault Diagnosis: Case Studies of Generator Transformers

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Abstract: In power transformers, locating the partial discharge (PD) source is as important as identifying it. Acoustic Emission (AE) sensing offers a good solution for both PD detection and PD source location identification. In this paper the principle of the AE technique, along with in-situ findings of the online acoustic emission signals captured from partial discharges on a number of Generator Transformers (GT), is discussed. Of the two cases discussed, the first deals with Acoustic Emission Partial Discharge (AEPD) tests on two identical transformers, and the second deals with the AEPD measurement of a transformer carried out on different occasions (years). These transformers are from a hydropower station and a thermal power station in India. Tests conducted in identical transformers give the provision for comparing AE signal amplitudes from the two transformers. These case studies also help in comprehending the efficacy of integrating Dissolved Gas is (DGA) data with AEPD test results in detecting and locating the PD source.

Keywords: Acoustic Emission, Condition Monitoring, Dissolved Gas is, Partial Discharge, Transformer.

1 Introduction

The healthy and safe operation of transformers in power stations is critical, because it involves huge investment and maintenance costs. Unwarranted and unforeseen interruptions of these transformers may lead to major financial loss. Hence, performance of these transformers should be monitored at regular intervals in order to maintain uninterrupted power to the end user. Reliability of the transformer has a great influence on the performance of utility companies. The operating reliability of transformers depends mainly on their insulation status. According to statistics, insulation faults account for 80% of total transformer faults. A large number of technical papers can be cited from the

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published literature related to condition monitoring [1]. The major indicators of the insulation problems in transformers are rises in temperature, gas-in-oil, partial discharge and moisture. All dielectric problems involve partial discharges in the initial stages of the failure process. Looking at the criticality of power transformers in terms of reliability and downtime, condition monitoring becomes very important [2, 3]. The incipient faults are detected and remedial measures become possible through Partial Discharge (PD) detection and PD location identification. Hence early detection of unwanted electrical micro-discharges in the insulating system is very important.

PD is a localized electric discharge that partially bridges the insulation between conductors. PD testing is used as a diagnostic tool because of its widespread acceptance for quality control [1 – 3]. The purpose of PD testing on high-voltage (HV) in-service equipment is to determine the degree to which the insulation system has deteriorated. The PD level also gives the rate of deterioration during its operation [4]. The thermal, electrical and mechanical stresses, together with environmental factors, can cause the degradation of electrical insulation during operation. Many of these processes lead to partial discharges. Thus the periodic testing of PD activity over the life of the equipment facilitates preventative maintenance.

Diagnostic PD tests can be performed both offline and online. In offline diagnostic PD tests the equipment is disconnected from the power system for the duration of the test, whereas in online tests there is no outage of the HV apparatus. The drastic reduction in outage time for the online PD test reduces the outage cost due to reduced downtime [5, 6].

Dissolved gas analysis (DGA) is one of the online tests, which has been in use for several years. Dissolved gases in the oil produced by thermal ageing can provide an early indication of an incipient fault. Gases normally ed in DGA are hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, ethane ethylene and acetylene [7]. But it is not possible to identify and locate the PD source with DGA alone. So in recent years, PD detection and is using the Acoustic Emission (AE) method has gained popularity [8, 9]. AEs are transient elastic waves in the range of ultrasound, usually between 20 kHz and 1 MHz, generated by the rapid release of energy from a source. A PD results in a localized, nearly instantaneous release of energy. A fraction of the released energy heats the material adjacent to the PD and can evaporate some of it, creating a small explosion. The discharge acts as a point source of acoustic waves [10 – 13].

In this paper, two typical cases related to transformer condition monitoring via AE signal detection, taken from a vast number of online tests conducted on transformers at the generating stations, are presented. The testing diagnostic group of Central Power Research Institute (CPRI) of India has vast exposure to AEPD testing/diagnostics, both through field and laboratory measurements

[14 – 16]. The team has conducted more than 200 such tests at utility premises all over India over the last decade.

1.1 Acoustic emission partial discharge

The acoustic emission technique is a passive technique based on detecting the signals emitted from discharges. Acoustic methods have many advantages compared to all other methods used for PD detection [8, 17]. In the case of large apparatus like power transformers the PD source location is as important as identifying it. PDs show up only when the equipment is energized. Thus AEPD detection is much more suitable for the condition monitoring of power transformers, being an online technique. Acoustic methods provide an indication of the PD source location within an electrical apparatus. They are non-invasive and immune to electromagnetic noise. The sensitivity of this method does not vary with the test object capacitance [8]. The acoustic wave can be detected by a suitable sensor, the output of which can be analysed using a conventional data-acquisition system. These tests are conducted as per the IEEE std C57-127 [8]. AE data is useful, but it becomes more useful when used in conjunction with dissolved gas-in-oil data. If DGA shows a continuing increase of H_2 gas in combination with the detection of AE signals, then there is a good possibility that the PD is taking place in a specific area [8]. In this paper the AEPD signals from the two case studies, along with associated DGA results, are presented.

1.2 Sensors and measuring technique

A 16-channel AE system consisting of AE sensors made out of piezoelectric material is employed by CPRI of India for its field tests. The sensors are with integrated pre-amplifiers and are used for the condition monitoring of the transformer insulation [14, 18]. AE sensors are mounted on the walls of the transformer tank (metallic) which is at ground potential with the transformer being in service. Necessary safety precautions must be followed while mounting the sensors on high-voltage transformers. Sensors are mounted using magnetic holders at locations of importance. The contact between the sensor and the transformer tank is very important. It is advisable to wipe the area free of dirt, oil, bugs, etc, and polish it with a mild abrasive or abrasive cloth before placing the sensor. An acoustic couplant is essential for enhancing the mechanical and acoustical coupling between the transducer and the tank surface. It should be applied evenly to the mounting surface of the sensor before placement [8]. Sensors are assigned numbers for identification purpose. The coordinates (x, y, z) of the sensors are noted with an appropriate reference frame. The sensor-mounting layout depends on the type, size, design and rating of the transformer. Sensors are mounted at the same position each time for carrying out periodic monitoring (time-based condition monitoring).

The layout of sensors for typical cases like three-phase transformer and single-phase transformer is as shown in Figs. 1 and 2, respectively. The associated DGA results are also considered for assessing the condition of insulation.

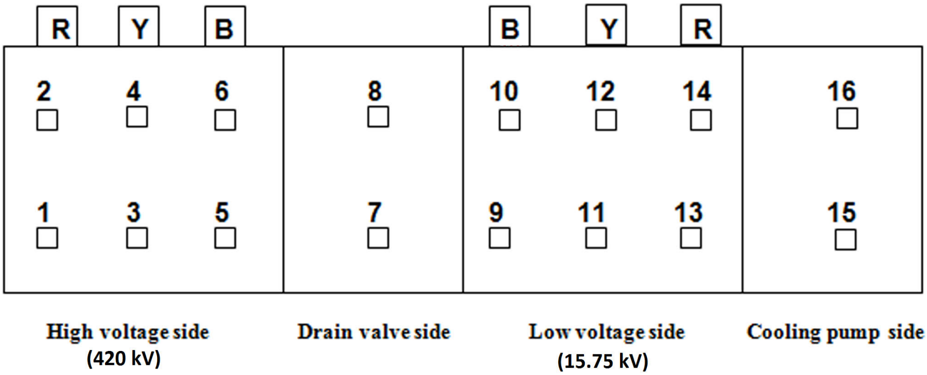

Fig. 1 – *AE-Sensor mounting layout for a typical 3-phase transformer. Each AE-Sensor corresponds to a channel in the data acquired (and reported).*

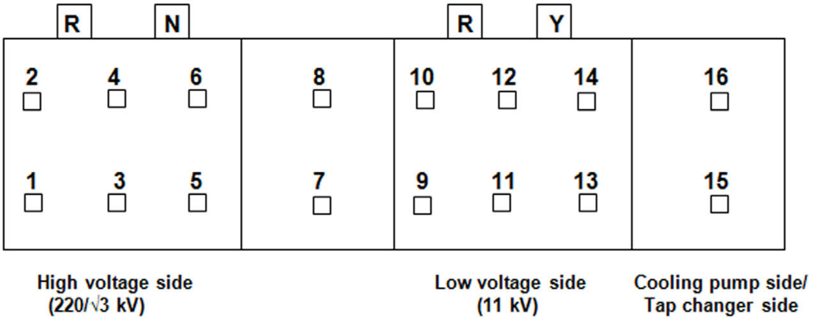

Fig. 2 – *AE-Sensor mounting layout for a typical 1-phase transformer. Each AE-Sensor corresponds to a channel in the data acquired (and reported).*

2 Case Studies

2.1 General

Acoustic Emission Partial Discharge tests conducted on generator transformers used in hydroelectric power stations and thermal power stations in India are reported here. Hydroelectric power stations normally have an Oil Forced Water Forced (OFWF) type of cooling system, instead of Oil Forced Air Forced (OFAF) type of cooling system for a coal-based power station. The operating temperature of generating transformers in hydroelectric power stations is comparatively lower than that of coal-based power stations.

2.2 Case Study-1: Identical transformers

This case study was reported from the field tests conducted on two identical generator 3-phase transformers (GT-1 and GT-2) in a thermal power station in India (each transformer of 250 MVA, 15.75 kV/420 kV, 3 Phase, Oil Forced Air Forced cooling).

The DGA results showed high hydrogen levels in one of the generator transformers, named GT-1. The hydrogen content had shown a steep rise of more than 1000 ppm for this unit. The DGA and Oil breakdown strength (BDV) test results conducted at this stage are given in **Table 1** (columns 3 and 5).

These two transformers were then tested further using AE sensors and detection system under (near) identical conditions of loading. The condition of transformers while these tests were conducted is summarized in **Table 2**.

A 16-channel AE system consisting of AE sensors made out of piezoelectric material was employed for the AEPD test. After cleaning the transformer tank surface, AE sensors were mounted on the walls of the transformer tank. The layout of sensors is depicted in Fig. 1. The view of this transformer with AE sensors mounted on it is shown in Fig. 3, in which sensors mounted on the high-voltage side of the transformer tank are seen.

The amplitude of the AE signals captured by the 16 channels of the AE-detection system for GT-1 and GT-2 are depicted in Figs. 4 and 5, respectively. These are plots of AE signal amplitude captured over a period of 30 s to 5 minutes against the AE sensor channel number. Some of the channels do not show any signals, indicating that the magnitude of AE activity is lower than the threshold value. In order to eliminate the background noise, it is general practice to set a threshold only above that at which the signals are recorded. The threshold set in the present study was 35 dB. For GT-1, the maximum AE amplitude among these 16-channels corresponded to channel number-2 with a corresponding amplitude of 62 dB. For GT-2, the maximum amplitude of among these channels corresponded to channel number-6 with corresponding amplitude of 46 dB. The maximum AE signals for these two identical transformers are compared in **Table 3**.

The transformer GT-1, which showed high hydrogen content during DGA, did show higher AE magnitude during the AEPD test compared to the other transformer, GT-2. Having identified a good possibility of high AE activity in GT-1 from the DGA and AEPD test, it was possible to locate the problem zone in the transformer. The AE magnitude recorded by channel-2 is higher than 60 dB. From the sensor layout given in Fig. 2 it is seen that channel-2 is close to the HV winding termination near the HV bushing. Hence the location of the problematic zone was suspected to be near the HV bushing termination. With this the internal inspections became relatively simpler for the maintenance personnel.

Table 1

DGA and BDV test results for identical generator transformers (GT-1 and GT-2).

TEST		GT-1		GT-2
DGA	Dissolved Gas type	Before maintenance	After maintenance	Before maintenance
	Methane [ppm]	817	6	28
	Ethane [ppm]	208	2	4
	Ethylene [ppm]	3	11	1
	Acetylene [ppm]	2	Not Detected	Not Detected
	Hydrogen [ppm]	8653	Not Detected	60
	Oxygen [ppm]	21775	21456	22465
	Nitrogen [ppm]	8400	55829	53287
	Carbon Monoxide [ppm]	Not Detected	288	Not Detected
	Carbon Dioxide [ppm]	2245	5118	1984
BDV	Breakdown Voltage [kVrms]	32	77	68

Fig. 3 –*View of 250 MVA 15.75* kV/*420* kV *generator transformer with sensors mounted (sensors mounted on the HV side of transformer tank are seen).*

Table 2

Load condition of transformers while capturing AE signal for two identical generator transformers (GT-1 and GT-2) tested.

PARAMETER	GT-1	GT-2
Power	176 MW	191 MW
Reactive power	42.5 MVAR	40 MVAR
HV side voltage	414.6 kV	428 kV
LV side voltage	15.69 kV	15.5 kV
HV current	253 A	268 A
LV current	6672 A	7400 A
Power factor	0.97	0.98
Frequency	49.8	49.8
Oil temperature	53º C	56º C
Winding temperature	71º C	72º C

Table 3

Maximum amplitude of Acoustic Emission signals captured for two identical generator transformers.

TRANSFORMER IDENTIFICATION	MAXIMUM AMPLITUDE OF AE SIGNAL DETECTED [dB]	CHANNEL SHOWING MAXIMUM AE SIGNAL AMPLITUDE
GT-1	62	2
GT-2	46	6

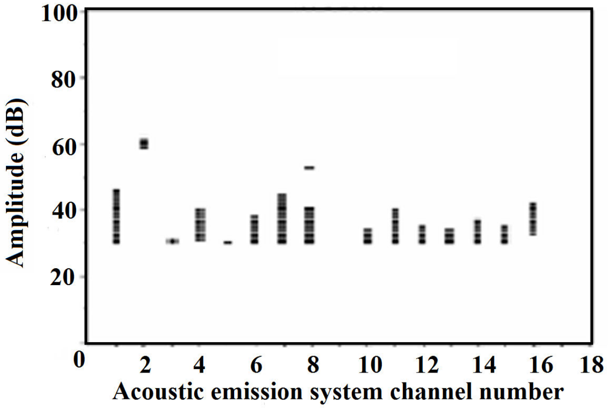

Fig. 4 – *AE Amplitude for 16 AE channels recorded for GT-1.*

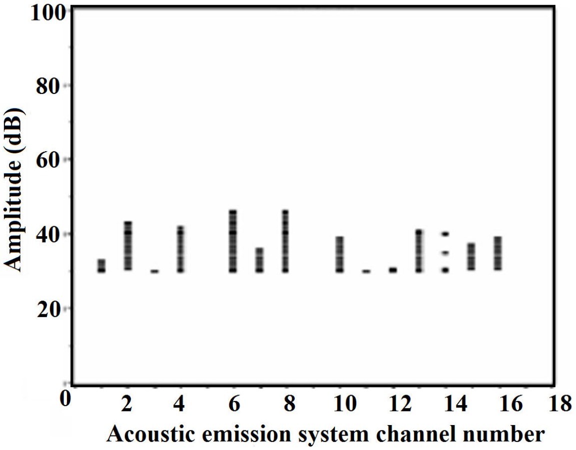

Fig. 5 – *AE Amplitude for 16 AE channels recorded for GT-2.*

The details of the problem are not available to the authors (as AEPD test personnel) as the case was referred to the manufacturers of the transformer. The DGA and BDV tests for GT-1 were reconducted after the maintenance activity. These results of DGA and BDV corresponding to pre- and post-maintenance scenarios are given in **Table 1** (columns 3 and 4) for comparison.

The parameters reported in column 4 of **Table 1** (post-maintenance test results) are within the permissible limits as per the IS:1866-2000 (reaffirmed in 2010) [7]. DGA indicates normal internal condition of the transformer after repair and re-commissioning.

2.3 Case study-2: Time-based trend monitoring

This case study gives the details of trend monitoring of the insulation condition by online AE tests conducted on a 1-phase generating transformer (GT-X), in operation at a hydroelectric power station in India. A single-phase generator transformer of 25 MVA, (11kV/230/√3 kV, 1 Phase with Oil Forced Water Forced type of cooling system) was tested for online acoustic emissions. The layout of AE sensors mounted on the transformer is depicted in Fig. 2. The test was first carried out in the year 2005 and repeated in the years 2009 and 2010 as part of a periodic monitoring and condition-assessment exercise. The view of the transformer with sensors mounted is shown in Fig. 6, in which the sensors mounted on the transformer tank on the HV bushing side are seen.

During March 2005, the AE test was carried out on the transformer for the first time. The magnitude of the AE signal was found to be 40 db (max) (see column 2, **Table 6**). Tests on transformer oil like DGA and BDV were also conducted. The oil test results were normal and no abnormalities were observed (see column 3, **Table 4**).

Table 4

DGA and BDV test results of transformer oil of GT-X in three different years.

TEST	DISSOLVED GAS TYPE	2005	2009	2010
DGA	Methane [ppm]	2	1	ND
	Ethane [ppm]	1	ND	ND
	Ethylene [ppm]	4	1	ND
	Acetylene [ppm]	ND	ND	ND
	Hydrogen [ppm]	ND	15	ND
	Oxygen [ppm]	31157	37721	-
	Nitrogen [ppm]	66310	53558	-
	Carbon Monoxide [ppm]	ND	ND	ND
	Carbon Dioxide [ppm]	763	572	ND
BDV	Breakdown Voltage [kVrms]	63	83	76

Table 5

Load condition of transformer GT-X while capturing AE signal.

PARAMETER	2005	2009	2010
Power	21.3 MW	20 MW	20 MW
Reactive power	5.2 MVAR	5.0 MVAR	5.5 MVAR
HV side voltage	231/√3 kV	230/√3 kV	230/√3kV
LV side voltage	11.2 kV	11 kV	11.04 kV
HV current	285 A	263 A	266 A
LV current	3400 A	3170 A	3210 A
Power factor	0.97	0.97	0.98
Frequency	49.8	49.8	49.3
Oil temperature	48º C	34º C	50º C
Winding temperature	60º C	46º C	56º C

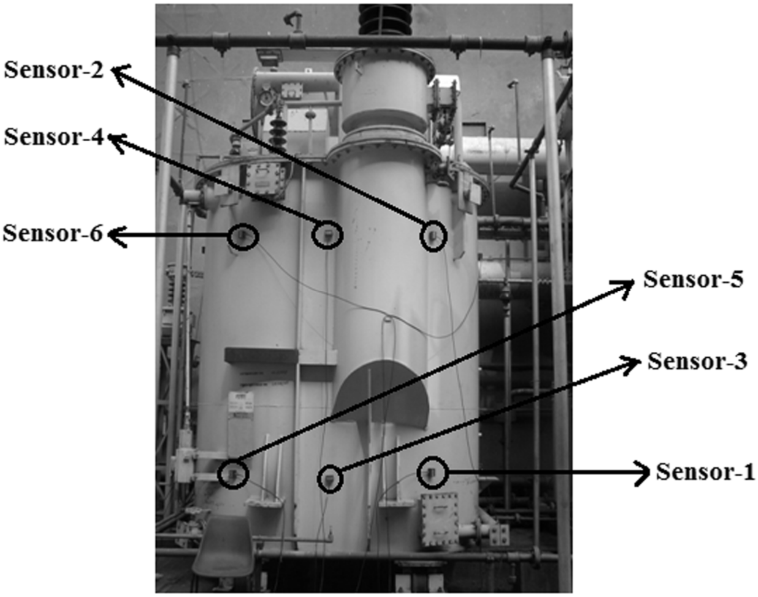

Fig. 6 – *View of 25 MVA 11 kV/230/√3kV single-phase Generator Transformer (GT-X) with AE sensors mounted.*

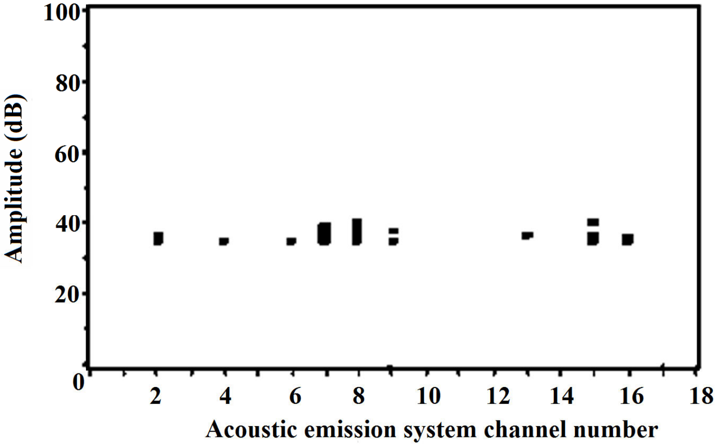

Fig. 7 – *AE Amplitude for 16 AE channels recorded for transformer GT-X in the year 2005.*

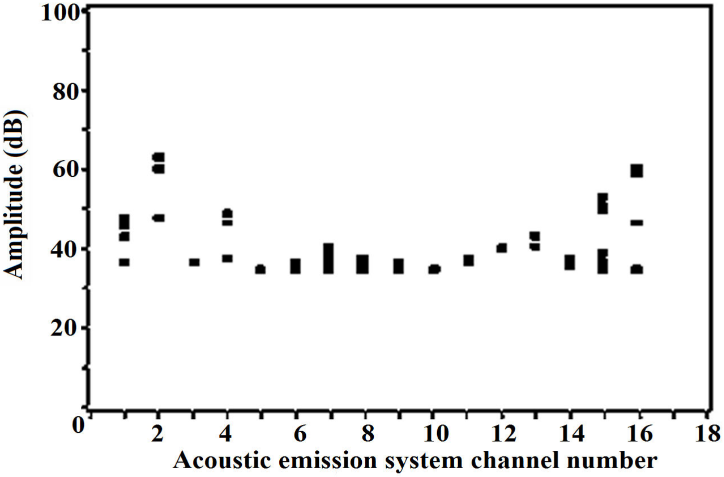

Fig. 8 – *AE Amplitude for 16 AE channels recorded for transformer GT-X in the year 2009.*

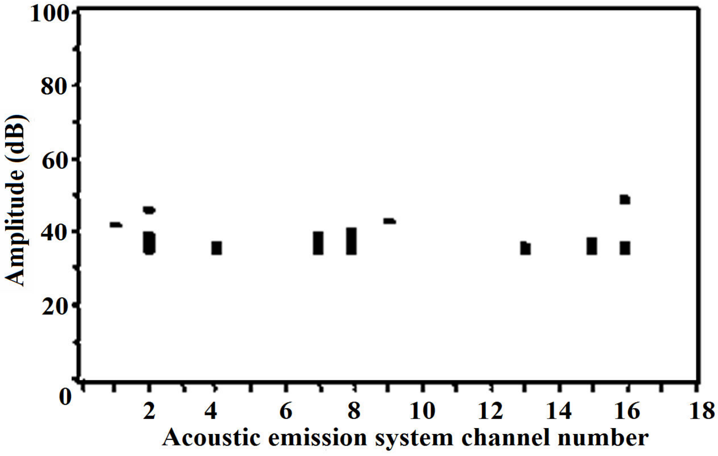

Fig. 9 – *AE Amplitude for 16 AE channels recorded for transformer GT-X in the year 2010.*

During January 2009, power station personnel observed that there was a minor issue with the transformer cooling system, resulting in an ingress of moisture. Therefore, maintenance activities were undertaken by the power station personnel for dehydration, degasification and oil filtration, and the transformer was put back into service. After four weeks of transformer energization, the transformer oil was tested again for DGA and BDV by the power station personnel in February 2009. From the DGA results, the hydrogen content was 15ppm, which was considered to be high, taking into account the time gap between the maintenance activity carried and the oil-testing date. At this point, power station personnel asked CPRI to carry out an AE test on the transformer during March 2009. The AE test results indicated an AE magnitude of 63 dB (max) at sensor positions 2 and 16 (see Fig. 8), indicating electrical discharge activity in the transformer's high-stress region near HV bushing. It was suggested to the power station personnel by CPRI to attend to the problem and repeat the AE test and DGA immediately after the necessary maintenance activity.

After completing the required maintenance (further details of maintenance activity are not available with the authors as their work is restricted to AE signal measurements in the field), the transformer was put back into service, and subsequently, a DGA test was carried out in January 2010 by the power station personnel, and CPRI was requested to repeat the AE test on the transformer. The AE test was carried out under near-identical conditions of loading during March 2010. AE signals captured during the test in 2005, 2009 and 2010 are depicted in Figs. 7, 8 and 9, respectively.

The DGA and Oil breakdown strength (BDV) test results carried out in the years 2005, 2009 and 2010 are given in **Table 4**. The condition of transformers while these tests were conducted is summarized in **Table 5**.

AE signals captured for this transformer during the year 2010 are depicted in Fig. 9. The maximum AE signals captured for the generator transformer (GT-X) are summarized in **Table 6** for the sake of comparison. As can be seen from **Table 6**, the magnitude of AE signals reduced to 49 dB in 2010 as compared to 63 dB in 2009, and no gases in DGA were detected, including hydrogen, as shown in **Table 4**, indicating the healthy condition of the transformer and the effectiveness of the maintenance activities carried out by the power station personnel.

This time-based trend monitoring of transformers adopting the AE method helps in fault detection, even though the AE method is thought to be apt for condition-based monitoring of power transformers.

Table 6

Maximum amplitude of Acoustic Emission signal captured for transformer (GT-X) recorded in different years.

TRANSFORMER IDENTIFICATION	MAX. LEVEL OF ACOUSTIC EMISSION SIGNALS (dB)		
	Year 2005	Year 2009	Year 2010
GT-X	40	63	49

3 Conclusion

An online acoustic emission technique was adopted to assess the internal condition of generator transformers at various power stations in India. Being an online technique AE testing can be carried out at various stages, such as immediately after commissioning, after a few years of operation. This helps in condition-based monitoring, but the identical transformer data and time-based monitoring data of the AE test further help to analyze the issue. Such field-data-based case studies are reported probably for the first time. This should help all practicing power engineers. The following specific conclusions can be made from these case studies:

1. DGA data and AEPD test data can supplement each other. So it is important to take into account gas results when interpreting AE data.
2. If the AE magnitudes are found to be high during the first measurement, then remedial measures can be suggested, otherwise the measured data would become the base data for future periodic measurement.
3. Problematic areas can be pinpointed by identifying the AE sensor which receives the signal with maximum AE amplitude.
4. Periodic monitoring has revealed improvements in the condition of transformer insulation when viewed using AE data. This is attributed to the necessary corrective maintenance activity carried out on those units.
5. The tests on identical transformer units facilitate the identification of incipient faults by comparing the AEPD levels.

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