ACOUSTIC EMISSION SIGNAL BASED INVESTIGATIONS INVOLVING LABORATORY AND FIELD STUDIES RELATED TO PARTIAL DISCHARGES & HOT-SPOTS IN POWER TRANSFORMERS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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DECLARATION

by the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **ACOUSTIC EMISSION SIGNAL BASED INVESTIGATIONS INVOLVING LABORATORY AND FIELD STUDIES RELATED TO PARTIAL DISCHARGES & HOT-SPOTS IN POWER TRANSFORMERS** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in Department of Electrical and Electronics Engineering is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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C E R T I F I C A T E

This is to certify that the Research Thesis entitled **ACOUSTIC EMISSION SIGNAL BASED INVESTIGATIONS INVOLVING LABORATORY AND FIELD STUDIES RELATED TO PARTIAL DISCHARGES & HOT-SPOTS IN POWER TRANSFORMERS** submitted by **TANGELLA BHAVANI SHANKER (Register Number: 092013EE09P04)** as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy.**

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Abstract

Power transformers are important and vital components of ac power systems. It is essential to monitor the condition of these transformers periodically in order to ascertain the performance for continuous operation for its expected average life of 25-30 years. The defects in power transformers lead to the deterioration of insulation and eventual premature failure. The deterioration of insulation of power transformers can be assessed by carrying out the condition monitoring tests periodically. The condition monitoring test techniques can be off-line or on-line. The off-line test techniques are being followed as given in IEEE Std. 62(1995). These tests require outage of the transformer, thereby causing interruption of power supply. Whereas, on-line test techniques do not require any outage. Hence, on-line diagnostic techniques have gained importance. Literature review shows application of Acoustic Emission (AE) detection technique as a promising on-line tool for condition monitoring/diagnosis of the power transformers. The general guidelines for the application of AE technique for this purpose are outlined in IEEE Std. C57.127 (2007).

Few typical case studies of AE signal measurements are discussed involving (i) two identical transformers, (ii) same transformer on different occasions (years) in power stations in India are reported. Some case studies with AE signals, involving On-Load Tap Changer (OLTC) and cooling system pump are also reported. These case studies also help in comprehending the efficacy of integrating the Dissolved Gas Analysis (DGA) data with the AE test results.

Laboratory experimental work is carried out by simulating the most probable defects like Partial Discharge (PD) and hot-spots (leading to heat-waves) in order to capture AE signals in the range of 0-500 kHz. The classification and characterization of the defects based on the energy distribution of AE signals over the different frequency ranges is carried out using Discrete Wavelet Transform (DWT) utilizing the MATLAB toolbox. The eight-level decomposition revealed that the dominant frequency ranges for the energy distribution of the AE signals due to PD and heat-wave are 125 kHz-250 kHz and 62.5 kHz–125 kHz, respectively. The AE signal data from the transformers (field test) involving PD and hot-spots are also analyzed using DWT. The laboratory based characterization of PD and heat-wave got validated through the analysis of field data. The proposed method of identifying defects by AE signal analysis using DWT would complement the DGA of the transformer-oil. Thus this would be a better substitute for DGA based analysis as AE based technique can be adopted in real time.

The Acoustic Emission Partial Discharge (AEPD) signal parameters such as discharge magnitude and peak frequencies are studied using Fast Fourier Transform (FFT) to understand the behavior of AE signals at temperatures ranging from 30°C to 75°C. The results reported are intended to give an understanding of behavior of AEPD signals over the entire working temperature range of a transformer. At temperatures above 65°C a reduction in AEPD magnitude and peak frequencies are observed. Such behavior is noticed and probably being reported for the first time. An attempt is also made to explain the same.

Key Words— Acoustic emission (AE), Acoustic emission partial discharge (AEPD), Discharge magnitude, Discrete wavelet transform (DWT), Dissolve gas analysis (DGA), Fast Fourier transform(FFT), Generator transformer(GT), Hot-spots (heat-waves), On-load tap changer (OLTC), Partial discharge (PD).

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List of Symbols

$f(t)$	: Signal
$\Psi(t)$	: Mother wavelet function
$\Phi(t)$	: Father wavelet function
N	: Order of mother wavelet
a	: Scale parameter
b	: Position parameter
C (a, b)	: CWT coefficient
δ	: Loss angle
#	: Complex conjugate function
Fs	: Maximum signal frequency
α	: AEPD magnitude
β	: Breakdown Voltage
γ	: Viscosity
θ	: Temperature

List of Abbreviations

AE	: Acoustic Emission
AEPD	: Acoustic Emission Partial Discharge
BDV	: Break Down Voltage
CPRI	: Central Power Research Institute
CWT	: Continuous Wavelet Transform
dBae	: Decibels acoustic emission
DGA	: Dissolved Gas Analysis
DSP	: Digital Signal Processor
DWT	: Discrete Wavelet Transform
FFT	: Fast Fourier Transform
FIR	: Finite Impulse Response
FT	: Fourier Transform
GT	: Generator Transformer
HV	: High Voltage
ICT	: Inter Connecting Transformer
LPH	: Liters Per Hour
MRA	: Multi Resolution Analysis
OFAF	: Oil Forced Air Forced
OFWF	: Oil Forced Water Forced
OLTC	: On-Load Tap Changer
OTL	: Oil Test Laboratory

PAC	: Physical Acoustics Corporation
PDIV	: Partial Discharge Inception Voltage
PDs	: Partial Discharges
RVM	: Residual Voltage Measurement
SFRA	: Sweep Frequency Response Analysis
SOM	: Self Organizing Map
STFT	: Short Time Fourier Transform
TDCG	: Total Dissolved Combustible Gases
UHF	: Ultra High Frequency

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The Government of India, Ministry of Power, has set ambitious targets of investments in the power sector for sustaining the economic growth. As on November 2016, the installed capacity of power generation in India has touched 308.814 GW with 214.004 GW from Thermal, 43.113 GW from Hydro, 5.780 GW from nuclear and remaining 45.917 GW from other sources (Ministry of Power 2016). Capacity addition of 54,000 MW and 1, 00, 000 MW were planned during the eleventh and twelfth five-year plan, respectively. Approximately 97,456 MVA of transformer capacity was added during the years 1983-1987 and 238,150 MVA during the years 1987-1989. Approximately 1, 28, 403 MVA of transformer capacity was added during the last two years i.e., 2014-2015 and 2015-2016. As the average life expectancy of the transformers is 25-30 years, they are expected to be replaced during the eleventh and twelfth five-year plan periods (Mehta 2010). The addition/replacement of the power transformers involves huge investments. Hence condition assessment/diagnosis of the existing transformers, for extending the life of the power transformers would be the focus area for the utilities in association with the organizations like Central Power Research Institute (CPRI) in India.

1.1.1 Importance of transformers in power system

In the power system, the transformers provide the vital link between the generation and the distribution of power. Condition of the transformers is very important for maintaining the continuity of power supply. The commonly used power transformers of importance are (a) Generator Transformers (GTs), (b) Interconnecting Transformers (ICTs) (c) Distribution transformers. The power rating of these transformers varies from few MVA to few hundreds of MVA and the voltage ratings ranging from 11 kV to 1000 kV. The transformers are capital intensive and require more attention. The proper maintenance helps in increasing the life expectancy of these transformers up to 50 years (Wang 2002)

1.1.2 Various defects in transformers

The defects in the transformers can occur due to (a) External conditions of the power system and/or (b) Internal conditions of the transformer. The defects due to external conditions are usually triggered by severe external system disturbances such as lightning strokes, switching surges, short circuits and system overload. When the transformers are new, they have sufficient electrical and mechanical strength to withstand these disturbances due to external system conditions. As the transformers age, their insulation strength degrades to a point that they cannot withstand severe external system conditions.

The defects due to internal conditions may occur in both the new transformers and the transformers in service. Some of the causes for the probable defects in the transformers are insulation deterioration, overheating, moisture, solid contamination in the insulating oil, Partial Discharge (PD) and design & manufacturing defects (Wang 2002).

The defects like voids, conducting particles, sharp conductor edge etc., present in the transformers lead to PDs. This degrades the electrical insulation leading to the catastrophic failure of the equipment. Hence the PD activity is a precursor of the insulation failure.

The defects such as loose connections lead to overheating (hot-spots), which in turn leads to excessive discharges. This results in the degradation of insulation leading to winding failure. The defect like core vibration may also leads to overheating of the core and eventual degradation of the insulation.

The defects due to external system conditions or internal defects present in the transformers would lead to its premature failure. The cost and time incurred in the repair/replacement of the transformers are very high. The condition monitoring/assessment and periodic maintenance are the key factors for the successful operation of the transformers. Hence the various condition assessment techniques are adopted by the operating personnel in order to keep the transformers in healthy condition.

1.2 LITERATURE REVIEW

An exploration of the available literature reveals that ample work has been done in the field of condition assessment of transformers. For monitoring the condition of insulation system of power transformers, detection of PD is considered to be a very appropriate tool. Among the various PD detection methods, Acoustic Emission Partial Discharge (AEPD) detection is found to be advantageous. This section gives a detailed literature survey in the area of condition assessment of transformers, PD and Acoustic Emission (AE) technique. The related subareas of research and the corresponding prominent literatures are depicted in Figure 1.1.

1.2.1 Condition assessment of transformer

The different condition assessment methods followed by the industry are either time based or condition based. The time based condition assessment are carried out on fixed time schedule i.e., during the shutdown period or periodic annual maintenance schedules. The condition based assessment is carried out depending on the observed changes occurring over a period of time, when the age of the transformer approaches the end of the normal design life. Thus, condition based maintenance is carried out only if the situation demands it, unlike in the case of time based maintenance (Han 2003)

Diagnostic techniques are essentially non-intrusive to assess the internal condition of the equipment and are classified into two categories such as off-line diagnostic techniques and on-line diagnostic techniques.

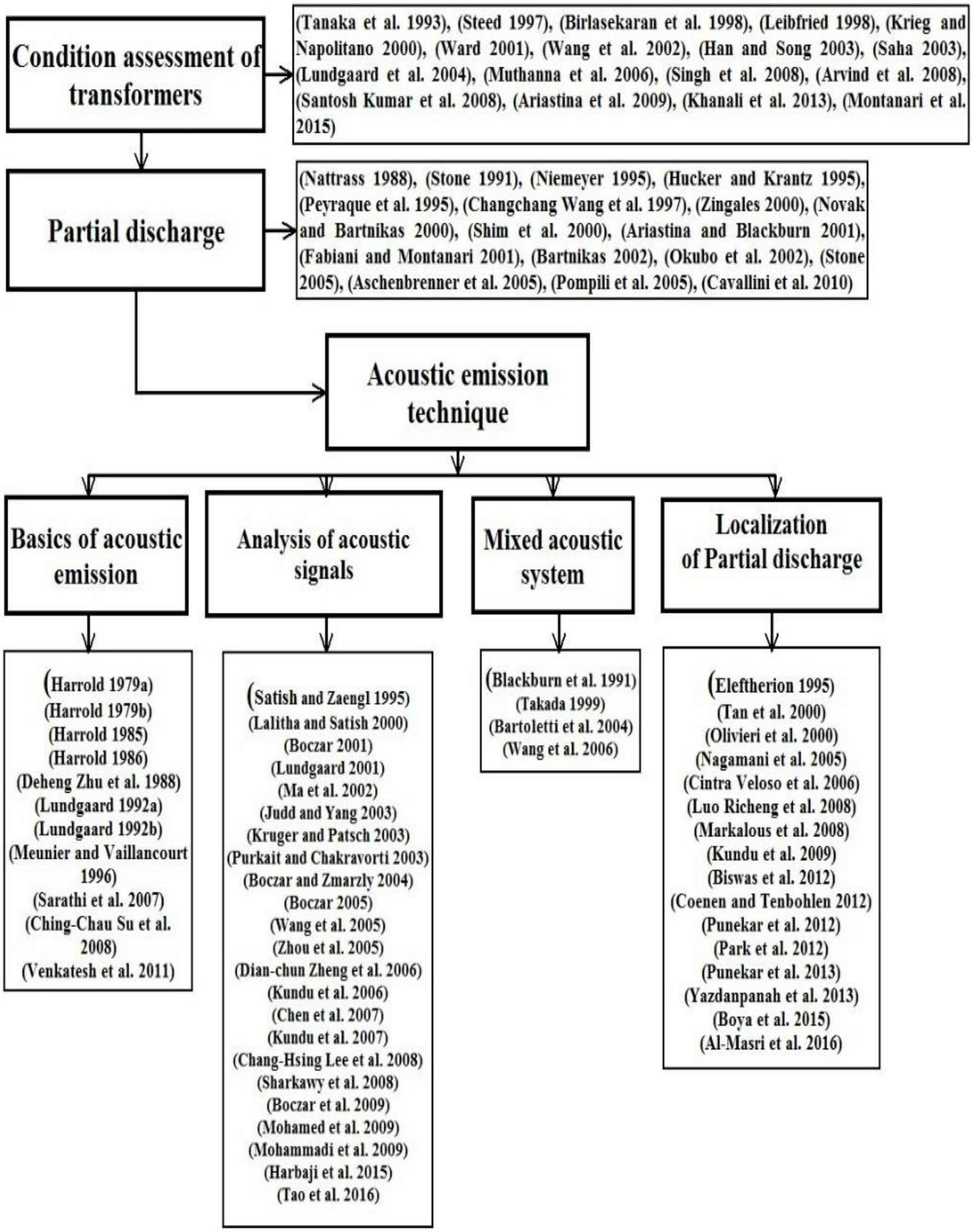


Figure 1.1: Block schematic depicting the literature review showing some of the prominent contributions on related subareas of research

i) Off-line diagnostic techniques

Off-line diagnostic techniques require the electrical disconnection of the transformer from the circuit to carry out the tests. During these tests the transformer will be out of service and thereby causing inconvenience to the end user. The major off-line condition assessment techniques of transformers are listed below.

a) Insulation Resistance/Polarization Index
b) Winding resistance test
c) Winding ratio test for two winding transformer
d) Magnetic Balance test
e) Capacitance & tanδ test or power factor test on windings and bushings
f) Surge comparison test
g) Residual Voltage Measurement (RVM)
h) Sweep Frequency Response Analysis (SFRA)
i) Dielectric Spectroscopy
j) Dielectric Polarization test on cellulose paper

ii) On-line diagnostic techniques

As the name suggests, these diagnostic techniques do not require the disconnection of transformers from the circuit and thereby no interruption of power to the end-user. Some of the on-line techniques that are normally applied to the transformers are

a) Dissolved Gas Analysis (DGA)
b) Furan analysis
c) Infrared thermography
d) AEPD test
e) Ultra High Frequency (UHF) PD detection

The DGA and Furan analysis are generally carried out at regular time intervals in order to know the internal condition of the transformers. In case of any deviations in the measured values above the permissible levels, further on-line test like AE-test are being carried out (Ward 2001).

1.2.2 Partial Discharges

The PD is a localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor. The PD is in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally, such discharges appear as pulses having duration of much less than 1 µs. However, more continuous forms can occur, such as the so-called pulse-less discharges in gaseous dielectrics (IEC 60270 2000).

The main reasons for the occurrence of PD are the non-uniform stress distribution in the insulation, impurities or inclusion of voids in the homogeneous mass of an insulating material, the presence of composite dielectrics resulting in unequal stress distribution owing to different dielectric constants.

PDs are of four types (Bartnikas 2002, Punekar et al. 2013)

a) Surface discharges appearing at the interfaces of dielectric surfaces
b) Internal discharges occurring in voids or cavities within solid or liquid dielectrics
c) Continuous impact of discharges in solid insulation forming discharge channels
d) Corona discharges occurring in gaseous dielectrics in the presence of inhomogeneous fields

The energy by-products of PDs such as electrical transients, chemical changes, electromagnetic emissions, vibration, sound, light, and heat are to be measured to detect and quantify PD, as direct measurement of PD is not possible (IEEE C57.127 2007). The non-invasive nature and the immunity to the electromagnetic noise and interference make acoustic methods of PD measurement more advantageous (Lundgaard 1992a).

All insulation related problems involve PDs in the initial stages of failure process. Hence, the early detection of PD sources in the insulation system is very important. The PD is considered as one of the important diagnostic techniques for assessing the condition of the power equipment (Lundgaard 1992b). The conventional electrical method for measurement of PD is well established and widely accepted (IEC 60270

2000). However, conventional electrical PD method has certain practical limitations as listed below:

Electrical PD test requires elaborate arrangements such as

a) PD free source
b) PD free coupling capacitors
c) PD detector with noise filter
d) Electromagnetic shield to suppress back ground noise.

Above limitations, particularly large background noise and elaborate arrangements at site, have led to the development of alternate techniques for the measurement of PD. Therefore, on-line techniques which does not require shutdown of the transformer, are gaining greater importance.

1.2.3 Acoustic Emission Partial Discharges

The AE detection technique is gaining importance as a powerful on-line technique for the detection of PD and other defects. The development in the area of high frequency sensors, high-speed instrumentation, signal processing and software tools have led to the enhanced application of AE technique. Some of the important terminology related to AE technique related to PD applications is elaborated in this subsection.

1.2.3.1 Basics of Acoustic Emission

The PD results in localized, instantaneous release of energy. In oil immersed power transformer, a part of the energy released due to the generation of PD heats up the adjacent material, and creates a small explosion by evaporating it. The discharge location acts as a source of acoustic waves. As the discharge duration is very short, they have broad acoustic spectrum. The intensity of acoustic waves depends upon the energy released (Lundgaard 1992a).

i) Definitions and Terminology related to Acoustic Emission detection

The document ASTM E-1316 (2016) gives the definitions and terminologies used in AE testing. Some of the important among them are given below:

a) **Acoustic Emission:** Elastic waves generated by the rapid release of energy from sources within a material.

b) **AE Activation:** The onset of AE due to the application of a stimulus such as force, pressure, heat etc.

c) **AE Amplitude:** The largest voltage peak in the AE signal waveform, customarily expressed in decibels acoustic emission (dBae).

d) **AE Channel:** A single AE sensor and the related components for transmitting, conditioning, detecting and measuring the signals.

e) **AE Counts:** The number of times the AE signal crosses the detection threshold. This is also known as “ring down counts”, “threshold crossing count”.

f) **AE Event:** A local material change giving rise to AE.

g) **AE Hit:** The detection and measurement of an AE signal on a channel.

h) **Rise-time:** The time from an AE signals first threshold crossing to its peak measured in microseconds.

i) **Duration:** The elapsed time between the first thresholds crossing to the last.

ii) Acoustic PD detection circuit

The acoustic PD detection circuit consists of sensors, preamplifier, filters and data acquisition system. The sensors are placed nearer to the locations where faults may be anticipated based on past experience or highest probability of problems occurrence. The use of a band-pass filter is optional. Its purpose is to negate the effects of signals that are not associated with PDs as much as possible. The data acquisition/processing systems are able to transmit collected data and/or warning alerts to locations outside the substation (IEEE.C57.127 2007).

There are mainly two types of PD detection systems, the all-acoustic system and the acoustic system with an electrical PD trigger. The all-acoustic system consists of one or more ultrasonic transducers to detect the presence of PDs whereas acoustic system with electrical trigger has, in addition, a voltage or current measurement device which detects PD electrically (IEC 60270 2000, Su et al. 2008, Kundu et al. 2007). The typical block schematic of AEPD detection systems is as shown in Figure 1.2.

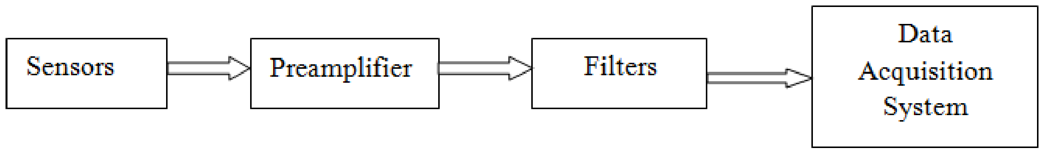


Figure 1.2: Typical block schematic of AEPD detection system

The AE signals obtained from the electrical apparatus are captured by the sensors and amplified to required levels by suitable pre-amplifiers and transferred to the signal processing instrument, where it is further amplified and filtered. The filtered AE signal will be passed through a comparator set with a predetermined threshold. The signal processing unit has the option to set the threshold which would be set by the operator of the instrument.

iii) Principles of acoustic emission detection

The AE tests are being carried out, owing to the advantage of detection of probable defects inside the transformer along with the location of the defect. The AE test, being non-destructive, non-invasive and on-line technique for condition assessment of internal condition of the transformer, is gaining importance. Further, AE signal analysis would help in classification of defects which would help the maintenance personnel to take appropriate remedial measures before any breakdown occurs.

1.2.3.2 Analysis of acoustic emission signals

The AE signals are basically non-stationary signals with overlapping bursts of unknown amplitudes. The main problem in AE signal analysis is the estimation of AE parameters, to understand the characteristics of PDs in the transformer oil. Multi resolution time-frequency analysis is required for the proper extraction of its features (Kundu et al. 2008, Boczar 2003, Boczar et al. 2004, Boczar et al. 2008, Boczar et al. 2009, Shu-Jen 2002).

i) Drawbacks in Fourier transform analysis

The Fourier Transform (FT) is a mathematical method of transforming a function of time into a function of frequency. The basic limitation of the FT is connected with the fact that, the accurate information on the frequency spectrum of a signal can be obtained only in the case when its-run is known in an unlimited time range. Additionally, the assumption that a signal is stationary in time (with reference to frequency) is required. As FT does not give joint time-frequency representation of the signals, the use of FT analysis is not preferable in processing non-stationary AEPD signals (Boczar and Zmarzły 2004)

The Short Time Fourier Transform (STFT) can provide joint time-frequency representation of the signal, but the resolution is limited. According to Heisenberg uncertainty principle, the product of standard deviation in time and frequency is limited (Mallat 1989). So, if the time resolution is high, frequency resolution will be less and vice versa. And the resolution depends upon the window length. In the case of STFT, the window length is fixed. So, a narrow window length gives good time resolution and poor frequency resolution and vice versa. When the signal requires more time resolution (or more frequency resolution) at some portions of the signal, the representation becomes inaccurate.

ii) Wavelet transform

A wavelet transform is the representation of a function or a signal by wavelets. The wavelets are defined by the wavelet function $\psi(t)$ (i.e. the mother wavelet) and scaling function $\varphi(t)$ (also called father wavelet) in the time domain. The wavelet function is a band pass filter and the scaling function is a low pass filter. The scaling at each level halves the bandwidth of the wavelet function. This requires infinite number of levels to cover the entire frequency spectrum. The scaling function filters the lowest band of the transform and ensures that the entire spectrum is covered (Misti et al. 1996).

The wavelet analysis represents windowing technique with variable sized regions. This is realized by comparing the signal with time shifted and scaled versions of the base wavelet. The wavelet transform allows the use of long time intervals where more precise low-frequency information is required, and shorter time intervals where the high-frequency information is required.

The wavelets are scaled and translated copies (known as "daughter wavelets") of a finite-length or fast-decaying oscillating waveform is known as the "mother wavelet". There are basically five families of wavelets, namely Crude wavelets, infinitely regular wavelets, Orthogonal wavelets, Biorthogonal wavelets and Complex wavelets. They are categorized based on their properties and the type of analysis (Misti et al. 1996).

iii) Features of wavelets

The features of mother wavelets have considerable influence on the accuracy of time-frequency representation of the signal. There are mainly five features of the wavelets which influence the analysis of a signal, namely, orthogonality and biorthogonality, support width, regularity, vanishing moments and group delay difference.

There are two types of wavelet transform (Misti et al. 1996)

- Continuous Wavelet Transform (CWT)
- Discrete Wavelet Transform (DWT)

iv) Continuous Wavelet Transform

The CWT compares the signal with that of shifted and compressed or stretched versions of a wavelet. By comparing the signal with that of the wavelet at various scales and positions, a function of two variables is obtained. The two-dimensional representation of a one dimensional signal is redundant. If the wavelet is complex-valued, the CWT is a complex-valued function of scale and position. If the signal is real-valued, the CWT is a real-valued function of scale and position. For a scale parameter a > 0, and position b, the CWT is given in equation 1.1.

$$C\ (a, b; f\ (t), \Psi\ (t)) = \int_{-\infty}^{\infty} \left(\frac{f(t)}{\sqrt{a}}\right) * \Psi^{\#}\left(\frac{t-b}{a}\right) dt \qquad (1.1)$$

Where # denotes the complex conjugate, f (t) is the signal and Ψ (t) is the mother wavelet.

By continuously varying the values of the scale parameter a, and the position parameter b, CWT coefficients C (a, b) are obtained. The CWT coefficients at lower scales represent energy in the input signal at higher frequencies, while CWT coefficients at higher scales represent energy in the input signal at lower frequencies (Misti et al. 1996). Figure 1.3 shows the CWT coefficient spectrum of a signal.

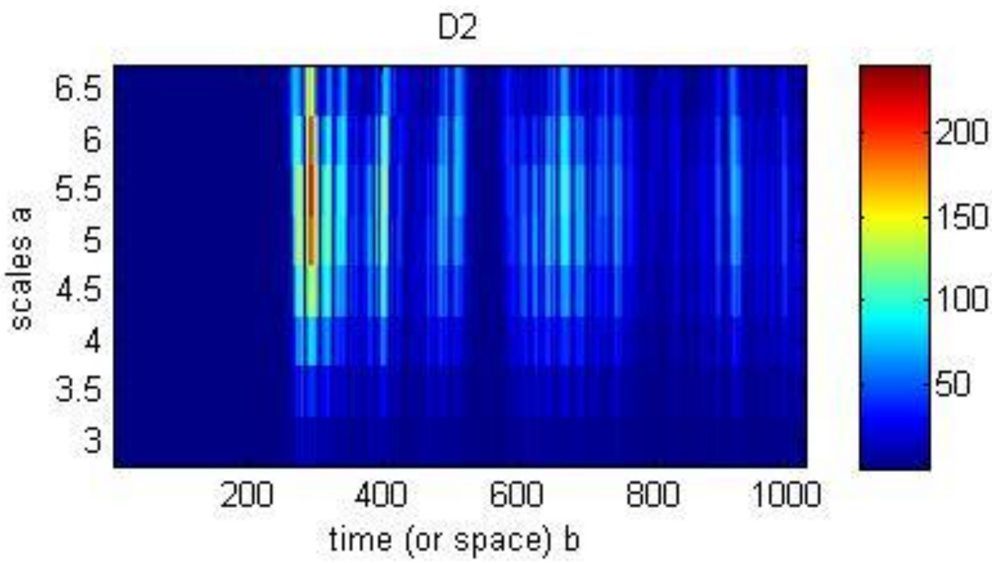


Figure 1.3: CWT coefficient spectrum of a signal

v) Discrete Wavelet Transform

In CWT, scales and position take continuous values and has redundant information. If the scales are dyadic, then it is called DWT. The DWT based analysis uses the concept of filter banks. The filters of different cut-off frequencies analyze the signal at different scales. Resolution is changed by the filtering, where the scale is changed by up-sampling and down-sampling.

In the initial stage of DWT, the signal is decomposed into approximations and details. Approximation contains low frequency components and details contain high frequency components. Then at each stage, approximation of previous stage is decomposed into high frequency and low frequency components, but the detail will remain intact. Each mother wavelet has decomposition of low pass and high pass filters. There are corresponding reconstruction filters to synthesize the decomposed signal. The decomposition filter and corresponding reconstruction filter are together called as quadrature mirror filters (Misti et al., 1996). Figure 1.4 shows the three-level decomposition of signal and the frequency bands of approximation and details.

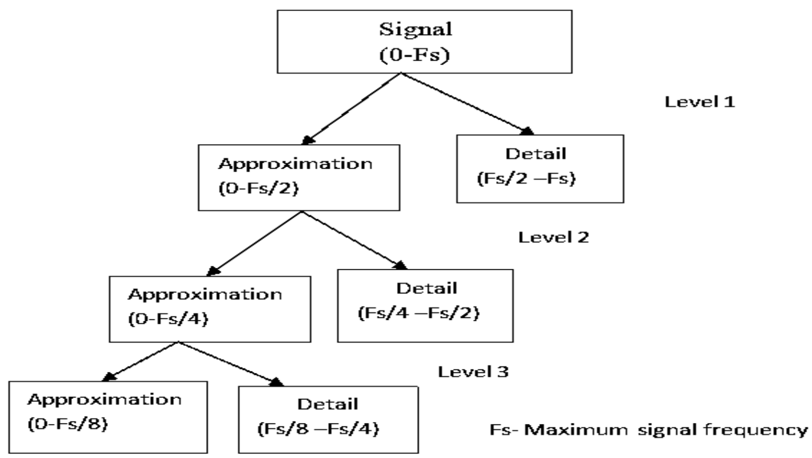


Figure 1.4: Three-level decomposition of signal using DWT

vi) Symlet wavelets for DWT analysis

Among the five wavelet families, DWT analysis with Finite Impulse Response (FIR) filters is possible only for Orthogonal and Biorthogonal wavelets. Daubechies, Coiflets and Symlets belong to Orthogonal wavelet family. Daubechies wavelets are compactly supported, with extreme phase and highest number of vanishing moments for a given support width. The associated scaling filters are minimum-phase filters. Symlets are near symmetric compactly supported wavelets with highest number of vanishing moments for a given support width (Misti et al. 1996). Associated scaling filters of Symlets are near linear-phase filters. Coiflets are compactly supported wavelets with highest number of vanishing moments for both basis and scaling function for a given support width. They are near symmetric wavelets (Misti et al. 1996). The only difference between Daubechies and Symlet family is in symmetry. Daubechies wavelets and Symlets of same order have same support width and vanishing moments, but Daubechies wavelets are asymmetric and Symlets are near symmetric. Coiflets are developed for a particular application in numerical analysis that requires scaling function which possesses highest number of vanishing moments. For a given support width, Coiflets have double the number of vanishing moments and increased support width compared to Symlets of the same order (Mallat 1989). Due to this, among Orthogonal wavelets, Symlet family is preferable for DWT analysis (Athira et al. 2014). In the present study, Symlet mother wavelets of MATLAB toolbox is used for DWT analysis. The features such as support width, filter length and vanishing moments depend upon the order (N) of mother wavelet. The features of Symlet wavelet family are given in Table 1.1.

In the present study, DWT using Symlet-8 mother wavelet is used for decomposing the AE signal of frequency 0-500 kHz, into eight frequency ranges. The process of decomposition is similar to 3-level decomposition depicted in Figure 1.4.

Table 1.1 Features of Symlet wavelet family

Wavelet	**Support width (2N-1)**	**Filter length (2N)**	**Vanishing moments (N)**
Sym1	01	02	01
Sym2	03	04	02
Sym3	05	06	03
Sym4	07	08	04
Sym5	09	10	05
Sym6	11	12	06
Sym7	13	14	07
Sym8	15	16	08

The frequency ranges are of the decomposition are:

D1 (250 kHz - 500 kHz),

D2 (125 kHz - 250 kHz),

D3 (62.5 kHz - 125 kHz),

D4 (31.25 kHz - 62.5 kHz),

D5 (15.63 kHz - 31.25 kHz),

D6 (7.81 kHz - 31.25 kHz),

D7 (3.90 kHz - 7.81 kHz) and

A7 (0 kHz - 3.90 kHz).

Where, frequency ranges D1 to D7 are the details, and residue A7 is the approximation.

An attempt has been made to understand the available literature in the area of on-line diagnosis of power transformers employing AE technique. The evolution of AE technique over the years, for the condition assessment of power transformers (and related literature) is as follows.

During early eighties, Harrold (1979a, 1979b, 1985 and 1986) has dealt with the fundamentals of acoustics in his paper. The relationship between the acoustical parameters and corona discharge quantities were also studied. Application of acoustical techniques for detection and location of corona discharges in electrical apparatus such as rotating machines, transformers, capacitors and specialized insulation systems have been discussed. The author expressed that the field of acoustical methods for the detection of discharges will continue to play a most important role wherever the location of the discharge site is of prime concern.

In early nineties, Lundgaard (1992a and 1992b) has explained the practical application of the AE technique for the PD detection where the electrical methods are insensitive as in the case of large capacitors. The major advantages of AE technique are its immunity to electromagnetic interference under field conditions and the ability to locate the PD sources within a large apparatus such as power transformers. The author has explained the benefit of acoustic techniques and emphasizes the application of acoustic technique for on-site testing.

Zhu et al. (1988) have studied the AE method to detect the PD in insulation of power transformer by the simulation of six typical oil gaps. The frequency spectra of the AE of the PD in these gaps have been investigated. The AE due to magnetic noise and the frequency spectra associated with the magnetic noise have also been investigated and presented in their paper.

Theory for multi resolution signal decomposition using the wavelet representation was dealt by (Mallat 1989).

Blackburn et al. (1991) have presented the findings of simultaneous application of electric/acoustic method for the detection and location of PDs in power transformers.

Typical case study of 330/√3 kV / 35 MVA transformer has been studied. An acoustic detection sensitivity of 20 dB has been reported.

Eleftherion (1995) has dealt with the application of the AE technique for the transformer PD source localization in the field and factory environments. This is using a multi-channel computerized AE instrument (Model: SPARTAN-AT) along with location software-package. He suggested the possibility of advancement in the application of AE with the aid of utilities and laboratory interactions.

Musil et al. (1995) presents the properties of transformer oil such as viscosity as a function of temperature and pressure. The AC breakdown voltage as a function of temperature with varying water content is also discussed in this paper.

Blackburn et al. (1991) studied the propagation of AE signals due to PDs in oil filled transformers. The findings of their research revealed that the acoustic signals were found to propagate according to a rectangular hyperbolic function both inside the oil and longitudinally within the tank wall at speeds of 138 cm/ms and 495 cm/ms, respectively. It was reported that an approximate relationship exists between AE signal magnitude and electrical PD source expressed in pC, provided no large obstacle is present in the signal path.

Boczar (1997, 2001) has studied frequency spectra and associated bandwidths of the AE signals related PD measurements. The spectral analysis carried out in his work has enabled to identify a specific type of PD from the associated frequency spectra. Further research work was suggested, based on his observation, for the use of AE method for detection, location and measurement of PD generated in insulation systems of electric power installations.

Olivieri (2000) in their paper suggested that PD measurements by both acoustic and electromagnetic methods can supplement the findings of other techniques such as DGA, in order to increase the reliability of the final diagnosis of power transformers.

Kang (2001a) discusses the automatic classification of On Load Tap Changer (OLTC) vibration signatures using a Self Organizing Map (SOM) and the development of extraction procedures.

Kang (2001b) deals with the condition monitoring of power transformer on-load-tap-changers and detection of ageing from its vibration signatures.

Miller et al. (2002) investigated the suitability of AE technique to detect, locate and assess different active gassing sources in transformers. The test procedures adopted for carrying out the work involving certain case studies (in collaboration with Electric Power Research Institute and other utilities) is reported. The authors intend to develop pattern recognition and signal classifier tools as their further work.

Nunez (2003) has presented case studies for the application of AE as a useful tool for monitoring and analyzing PD and other problems in power transformers. The studies were carried out both in the field and the manufacturer's premises. They have attempted to provide early warnings in order to avoid premature failures.

Boczar et al. (2004), applies the wavelet analysis for processing the AE pulses generated by PD in oil insulation systems. The frequency structures of AE pulses generated by PD in six basic forms such as a) those due to multi point-plane, b) surface type, c) multi-point type with press board insulation, d) gas bubble, e) point-plane spark gap and f) indefinite potential particle have been studied and reported in their paper. The research carried out is aimed at creating fingerprint for each of these PD forms, which would make unique identification possible. The experiments were carried out by the authors under laboratory conditions without taking into account the interfering signals. They suggest further research by taking this aspect into consideration and to broaden the application of AE method in the diagnosis of insulation systems operating in the electric power systems.

Wang et al. (2005) have studied the shift in the acoustic energy of the acoustic waves generated by PD in the transformer oil at different temperature. Acoustic waves generated by PD at two temperatures, namely, 25ºC and 40ºC were studied. Authors have analyzed the data with Fast Fourier Transform (FFT); their findings revealed that acoustic energy at 40ºC is larger than that at 25ºC.

Nagamani et al. (2005) have carried out experimental studies to characterize AE signals by simulation of defects in power transformers like PD, arcing and core vibration.

Detection and location of simulated defects have been verified with the AE system. The authors have performed FFT based analysis to discriminate noise from PD. Application of AE technique in the field has also been discussed.

Giscard et al. (2006) have dealt with the PD source localization in oil filled transformers using genetic algorithms.

Kundu et al. (2007) have analyzed AE signals using DWT by decomposing them into five different frequency bands such as D1 (250 kHz - 500 kHz), D2 (125 kHz - 250 kHz), D3 (62.50 kHz - 125 kHz), D4 (31.25 kHz - 62.5 kHz), D5 (15.625 kHz - 31.25 kHz). The AEPD signals for different sensor to source distance were analyzed through laboratory experiments.

Markalous et al. (2008) dealt with the detection and location of PDs in power transformers using Acoustic and Electromagnetic signals. The authors suggested that a comprehensive PD diagnostics for a transformer on-line/on-site can be obtained by carrying out electric PD measurements along with AE and electromagnetic measurement (UHF range).

Mohammadi et al. (2009). studied the AE signals generated due to PD and analyses the signals in time, frequency and time-frequency domains. Investigation indicated that frequency domain descriptors for classifying different PD patterns provided good results.

Some of the recent researches in the area of AEPD detection in power transformers include;

Kundu (2012) presents the identification and localization of two simultaneous PD sources using AE technique. The AE signals are measured for laboratory simulated PD in an oil-pressboard insulation system for three different electrode systems. The measurements of AEPD signals are carried out for two simultaneous PD sources. The measured signals are analyzed using DWT and box counting fractal dimension. Energy distribution in different frequency bands of DWT decomposed signal along with box counting fractal dimension is used for the classification of two simultaneous PD sources.

Harbaji et al. (2015) have dealt with the classification of different common PD types under different AE measurement conditions. The PD from a sharp point to ground plane, surface discharge, PD from a void in the insulation, and PD from semi parallel planes are considered. The collected AE signals are processed using pattern classification techniques to identify their corresponding PD types.

Zheng et al. (2015) have shown the use of algorithm such as semi-definite-relaxation method for UHF signal based PD localization. These algorithms are also applicable to AEPD source localization.

Al-Masri et al. (2016) presents an algorithm for the detection of a bias fault (error due to improper calibration or ageing of AEPD sensors) in the measurements of PD in the transformer insulation system using acoustic signals.

With the understanding of AEPD detection technique based on the related literature as discussed above, the motivation for the present research is given in the following section.

1.3 MOTIVATION FOR THE RESEARCH

The power transformers are a critical component of the power system and it involves huge investments. The condition monitoring plays a key role in upkeep of power transformers and for continued service life. There are several off-line and on-line techniques to monitor the condition of transformers. The off-line tests require outage of the transformers, thereby causing disruption of the power supply to the end user. Researchers were working on to identify on-line tests to assess the overall condition of the transformers. Of several on-line techniques, AE technique is gaining focus by most of the researchers for on-line condition monitoring of the transformers. Development of high frequency sensors, high-speed instrumentation, signals processing, and software tools has led to enhanced application of AE technique. Study of AE signals from various defects is gaining importance and considered as a promising area of research. This motivated to undertake a research work on AE based on-line diagnosis. The research work envisages insight into detection of AE signals from various defects like PD sources and hot-spots (heat-waves) in power transformers. It is observed that although DGA results of transformer oil can be used to classify the faults, such a method based on AE signals is not studied and reported in the literature. Thus AE signal analysis both in laboratory and correlation with field results resulting in classification of these defects got motivated. Although there are many technical contributions involving AEPD analysis, there are no reports involving field experiences in the literature. The outcome of this research work would help the power utilities and transformer industry for early detection of these defects. This also would greatly help the substation personnel for scheduling maintenance/repair of transformers.

1.4 OBJECTIVES OF THE RESEARCH WORK

The major objectives of the research work are as follows:

- **Field study** on condition monitoring and on-line diagnosis of the power transformers using the AE fault detection technique.
  These are the in-situ case studies which would add value to the body of knowledge under AE based transformer fault detection technique.
- **Laboratory study** to simulate the most probable defects (and different types of defects) in the power transformers oil insulation and to characterize the detected AE signals using DWT.
- **Correlating field study results** with those obtained in laboratory study, by analyzing the AE data obtained by in-situ studies on power transformers.
- **Laboratory study** to analyze the effect of transformer oil temperature on AE signals.

The organization of the thesis (with titles of the chapters) is presented in the next section.

1.5 ORGANISATION OF THE THESIS

CHAPTER 1: INTRODUCTION

Chapter 1 includes an introduction to Indian power scenario, the various defects in transformers, the various condition monitoring and diagnosis techniques used for power transformers; the AE detection technique applied to transformer faults diagnostics and the AE signal analysis. A pertinent literature review is also given culminating in to motivation for the present research work. The objectives of the present research work are listed. A glimpse of the research investigation and organization of the thesis is also given.

CHAPTER 2: ACOUSTIC EMISSION BASED TRANSFORMER FAULT DIAGNOSITICS: FIELD STUDIES

Chapter 2 gives some of the case studies related to the transformer fault diagnostics using AE signals. Few typical case studies of fault diagnosis (in-situ studies) are narrated. The method explained in IEEE.C57.127 (2007) is applied to cases with AE data acquisition system available at CPRI, Bangalore, India. Some specific, interesting observation made in the process of field measurements are elaborated and discussed. It deals with the in-situ condition monitoring and diagnosis of different transformers and application of AE detection technique. AE signals captured for GTs in thermal power stations, GTs in Hydro Power stations and Inter Connecting Transformers (ICTs) in Grid sub-stations are analyzed and reported. Some observations and studies related to OLTC are also included.

CHAPTER 3: LABORATORY EXPERIMENTAL SET-UP, PROCEDURE AND METHODS.

In Chapter 3 details of the laboratory experimental set-up used to carry out some specific experimental work along with instrumentation is narrated. The AE signals are acquired in the laboratory by simulating various defects like PD and hot-spots (heat-waves) in the experimental set-up. The experimental set-up is also intended to carryout study of oil properties at different temperatures and to study the associated AE signals parameters. Hence the experimental set-up, the data acquisition system, and general procedure adopted in conducting the experiments are described in this chapter.

Also the method that would be adopted for AE signal analysis involving DWT is described. The customized algorithm and code implemented using the toolbox of MATLAB is also given.

CHAPTER 4: ANALYSIS OF ACOUSTIC EMISSION SIGNALS FOR DEFECT CLASSIFICATION IN POWER TRANSFORMERS: EXPERIMENTAL/ FIELD DATA

Chapter 4 deals with the laboratory experimental results of the simulated defects and their DWT analysis and classification into characterizing frequency ranges. The in-situ condition monitoring & diagnosis of different transformers and application of AE detection technique with DWT as the basis also discussed. The field results are correlated with the laboratory based analysis for differentiating the AEPD from AE signals due to hot-waves (hot-spots).

CHAPTER 5: BEHAVIOUR OF ACOUSTIC EMISSION PD SIGNALS IN TRANSFORMER OIL AT DIFFERENT TEMPERATURES

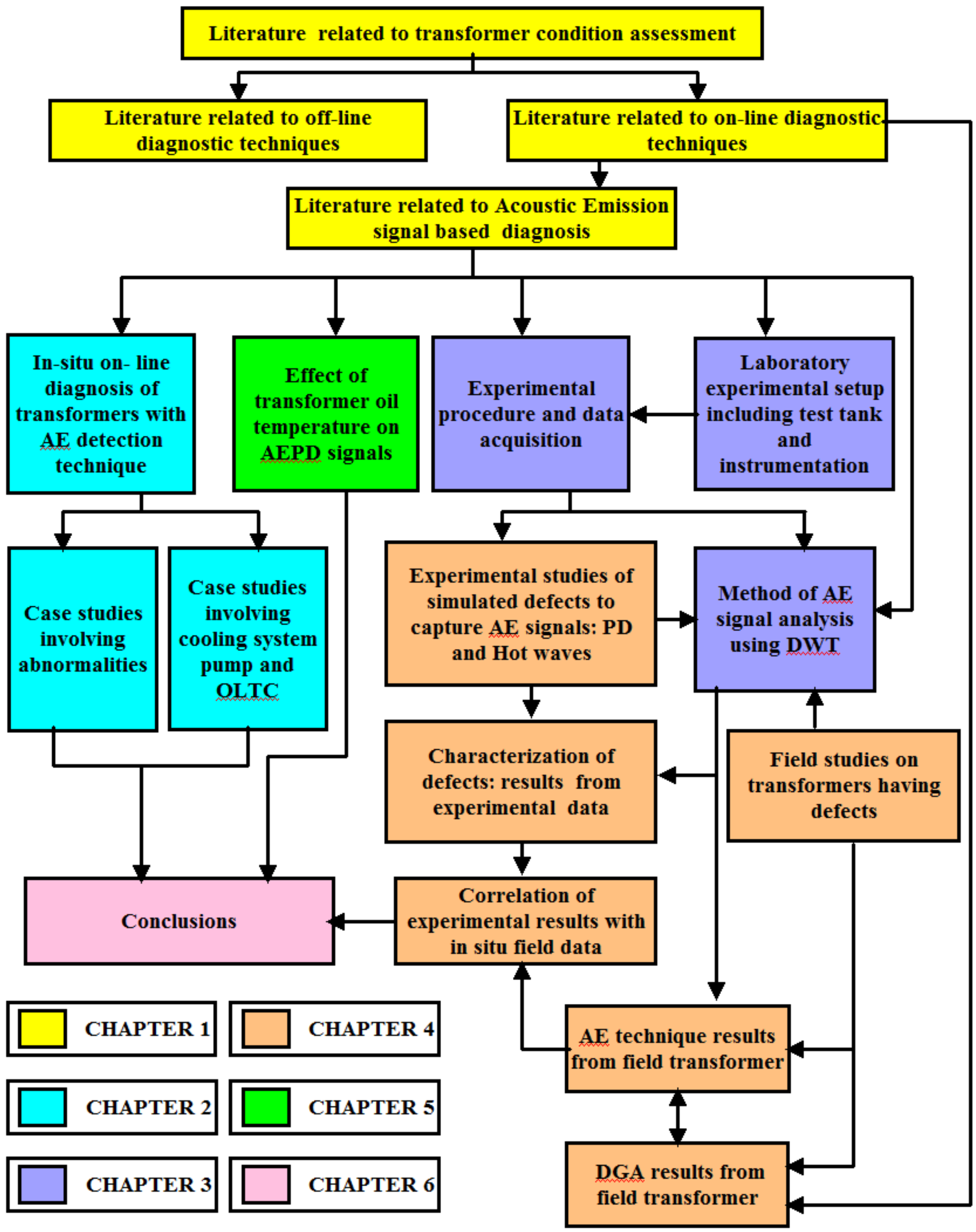
Chapter 5 deals with the laboratory study of AEPD signals over the working temperature range of the power transformers (working in the field). The results are viewed with reference to other transformer oil parameters like Break Down Voltage (BDV), viscosity etc. Effort is also made to understand and explain the changes seen in the AEPD signals with increase in transformer oil temperature.

CHAPTER 6: CONCLUSIONS AND SCOPE FOR FURTHER STUDY

Chapter 6 summarizes the research work reported in the thesis along with the scope for future research work.

The overview of the research work carried out and reported in this thesis is presented in the form of block schematic as shown below. This is intended to give the reader a quick overall organization and interconnectivity of the chapters in one page.

OVERVIEW OF THE RESEARCH WORK



CHAPTER 2

ACOUSTIC EMISSION BASED TRANSFORMER FAULT DIAGNOSITICS: FIELD STUDIES

2.1 INTRODUCTION

The healthy and the safe operation of the transformers in power stations are critical, as it involves huge investment and maintenance costs. The unwarranted and the unforeseen interruptions of these transformers may lead to major financial losses. Hence, the performance of these transformers should be monitored at regular intervals in order to maintain uninterrupted power to the end user. The operating reliability of transformers depends mainly on their insulation status. According to statistics, the insulation faults accounts for 80% of the total transformer faults (Han 2003). All insulation related problems involve PDs in the initial stages of the failure process (Wang 2002 and IEEE Std. C57.127 2007). In power transformers, locating the PD source is as important as identifying it. The AE sensing offers a good solution for both the PD detection and the PD source localization.

In this chapter, the few case studies related to the transformer condition monitoring via the AE signal detection, taken from a vast number of online tests conducted on the transformers at the generating stations are presented. The principle of the AE technique, along with in-situ findings of the on-line AE tests carried out on a number of transformers is discussed. This chapter is divided into two sections, the first section deals with the detection of the acoustic signals from the defects in the transformers and the second section deals with the detection of acoustic signals from other factors such as the operation of cooling system pumps and OLTCs. The testing diagnostic group of CPRI India has vast exposure to AEPD testing/diagnostics, both through field and laboratory measurements (Nagamani et al. 2005, Shanker et al 2010). The team has conducted more than 200 such tests at utility premises all over India over the last decade.

2.2 IMPORTANCE OF PD DETECTION

The purpose of the 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 (Stone 1991). 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 PDs. Thus the periodic testing of the PD activity over the life of the equipment facilitates preventative maintenance.

The diagnostic PD tests can be performed both off-line and on-line. In the off-line diagnostic PD tests the equipment is disconnected from the power system for the duration of the test, whereas in the on-line tests there is no outage of the HV apparatus. The drastic reduction in the outage time for the online PD test reduces the outage cost due to reduced downtime (Leibfried 1998 and Kawada 1984).

The DGA is one of the on-line tests, which has been in use for several years. The dissolved gases in the oil produced by thermal ageing can provide an early indication of an incipient fault. The gases normally analyzed in the DGA are hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, ethane, ethylene and acetylene (IS:1866 2000 and Koch et.al 2015). But it is not possible to identify and locate the PD source with DGA alone. So in recent years, PD detection and its localization using the AE method has gained popularity (IEEE.C57.127 2007 and Ramu 2010).

2.3 AEPD DETECTION TECHNIQUE

The AE technique is a passive technique based on detecting the signals emitted from the discharges. Acoustic methods have many advantages compared to all the other methods used for the PD detection (IEEE.C57.127 2007 and Santosh et al. 2009). In the case of large apparatus like power transformers, the PD source location is as important as identifying it. The PDs show up only when the equipment is energized. Thus the AEPD detection, being an online technique, is much more suitable for the condition monitoring of power transformers. The 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 (IEEE.C57.127 2007). 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 (2007). The AE data is useful, but it becomes more useful when used in conjunction with dissolved gas-in-oil data. If the 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 (IEEE.C57.127 2007).

2.4 SENSORS AND MEASURING TECHNIQUE

A 16-channel AE system consisting of AE sensors made out of piezoelectric material is employed by CPRI India for its field tests. The sensors are with integrated pre-amplifiers and are used for the condition monitoring of the transformer insulation (Nagamani et al. 2005 and Pollock 1989). The 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 HV transformers. The sensors are mounted using the magnetic holders at the 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 sensors. An acoustic couplant is essential for enhancing the mechanical and the acoustical coupling between the transducer and the tank surface. It should be applied evenly to the mounting surface of the sensor before placement (IEEE.C57.127 2007). 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 case studies discussed in the following sections deals with the detection of the acoustic signals from the defects in the transformers working at site (see section 2.5). In some cases, during the in-situ AE tests, AE signals are also detected which are from the other factors such as the operation of cooling system pumps and OLTCs. Few case studies involving such AE signals are also discussed (see section 2.6).

2.5 CASE STUDIES: AE SIGNALS FROM DEFECTS

2.5.1 General

The AEPD tests conducted on the GTs used in the hydroelectric power stations and the thermal power stations in India are reported here. The 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 the coal-based power stations. The operating temperature of the generating transformers in the hydroelectric power stations is comparatively lower than that of the coal-based power stations.

Of the two cases discussed, the first deals with AEPD tests on two identical transformers, and the second deals with the AEPD measurement carried out in a transformer at different occasions (years). The tests conducted in the identical transformers give the provision for comparing the AE signal amplitudes from the two transformers. These case studies also help in comprehending the efficacy of integrating the DGA data with the AEPD test results in detecting and locating the PD source.

2.5.2 Case Study-1: Identical transformers

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

The DGA results showed high hydrogen levels in one of the GTs, named GT-1. The hydrogen content had shown a steep rise of more than 1000 ppm for this unit. The DGA and oil BDV test results conducted at this stage are given in Table 2.1 (columns 3 and 5).

It is to be noted that the key gas hydrogen content of GT-1 is seen to be 8653 ppm, where as that of GT-2 is 60 ppm. These are identical transformers. Identical in construction as they are of the same make. Their construction being identical, comparison of AE signals is thought to be helpful in fault localization.

These two transformers were then tested using the AE sensors and the detection system under (near) identical conditions of loading. The load condition of the transformers while the AE tests were conducted is summarized in Table 2.2.

A 16-channel AE system consisting of the AE sensors (16 in number) 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 Figure 2.1. The view of this transformer with AE sensors mounted on it is shown in Figure 2.2, in which sensors mounted on the high-voltage side of the transformer tank are seen (visible).

Table 2.1: DGA and BDV test results for two identical GTs

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 (kV rms)	32	77	68

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 Figure 2.3 and Figure 2.4, respectively. These are plots of AE signal amplitudes (captured over a period of 30 seconds 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 which the signals are recorded. The threshold set in the present study was 30 dBae. For GT-1, the maximum AE amplitude among these 16-channels corresponded to that of channel number-2. This channel number-2 showed and AE amplitude of 62 dBae. For GT-2, the maximum amplitude among these channels corresponded to channel number-6 with corresponding amplitude of 46 dBae. The maximum AE signals for these two identical transformers are given in Table 2.3 for the sake of comparison.

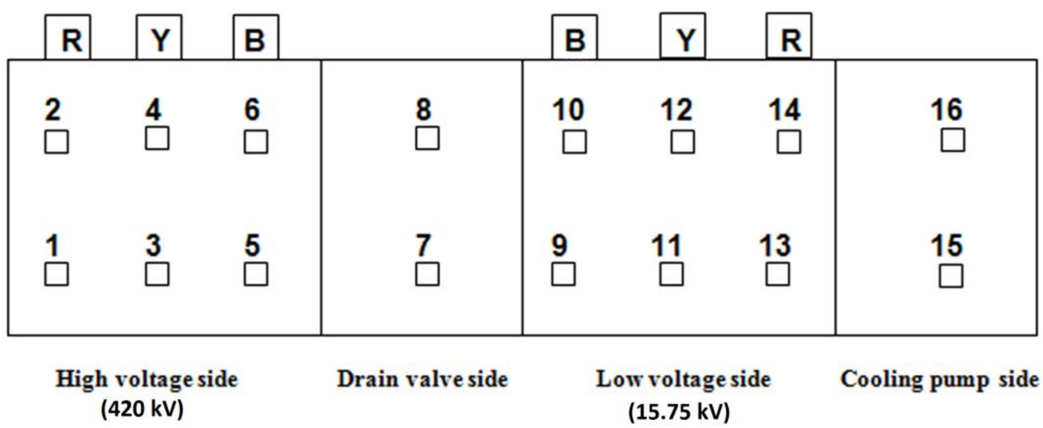


Figure 2.1: AE-Sensor mounting layout for a 3-phase, 15.75 kV/420 kV transformer

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 high AE activity in GT-1 near the sensor number-2 it was possible to locate the problem zone of this transformer from these AEPD test results. On the contrary DGA results can only identify a possible problem within the transformer but cannot localize it within the transformer body.

Figure 2.2: View of 250 MVA 15.75 kV/420 kV GT with sensors mounted (sensors mounted on the HV side of transformer tank are seen)

Table 2.2: Load condition of transformers while capturing AE signal for two identical GTs

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	15.7 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	53 ºC	56 ºC
Winding temperature	71 ºC	72 ºC

The AE magnitude recorded by channel-2 is higher than 60 dBae. From the sensor layout given in Figure 2.1 it is seen that channel-2 is close to the HV winding terminal near the HV bushing. Hence the location of the problematic zone was suspected to be near the HV bushing terminal. With this the internal inspections became relatively simpler for the maintenance personnel.

The details of the actual problem of the transformer are not available to the authors (as AEPD test personnel) as the case was referred to the manufacturer of the transformer. The DGA and BDV tests for GT-1 were conducted again after the maintenance activity. These results of DGA and BDV corresponding to pre- maintenance and post-maintenance scenarios are given in Table 2.1 (columns 3 and 4) for comparison.

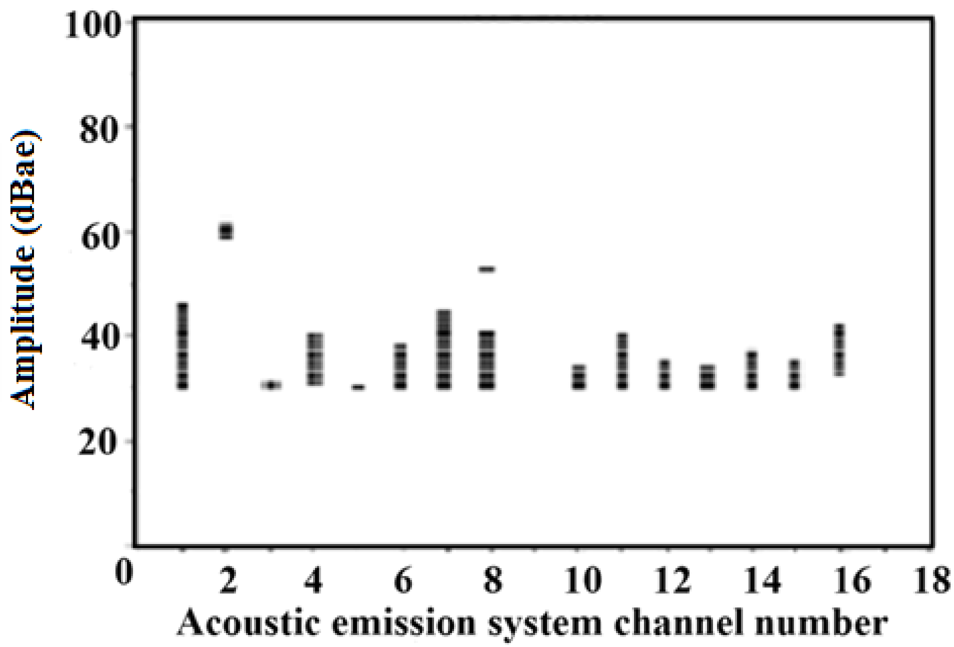


Figure 2.3: AE Amplitudes for 16 AE channels recorded for GT-1

The parameters reported in column 4 of Table 2.1 (post-maintenance test results) are within the permissible limits as per the IS: 1866 (2000) (reaffirmed in 2010). The DGA indicates normal internal condition of the transformer GT-1 after repair and re-commissioning. Although pin-pointing the fault location is not attempted in this study, with 16 sensors it is possible to identify the zone of fault.

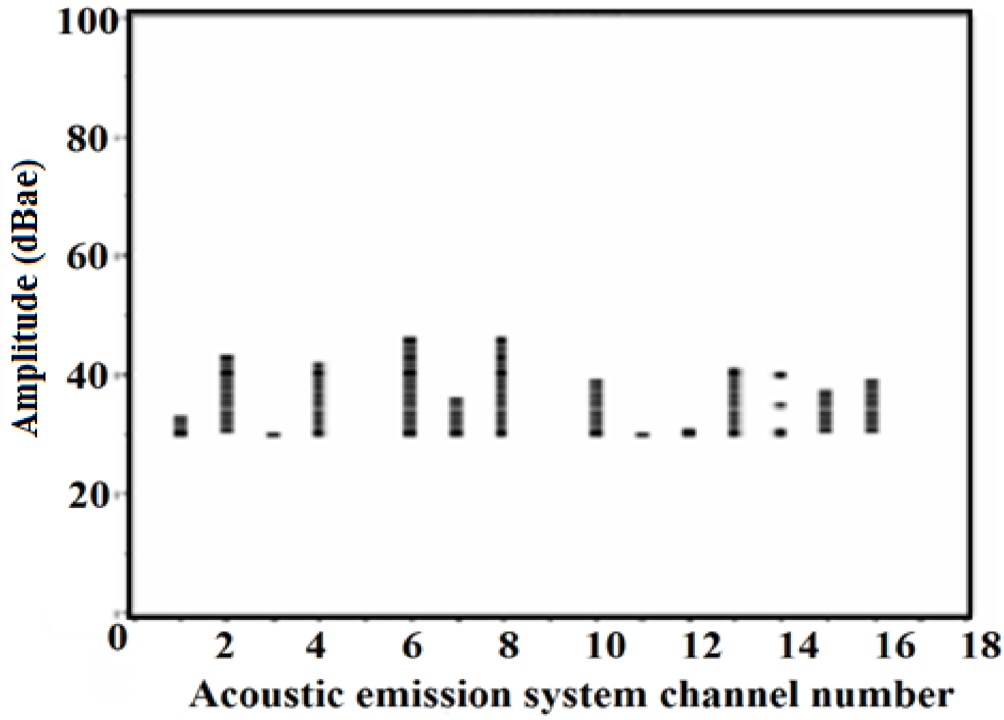


Figure 2.4: AE Amplitudes for 16 AE channels recorded for GT-2

Table 2.3: Maximum amplitude of AE signals captured (out of 16 sensors mounted) for two identical GTs

TRANSFORMER IDENTIFICATION	MAXIMUM AMPLITUDE OF AE SIGNAL (dBae) DETECTED	CHANNEL SHOWING MAXIMUM AE SIGNAL AMPLITUDE
GT-1	62	02
GT-2	46	06

2.5.3 Case study-2: Time-based trend monitoring

This case study gives the details of the trend monitoring of the insulation condition by the online AE tests conducted on a 1-Phase generating transformer (GT-X), in operation at a hydroelectric power station in India. A single-phase GT of 25 MVA (11kV/220/√3 kV, with OFWF type of cooling system) was tested for online AEs. The layout of AE sensors mounted on the transformer is depicted in Figure 2.5. 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. A view of the transformer with sensors mounted is shown in Figure 2.6, in which the sensors mounted on the transformer tank on the HV bushing side are seen (visible).

During March 2005, the AE test was carried out on the transformer for the first time. The threshold value set in the present study was 35 dBae. The magnitude of the AE signal was found to be 40 dBae (max.) (see column 2, Table 2.6). Some of the channels do not show any signals, indicating that the magnitude of AE activity is lower than the threshold value. The other tests on transformer oil (like the DGA and the BDV) were also conducted. The oil test results were normal and no abnormalities were observed. The DGA and the BDV test results conducted at this stage (year 2005) are given in Table 2.4 (columns 3).

During January 2009, power station personnel observed that there was a minor issue with the transformer cooling system, resulting in 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 15 ppm. As this was after an incident with this transformer, even this amount of hydrogen was considered seriously by the generating organization. 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 dBae (max.) at sensor positions 2 and 16 (see Figure 2.8), indicating electrical discharge activity in the transformer's high-stress region of the HV bushing (near the R-phase). It was suggested to the power station personnel by CPRI to attend to the problem and repeat the AE test and the 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. Soon after that the 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 Figure 2.7, Figure 2.8 and Figure 2.9, respectively.

The DGA and Oil breakdown strength (BDV) test results carried out in the years 2005, 2009 and 2010 are given in Table 2.4. The load condition of the transformers while these tests were conducted is summarized in Table 2.5.

The maximum of AE signals amplitudes (among the 16 sensors) captured for the GT (GT-X) are listed in Table 2.6 for the sake of comparison. As it can be seen from Table 2.6, the magnitude of AE signals reduced to 49 dBae in 2010 as compared to 63 dBae in 2009, and no gases in DGA were detected, including hydrogen, as shown in Table 2.4, indicating the healthy condition of the transformer. This also showed the effectiveness of the maintenance activities carried out on the transformer by the power station personnel.

The important inference of this test involving time based maintenance is that, even though DGA may not show very high value (but show some value post maintenance), there can be some issues (or defects) which can be detected by the AE technique. If there is any defect of low magnitude, for it to reflect on to DGA test results, it may take some time. These may get detected in AE online test.

In this test, sensors 2 and 16 which were nearer to the fault detected, showed AE signals with higher magnitude (> 60 dBae). It is logical to think that sensor 4 also should have captured AE signals with similar high magnitude. This may not have happened due to orientation of the fault. The direct signal reaching this sensor may have been blocked by some barriers. Thus it is to be noted that, use of more number of sensors help in localization of the faulty zone within the transformer (if not pinpoint the fault location). This also requires a thoughtful placement of sensors prior to the AE test signal collection.

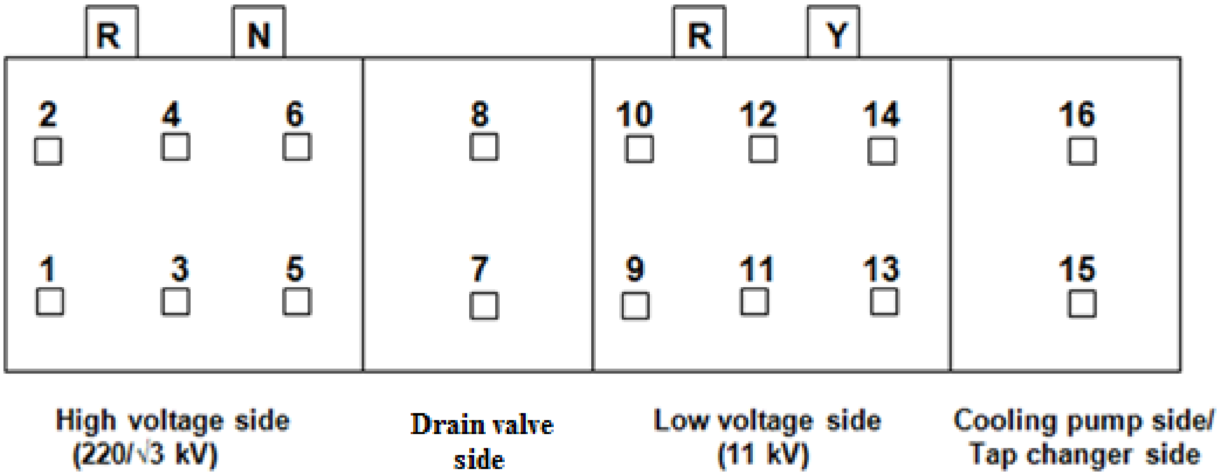


Figure 2.5: AE-Sensor mounting layout for a 11 kV/220/√3 kV, 1-Phase transformer

Table 2.4: DGA and BDV test results of transformer oil of GT-X in 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 (kV rms)	63	83	76

Table 2.5: 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	48 ºC	34 ºC	50 ºC
Winding temperature	60 ºC	46 ºC	56 ºC

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 2.6: Maximum amplitude of AE signal captured (out of 16 sensors mounted) for transformer (GT-X) recorded in different years

TRANSFORMER IDENTIFICATION	MAX. LEVEL OF AE SIGNALS (dBae)		
	Year 2005	Year 2009	Year 2010
GT-X	40	63	49

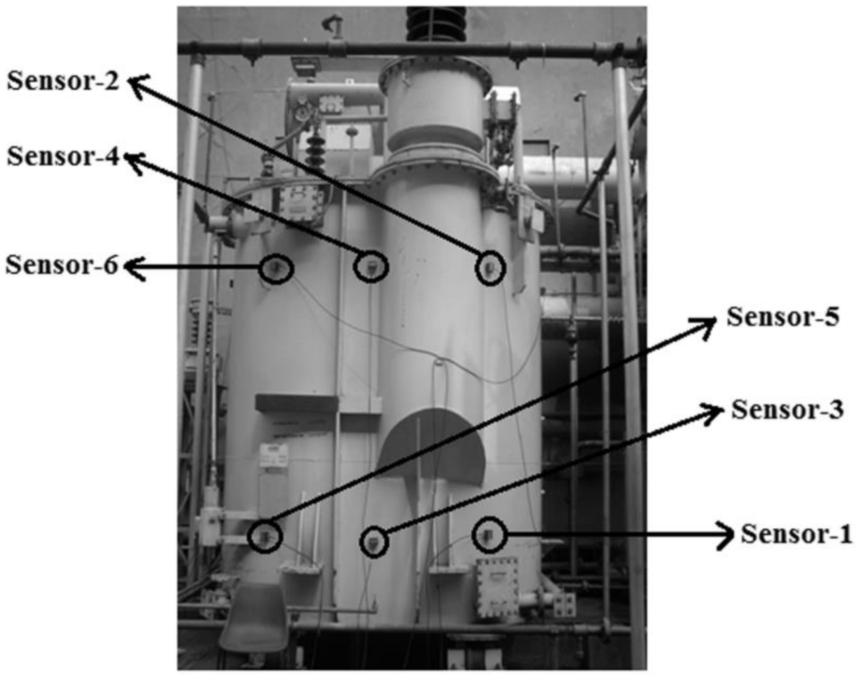


Figure 2.6: View of 25 MVA 11 kV/220/√3kV single-phase GT (GT-X) with AE sensors mounted

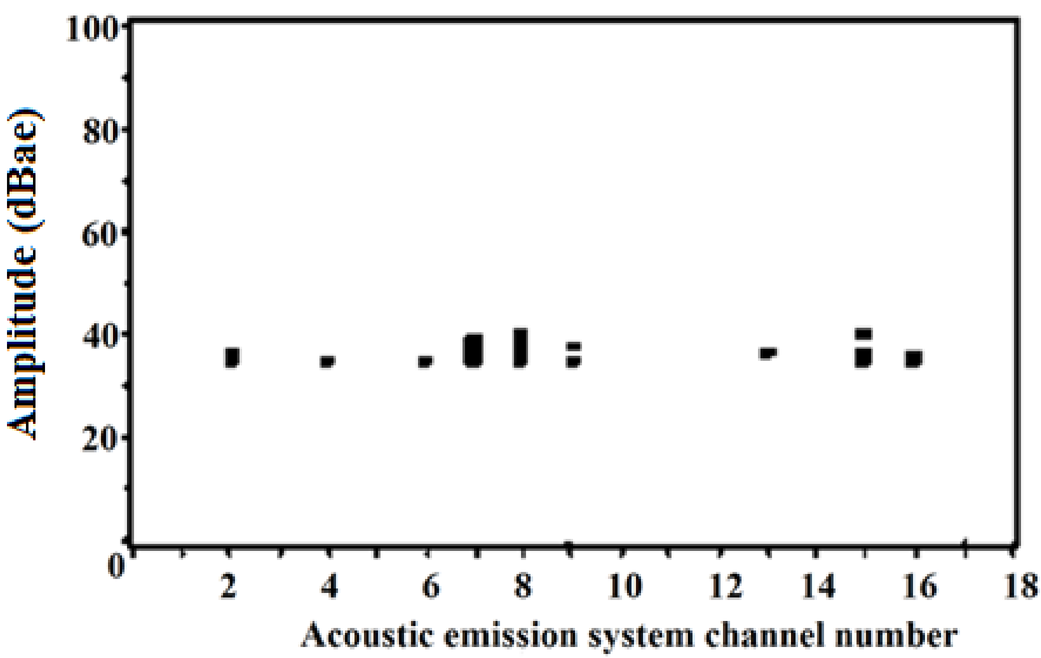


Figure 2.7: AE Amplitudes for 16 AE channels recorded for transformer GT-X in the year 2005

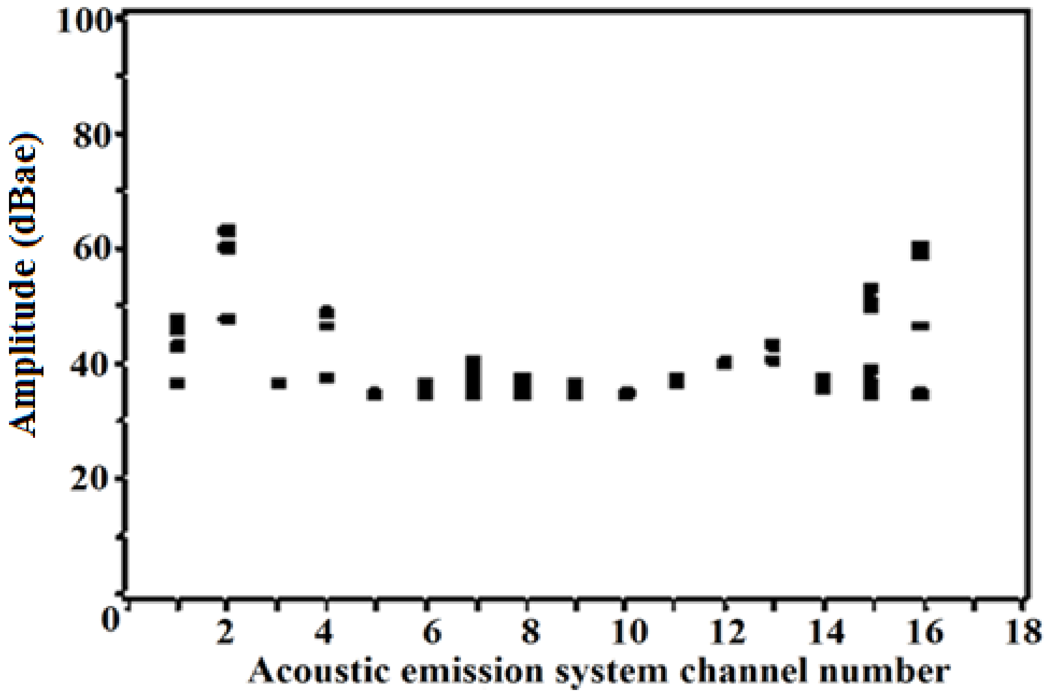


Figure 2.8: AE Amplitudes for 16 AE channels recorded for transformer GT-X in the year 2009

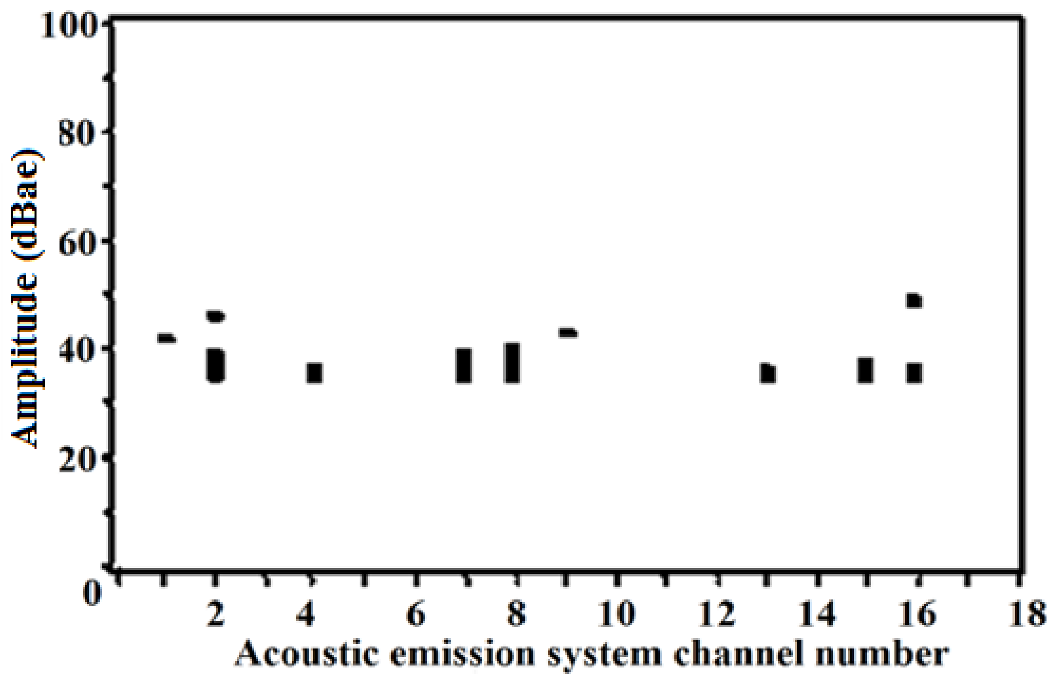


Figure 2.9: AE Amplitudes for 16 AE channels recorded for transformer GT-X in the year 2010

2.6 CASE STUDIES: AE SIGNALS DUE TO OTHER FACTORS

2.6.1 General

Two other important sources that results in an AE signal in the power transformers are the operation of the cooling system pumps and the OLTCs.

The three-phase, 123 MVA, 13.8 kV/420 kV identical GTs (GT-A and GT-B) in a hydro power station in India was a typical case involving AE signals due to the cooling system pumps. It is essential to ascertain the presence or absence of AE due to the operation of cooling system pumps.

The OLTC forms a vital part of a transformer. In another study, AE signals from a 230 kV power transformers got captured during OLTC operation employing the AE sensors and the AE work station. These two cases studies involving AE signals are reported in this section.

2.6.2 Case Study-3: AE signals due to operation of cooling system pump

This case study was conducted on a 3-Phase, 123 MVA, 13.8 kV/420 kV identical GTs (GT-A and GT-B) in a hydro power station in India. These transformers are identical in terms of their rating and design. The hydro power station uses OFWF type of cooling system. All the tested parameters of the DGA test were within the permissible limits, so the test result indicates normal internal condition of the transformer. These two transformers are tested for AE under identical conditions. The oil temperature of the two transformers at the time of test was around 45 ºC. The load on the two transformers, GT-A and GT-B were 90.5 MW and 90 MW respectively.

A 16-channel AE system consisting of the AE sensors (16 in number) made out of piezoelectric material is employed for the AEPD test. After cleaning the transformer tank surface, the AE sensors are mounted on the walls of the transformer tank. The layout of sensors is depicted in Figure 2.10. The view of the transformer with sensors mounted is shown in Figure 2.11, in which the sensors mounted on the transformer tank on the LV bushing side are seen (visible).

The peak magnitude of the AE signals captured by the 16 channels for GT-A and GT-B with the cooling system pumps in operation are depicted in Figure 2.12 and Figure 2.13 respectively. Some of the channels do not show any signals indicating that the peak magnitude of the AE activity lower than the threshold value of 35 dBae. For GT-A, the maximum magnitude of the AE activity among these channels corresponds to channel number-16 with amplitude of 64 dBae. For GT-B the maximum magnitude of the AE activity among these channels corresponds to channel number-16 with amplitude of 57 dBae. During the measurement, an increased AE activity was observed for GT-A compared to GT-B with the cooling system pumps in operation.

Though the AEPD test was showing high AE activity, the results of the DGA were normal. The magnitudes of the AE signals captured by the sensors at the cooling systems pump side are found to be higher compared to the other sensors. This sensor was placed near the oil circulation inlet pipe of the transformer which was connected to the cooling system pumps. As high magnitude of AE signals were recorded by these sensors, it was essential to ascertain the source of these AE signals. Another measurement was carried out by switching-off the cooling system pumps of both transformers. The peak magnitude of the AE signals captured by the 16 channels for GT-A and GT-B with the cooling system pumps put off are depicted in Figure 2.14 and Figure 2.15, respectively. It was observed that the magnitude of the AE signals was below 60 dBae. Based on the experience from many AEPD tests, the transformers with AE signal amplitudes less than 60 dBae is considered to be satisfactory as far as the health of the transformer is concerned. The peak magnitudes of AE signals (among 16 sensors) for the two transformers with cooling system pumps ON and OFF are given in Table 2.7.

After detailed discussion with the operating personnel, it was identified that the cooling water pumping system of GT-A was having some technical problems. This pump motor was contributing to the AE signals. This was confirmed by performing the on-line AE test. Since multiple sensors were used, it was possible to show the position of the problematic area and to search for the cause of higher AE signals. This could initiate the necessary maintenance related actions (related to cooling water pump system). This exercise has helped the operating personnel to take remedial measures for improving the performance of the pump motors of the cooling system.

The inference drawn from this case study are (i) at times, causes like operation of cooling water pump system can bring up the AE signal magnitudes and may give a false alarm, (ii) even such sources of AE signals can be detected by the AE test technique, which may help in overall maintenance (although not related to PDs).

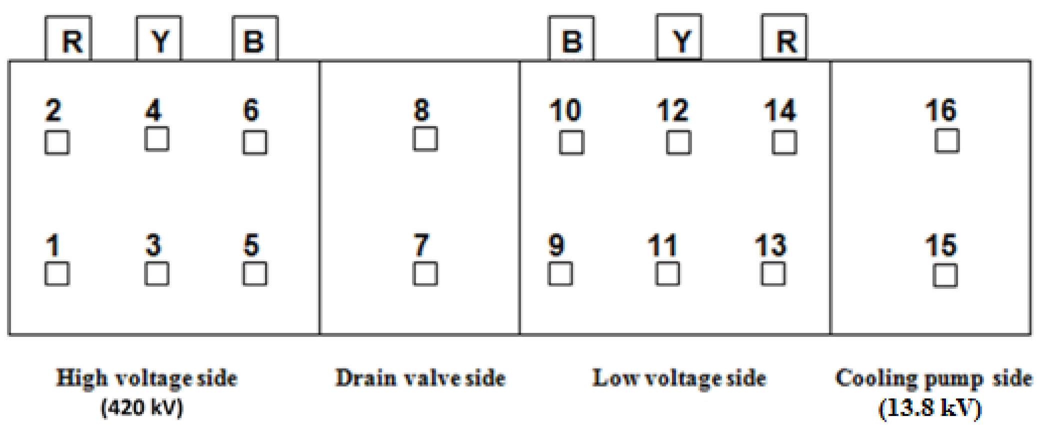


Figure 2.10: AE-Sensor mounting layout for a 3-phase, 13.8 kV/420 kV transformer

Figure 2.11: View of 123 MVA 13.8 kV/420 kV GT with sensors mounted (sensors mounted on the LV side of transformer tank are seen)

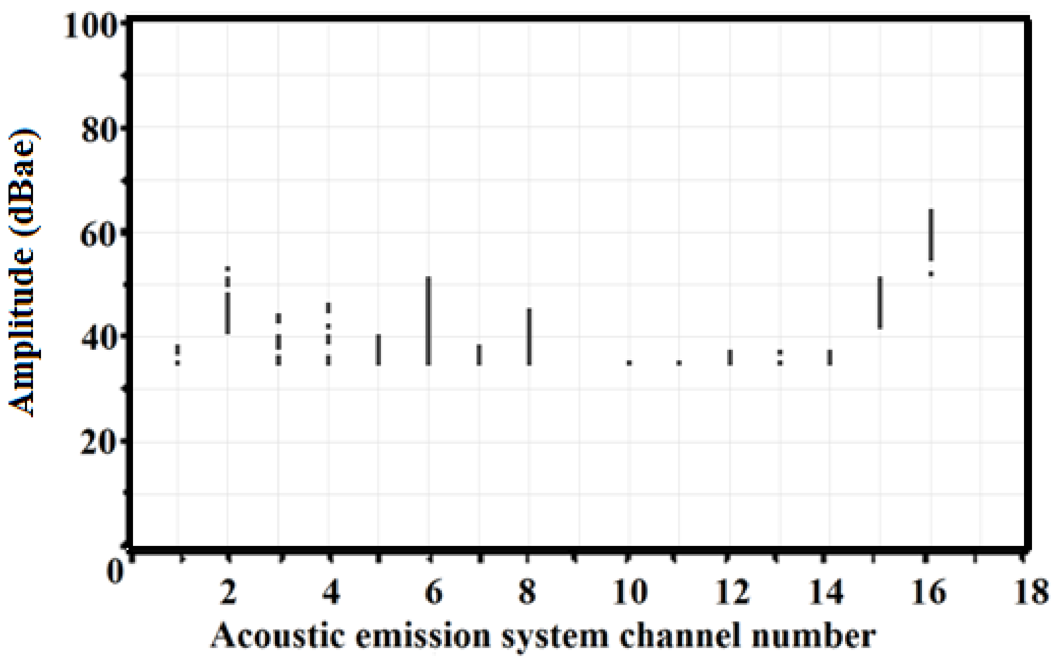


Figure 2.12: AE Amplitudes versus channels for GT-A with cooling system pump in operation

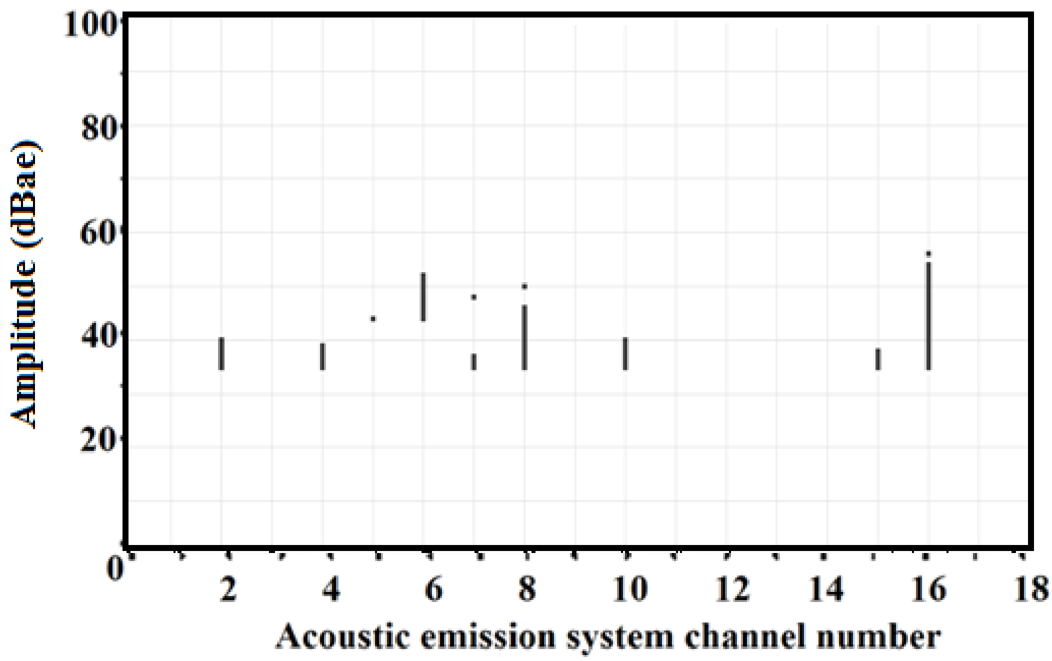


Figure 2.13: AE Amplitudes versus channels for GT-B with cooling system pump in operation

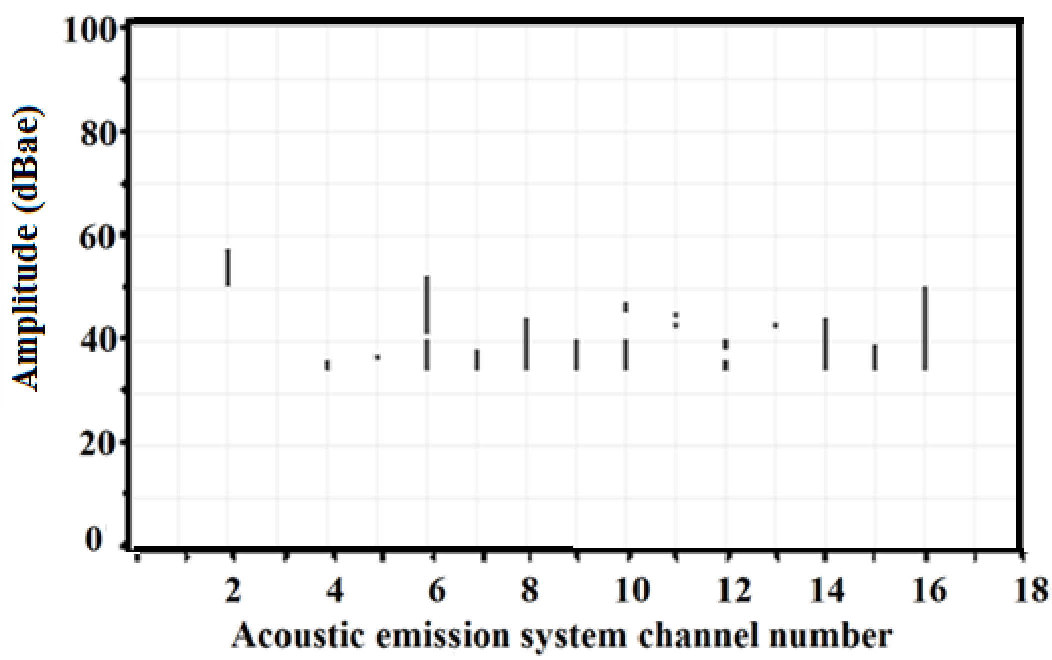


Figure 2.14: AE Amplitudes versus channels for GT-A with cooling system pump OFF

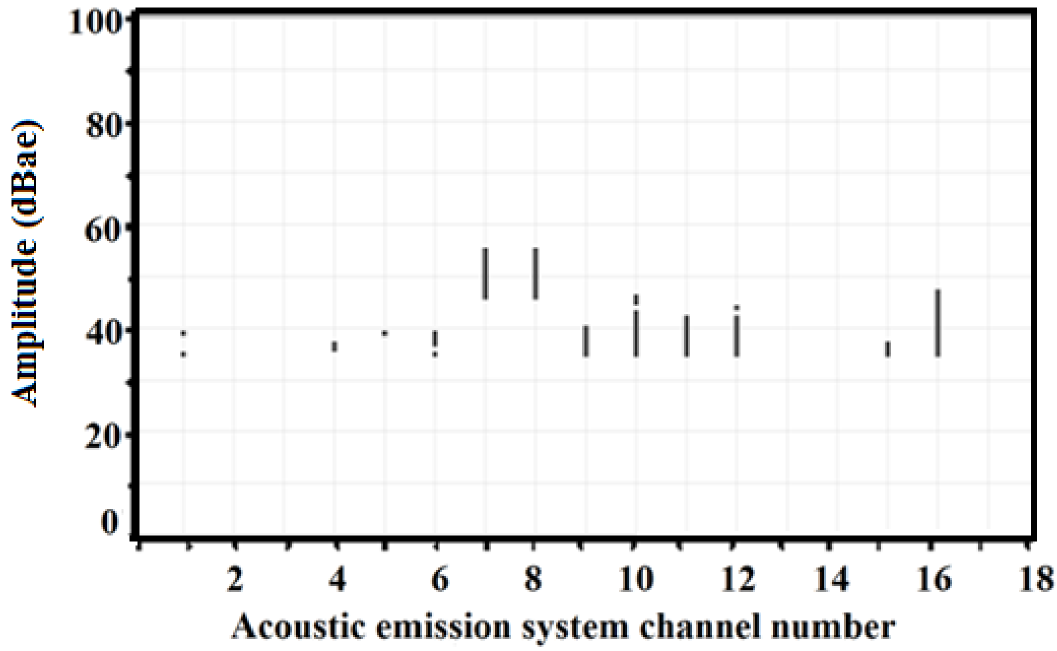


Figure 2.15: AE Amplitudes versus channels for GT-B with cooling system pump OFF

Table 2.7: Maximum level of AE signals captured from GTs GT-A and GT-B

Transformer Identification	Max. level of AE signals (dBae)	
	With cooling system pumps ON	With cooling system pumps OFF
GT-A	64 dBae (channel 16)	57 dBae (channel 2)
GT-B	57 dBae (channel 16)	55 dBae (channel 8)

2.6.3 Case Study-4: AE signals due to operation of OLTC

This case study is of a 3-phase power transformer in operation with externally fitted OLTC at a substation in India. The ratings of the power transformer considered for the study are 230 kV/3.3 kV and 20 MVA. The OLTC was with 25 tap positions and was fixed external to the transformer.

A 16-channel AE system consisting of the AE sensors made out of piezoelectric material was employed for the AEPD test. After cleaning the transformer tank surface, the AE sensors were mounted on the walls of the transformer tank. The layout of the sensors is depicted in Figure 2.16. The view of this transformer with AE sensors mounted on it is shown in Figure 2.17, in which sensors mounted on the lower portion of the high-voltage side of the transformer tank and OLTC compartment are seen.

The AE signals from OLTC are recorded for a time period of about 120 seconds to cover the complete event of tap changing. The OLTC was operated intentionally for acquiring data. Threshold for AE signal in the data acquisition and measuring system was set at 30 dBae.

The amplitude of the AE signals captured as a function of time during tap changing operation from tap-22 to tap-23 and back to tap-22 with load of about 20 A and power factor of 0.95 on HV side (230 kV) of the transformer load is shown in Figure 2.18. There were no AE signals (threshold of 30 dBae is chosen) before and after tap changing operation. The time zoomed figure of Figure 2.18 depicting the details of AE signals from start to completion of tap changing operation from tap-22 to tap-23 (typical) is shown in Figure 2.19.

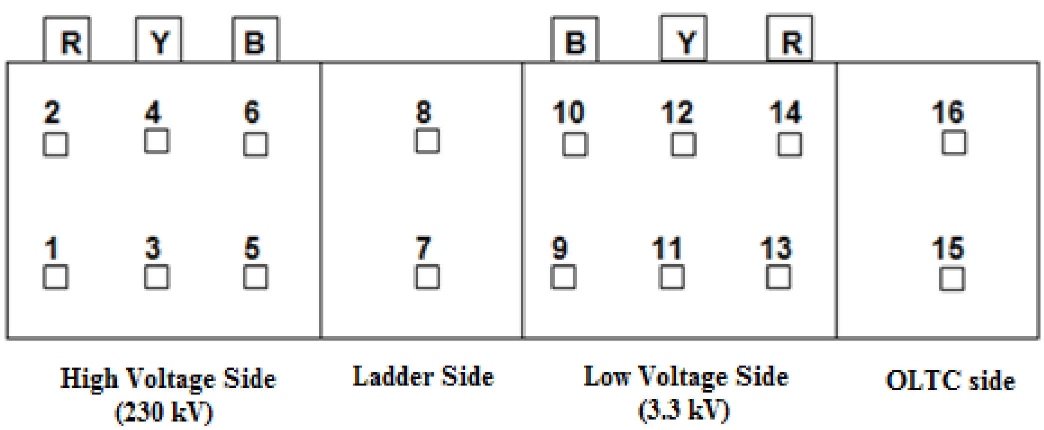


Figure 2.16: AE-Sensor mounting layout for a 3-phase, 230 kV/3.3 kV transformer

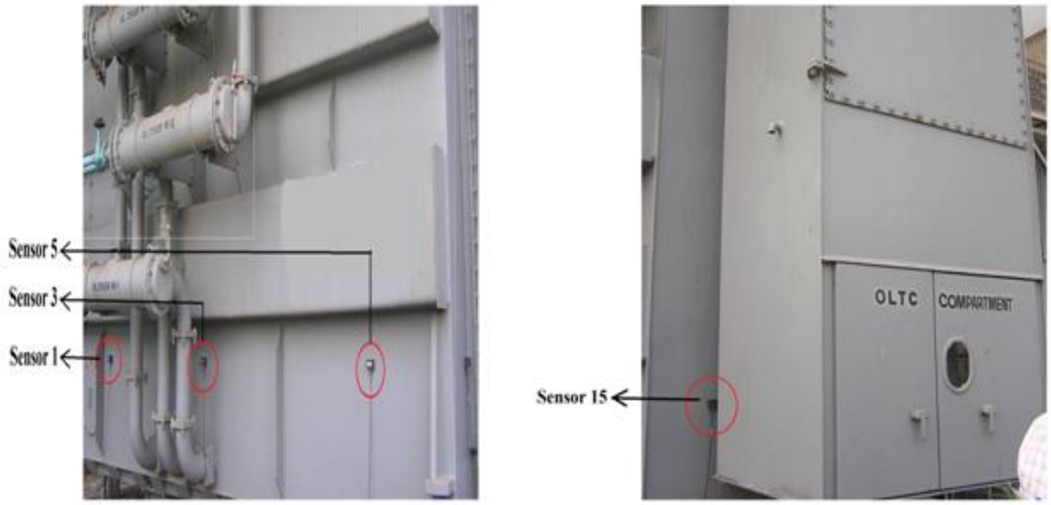


Figure 2.17: View of 20 MVA 230 kV/3.3 kV GT with sensors mounted (sensors mounted on the lower side of transformer tank near HV side and OLTC compartment are seen)

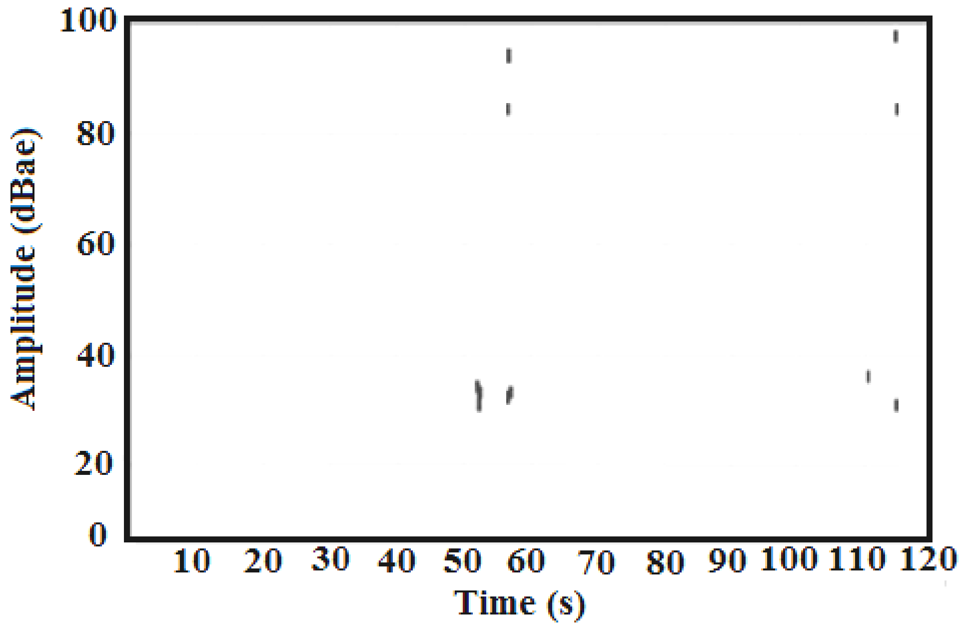


Figure 2.18: Amplitude of AE signals (dBae) versus Time (s) during tap changing operation from Tap 22 to Tap 23 and back to 22

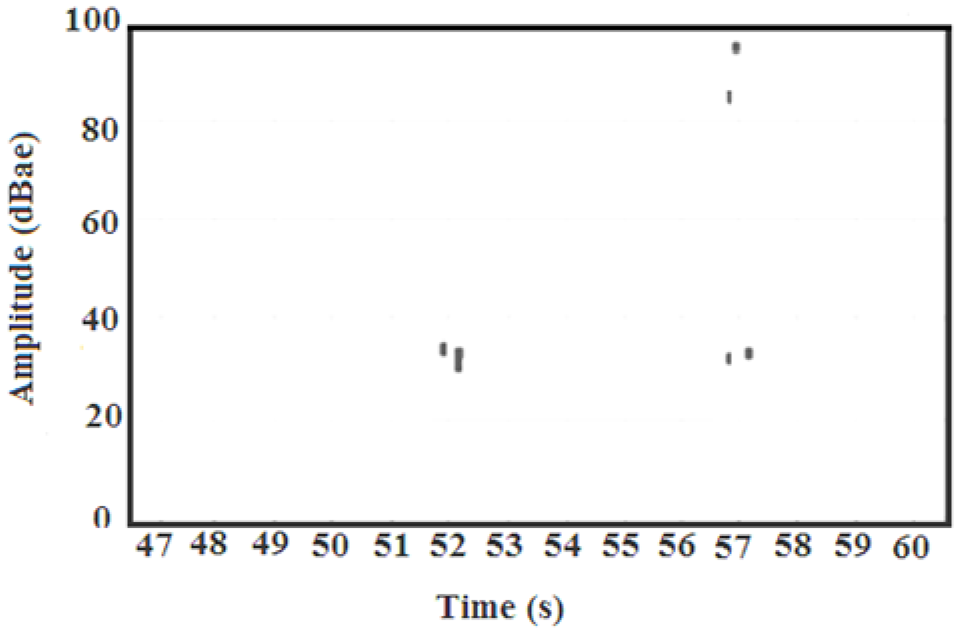


Figure 2.19: Amplitude (dBae) versus Time(s) during tap changing operation from Tap 22 to Tap 23

It can be seen from Figure 2.19, the tap changing event has been recorded between 51.5 s to 57.5 s. (with instant of starting of data acquisition as the reference). Initially, few low amplitude AE signals in the range of 30 dBae to 35 dBae were recorded. At 57th second a sudden burst of the AE signals of very high amplitude above 90 dBae were observed.

Under normal test scenario in detecting AEPDs, if this magnitude of AE signals is observed then it amounts to a severe fault situation. Thus if transformer with OLTC is being tested using AE technique then these signals above the threshold (>35 dBae) could be due to OLTC operation.

2.7 SUMMARY

An online AE technique was adopted to assess the internal condition of the GTs at various power stations in India. Being an online technique, AE testing can be carried out at various stages such as immediately after commissioning and after a few years of operation. This helps in the condition assessment of the transformers. The identical transformer data and time-based monitoring data of the AE test further help to analyse and locate the fault. One should be also aware of other probable causes (other than defects in transformers) that can result in AE from the transformers. The following specific conclusions can be made from these case studies:

a) The field experience in transformers fault detection by using AE technique suggests that AE amplitude above 60 dBae can indicate an abnormal condition.
b) The DGA data and the AEPD test data can supplement each other. So it is important to take into account the DGA results when interpreting the AE data.
c) 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.
d) The problematic areas can be pinpointed by identifying the AE sensor which receives the signal with maximum AE amplitude. Thus more number of sensors (16 in the present study) helps in fault zone localization, if not pin-point.
e) The periodic monitoring using AE technique can evolve corrective measures. 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.
f) The operation of the cooling system pumps and the OLTCs can also result in AEs, this should not be misunderstood as a defect in the transformer (not to be diagnosed as the PD type of defect in the transformer).

CHAPTER 3

LABORATORY EXPERIMENTAL SET-UP AND INSTRUMENTATION

3.1 GENERAL

The most probable and the most common defects in the transformers that result into the emission of the acoustic signals are the PDs and the hot-spots (heat-waves). These defects in the transformer are simulated in the laboratory by using the appropriate experimental set-up and test arrangement. A detailed investigation on the PD defect in the transformer oil has been carried out in the laboratory by simulating the PD defect using the point-plane electrode geometry. The hot-spots (heat-waves) are simulated in the laboratory by using the heaters of suitable rating. The laboratory model is fitted with these heaters for raising the temperature of oil along with the oil circulation arrangement for having the uniform oil temperature.

The AE signals due to these simulated defects are acquired, and analyzed using FFT and DWT. The distribution of energy content of the AE signals over the different frequency ranges is studied. This helps in the characterization of the AE signals for the identification of these defects (PD and hot-spots). The effect of the temperature of the transformer oil on the AEPD signal parameters, such as Discharge magnitude and the peak frequency are studied at temperatures ranging from 30 °C to 75 °C.

Before simulating these defects through laboratory experiments, some of the important electrical and chemical properties of the transformer oil in which these experiments are conducted need to be measured. This is to assess the condition of the transformer oil and confirming its suitability for carrying out the experimental studies.

This chapter gives the details of the laboratory experimental set-up and the instrumentation used to carry out the experimental work. The experimental set-up is intended to carryout study of oil properties at different temperatures and to study the associated AE signals parameters. The AE signals are acquired in the laboratory by simulating the various defects like the PD and the hot-spots (heat-waves). The standard test procedures that are carried out in the Oil Testing Laboratory (OTL) of CPRI, to verify the properties of the transformer oil used in the laboratory test are briefed. The results of the various tests conducted in the OTL that confirms the suitability of the transformer oil for further simulation studies are also included in this chapter. The method that is adopted for the AE signal analysis by using FFT and DWT is described. The customized algorithm and code implemented using the toolbox of MATLAB is also given.

3.2 LABORATORY EXPERIMENTAL SET-UP

The entire laboratory experimental set-up can be grouped into three major components. (1) The AE work station (2) The HV source and the associated measuring instruments (3) The experimental tank and the arrangement for the simulation of defects. These are explained below.

3.2.1 The AE work station

The AE work station includes the hardware and the software for acquiring the AE signals.

(i) Hardware

The AE work station is a Digital Signal Processor (DSP) based data acquisition system. The system consists of sixteen channels made from four numbers of 4-channel DSP boards. AE signal data is acquired from sixteen piezo-electric sensors of type DT15I. These signals are captured and stored in the associated programmable computer. The sensors have a frequency range of 10 kHz- 1 MHz and resonant frequency of 150 kHz with integrated pre-amplifier of 40 dBae gain. The AE workstation is fully equipped with the relevant software for the detection and analysis of the AE signals captured. The various components of the AE work station used in the present study are shown in Figure 3.1.

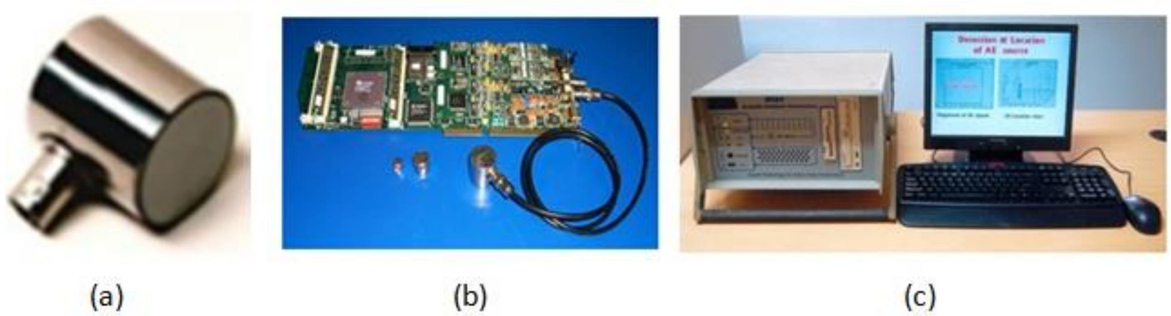


Figure 3.1: Components of AE work station at CPRI; (a) AE sensor with integrated pre-amplifier (b) AE-DSP board with a sensor connected (c) 16-channel AE work station (source: M/s Physical Acoustics Corporation (PAC), USA)

(ii) Software

The AE work station has necessary data acquisition software. It facilitates the analysis of the captured AE signals using FFT. The data acquired is further analyzed using DWT in the MATLAB environment.

3.2.2 The High Voltage source and the associated measuring instruments

The High Voltage (HV) source and the associated measuring instruments are used to source the simulated defects and to measure the related parameters.

(i) HV Source specification with associated panel meter (used for application of voltage to the point electrode)

- Input voltage: 0 - 415 V rms, 50Hz,
- Output Voltage range: 0 - 75 kV rms.
- Output current (maximum): 1.1 Amperes, rms

Associated panel meter

- Range: 0.0 -75.0 kV rms
- Resolution: 0.1 kV rms

(ii) Measuring instruments

- Digital Temperature Indicator
  - Make: FLUKE Corporation, USA

- Temperature range: -40 °C to +200 °C
- Resolution: 0.1 °C
- Accuracy: ± 1.0 °C

- Profile projector with digital measurement and recording (used for measurement of tip of the point electrode dimensions).
  - Make: Sipcon, India
  - Measuring range: 0-100 mm
  - Resolution: 0.0001 mm
  - Accuracy: ± 0.001 mm

3.2.3 The experimental tank and the defect simulation arrangement

To facilitate the laboratory experiments for simulating the defects and to capture the AE signals from these defects, suitable experimental set-ups are fabricated. The experimental tank and the defect simulation arrangement are as follows.

(i) The experimental tank

The experimental tank made up of mild steel with size 1.1 m x 1.1 m x 1.1 m and with wall thickness of 5 mm, filled with transformer oil, is used for the simulation study.

The defect simulation arrangement:

The experimental set-up to acquire the AE signals due to PD (using a needle arrangement) and hot waves (due to heating of oil; using heater arrangement) are fabricated. The schematic of the test set-up for simulating the PD defect is as shown in Figure 3.2. The laboratory model has a needle electrode of 0.03 mm diameter suspended from the top cover of the tank made up of an insulating sheet (Hylam sheet of 8 mm thickness). The PD in the oil filled tank is generated using the needle electrode with the bottom of the tank acting as plane electrode. The distance between the tip of the needle to the ground plane is 0.418 m. The AE signals due to the PD (defect) in the oil have been captured by applying the HV, at a power frequency of 50 Hz, to the needle electrode. This experiment is carried out at the oil temperature of 30 °C.

The schematic of the laboratory set-up for simulating the hot-spots (heat-waves) are shown in Figure 3.3. The test tank is fitted with four heaters of 230 V, 2 kW rating fitted on the two walls of the tank at a height of 100 mm from the bottom of the tank as shown in Figure 3.3. The temperature of the oil can be raised with the help of these heaters and uniform temperature can be maintained by circulating the oil with a pump. The details of the pump used for the circulation of the transformer oil in the laboratory set-up are as follows

- Pump used: 0.5 HP, 1-Phase, 240 V, Max. Current: 2.8 A, Speed: 2880 rpm.
- Flow rate: 1995 LPH (Litres Per Hour)
- Flow velocity: 0.95 m/s
- Velocity of sound in transformer oil: 1591 m/s

A temperature controller is provided in order to set and maintain a particular temperature of the oil. The AE sensors are mounted on the outer surface of the four lateral sides of the oil tank. The layout of the sixteen sensors (S1 to S16) is shown in Figure 3.4, the (x, y, z) coordinates of the tip of the pointed pin electrode are shown in Table 3.1. The coordinates of these sensors are shown in Table 3.2.

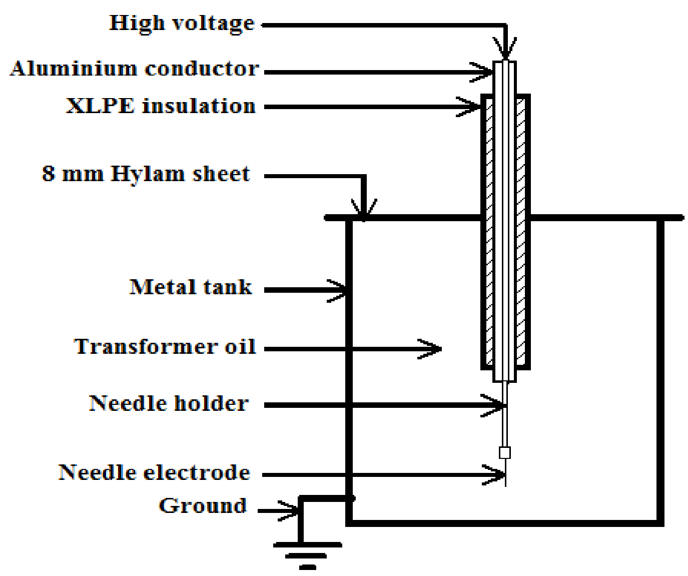


Figure 3.2: The oil test tank with the needle electrode arrangement to simulate the PD defect

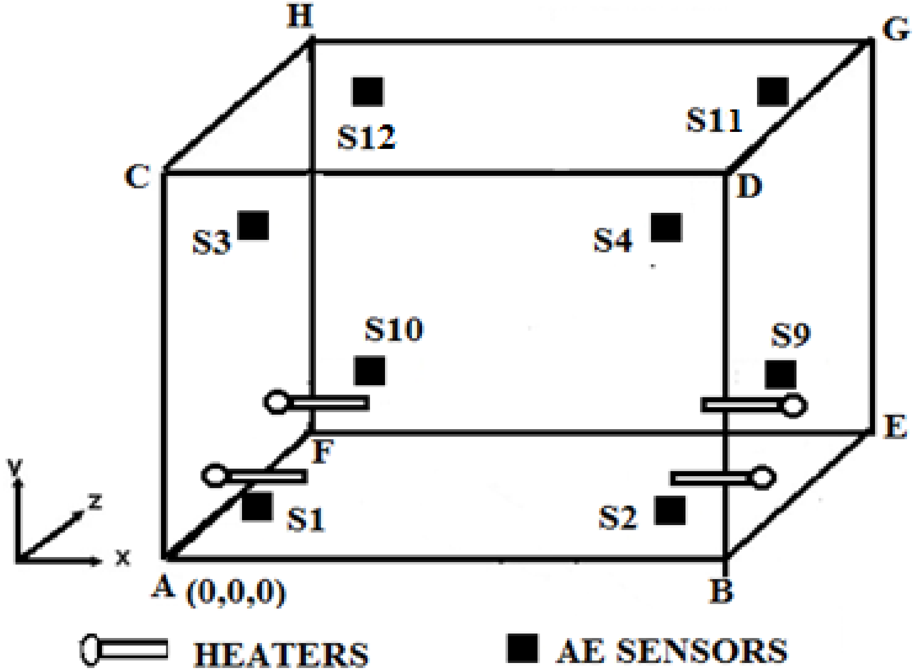


Figure.3.3: The oil test tank with the heater arrangement to simulate the hot-spots (heat-waves)

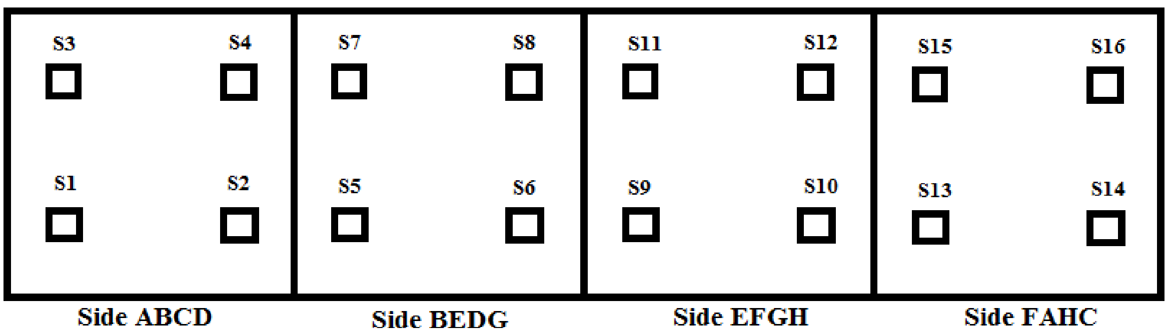


Figure 3.4: Layout of sensors on the outer surface of the experimental tank

Table 3.1: Measured coordinates of tip of the pin electrode

Identification of pointed pin electrode	X direction (m)	Y direction (m)	Z direction (m)
N1	0.511	0.418	0.665

Table 3.2: Coordinates of the sensors placed on the transformer tank (laboratory set-up) with coroner A as the reference (see figure 3.4)

Sensor number	X (m)	Y (m)	Z (m)
S1	0.112	0.101	0.000
S2	0.895	0.101	0.000
S3	0.112	0.821	0.000
S4	0.895	0.821	0.000
S5	1.007	0.101	0.111
S6	1.007	0.101	0.902
S7	1.007	0.819	0.111
S8	1.007	0.819	0.902
S9	0.895	0.101	1.001
S10	0.112	0.101	1.001
S11	0.895	0.827	1.001
S12	0.112	0.827	1.001
S13	0.000	0.103	0.113
S14	0.000	0.103	0.898
S15	0.000	0.826	0.113
S16	0.000	0.826	0.898

3.3 EXPERIMENTAL PROCEDURE

3.3.1 Acoustic Emission test with the simulated Partial Discharge

The PDs (corona discharges) were generated in the oil by pointed pin electrode suspended in the oil with the bottom of the tank acting as plane electrode. The voltage above the Partial Discharge Inception Voltage (PDIV) is applied to the pointed pin electrode with respect to solidly grounded tank. In the present study, PDIV is 15 kV rms (voltage at which AE signals inception occurred and they are detected). The distance between the tip of the needle to the ground plane is 0.418 m. This experiment is carried out at the oil temperature of 30 °C. The AE signals captured using the AE sensors mounted on the tank surface are analyzed by using DWT. The analysis of AE signals helps in the characterization of the PD defect.

Experiments to simulate PD at different temperatures are also carried out using the laboratory set-up (test tank shown in Figure 3.3). The transformer oil is heated and allowed to stabilize for a minimum period of 8 hours at the required temperature, before simulation of AEPD signals. The AEPD signal parameters such as discharge magnitude and peak frequency have been measured at voltages of 15 kV rms, 16 kV rms and 17 kV rms in the temperature range of 30 °C to 75 °C, in steps of 5 °C. The AE signals generated from PD in oil are captured with the AE sensors mounted on the tank (layout shown in Figure 3.4). All these experiments are repeated three times to check the consistency of measured test results.

3.3.2 Acoustic Emission test with the simulated hot-spots (heat-waves)

The AE heat-wave signals (due to the simulated defect) are captured by switching-on the heaters immersed in oil. The experiment was conducted with the oil temperature set to 75°C. This is with no application of HV to the needle electrode. The AE signals generated by the simulated defect is captured by employing 16 sensors made up of the piezoelectric material with the integrated pre amplifier strategically mounted, with the help of magnetic holders, on the transformer tank. The signals within the frequency range of 0-500 kHz are captured for the sake of analysis. The AE signals captured using the AE sensors mounted on the tank surface are analyzed by using DWT. The analysis of AE signals helps in the characterization of the hot-spots (heat-waves).

3.4 METHODS FOR ANALYZING THE AE SIGNALS

3.4.1 AE signal analysis using FFT

In order to classify the AE signals, FFT, a well-known tool for analyzing the signal is used initially. The FFT helps in peak frequency analysis of the AE signals (Veloso 2006 and Kundu et al. 2007). The AE signals captured due to PD during the experiments were analyzed using FFT software available with the AE work station. A number of AE signals were studied using FFT. A typical FFT of the AE wave due to the PD in oil is shown in Figure 3.5 which has a peak frequency of 187 kHz.

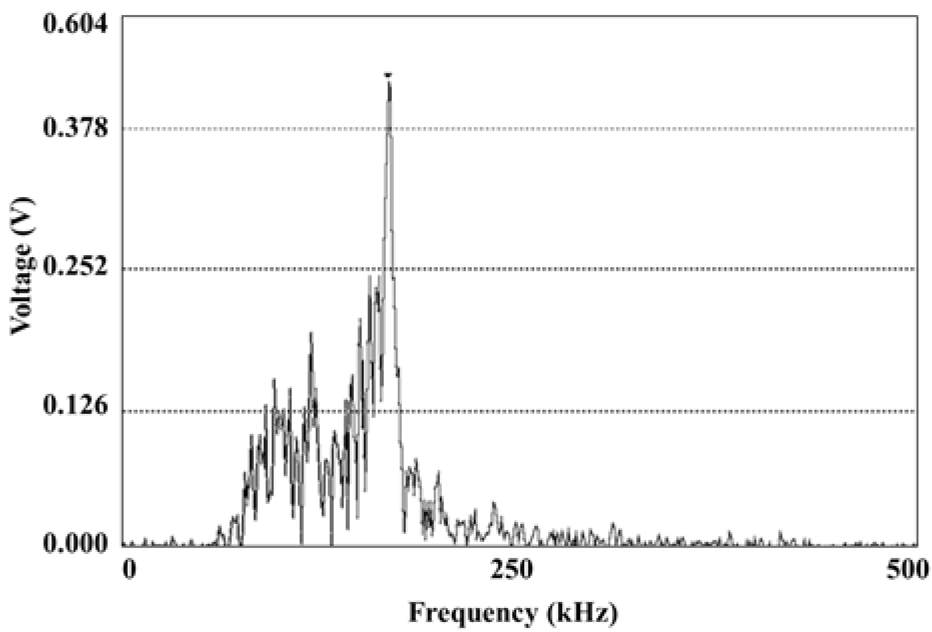


Figure 3.5: A typical FFT of the AE wave due to PD

3.4.2 AE signal analysis using DWT

Each AE signal (wave) captured was subjected to FFT which resulted in specific peak frequency. To decompose the AE waves into a number of range of frequencies for analysis by using Discrete Wavelet Transform (DWT), the toolbox of MATLAB with Symlet-8 mother wavelet is used. The flow chart of customized code developed in MATLAB environment is given in Figure 3.6. The program developed is used to decompose the AE waves into 8 levels of frequencies designated as D1, D2, D3, D4, D5, D6, D7 and A7. The frequency ranges of these are given in Table 3.3. The program will compute the energy distribution in each frequency level and the frequency level having the maximum energy contained would decide the characterizing frequency range of the AE signal.

Table 3.3: Frequency ranges for different decomposition levels

Decomposition Levels of detail and approximation coefficients	Frequency Range in kHz
D1	250 – 500
D2	125 – 250
D3	62.5 – 125
D4	31.3 - 62.5
D5	15.6 - 31.3
D6	7.81 - 15.6
D7	3.90 - 7.81
A7	0.00 - 3.90

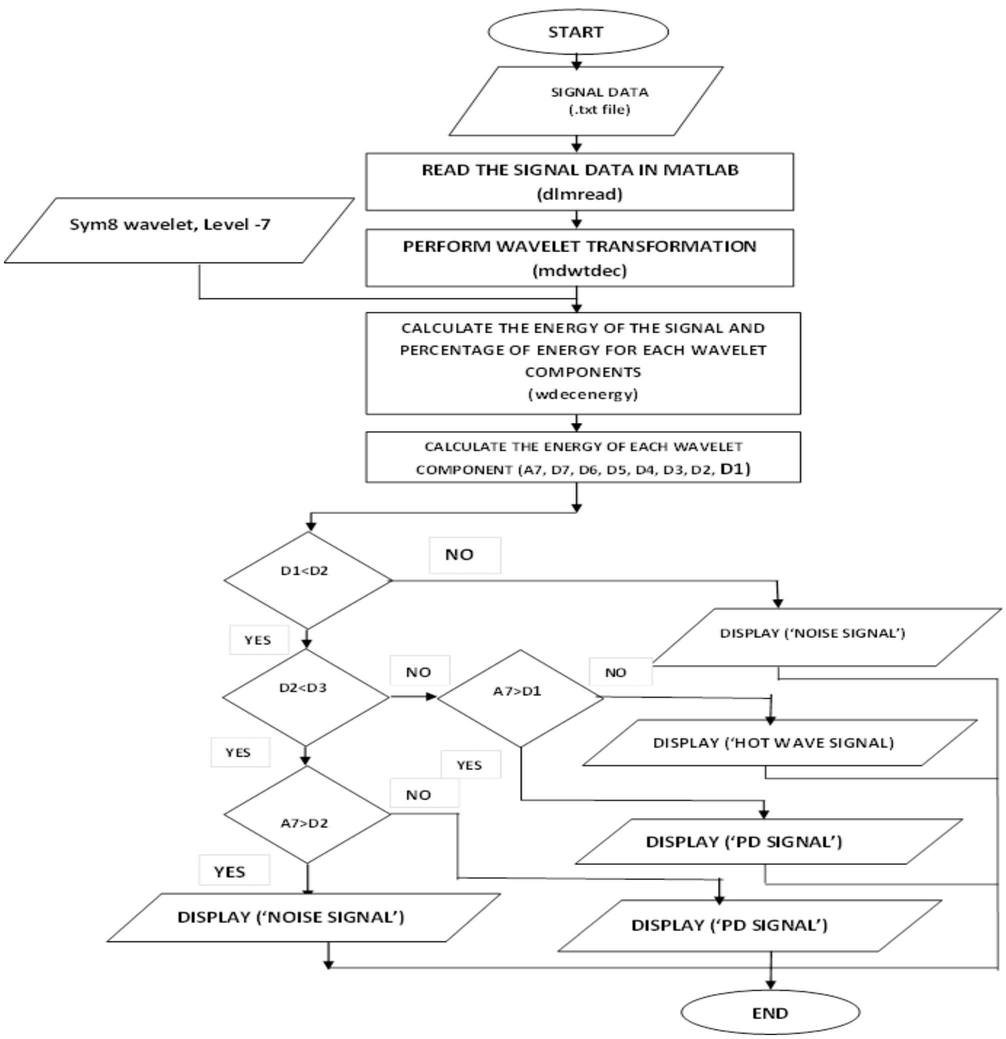


Figure 3.6: Flow chart for the program developed using Matlab toolbox for classification of AE signals in to PD, Hot-wave and noise signals

3.5 PROPERTIES OF TRANSFORMER OIL USED IN LABORATORY EXPERIMENTATION

The transformer oil of EHV grade is considered for the present study. It is essential to ensure the quality of the transformer oil used for the experimentation by studying its important properties. Therefore prior to carrying out the planned laboratory experiments, the properties of the transformer oil used in the laboratory set-up (test tank) are verified by using standard test procedures (IS-335 2005, IS-1866 2000 and IEC 60156 1995).

These tests are conducted in the OTL of CPRI, Bangalore, India.

The electrical properties of transformer oil such as dielectric constant; dissipation factor, viscosity, specific resistance (resistivity) and AC breakdown voltage (BDV) are measured at temperatures ranging from 30 °C to 75 °C in steps of 5 °C for understanding the behavior of the transformer oil. The measurements are taken after stabilizing the temperature of oil for 8 hours at each temperature. The oil temperature is measured with a temperature indicator of M/s Fluke, USA make (accuracy of ±1.0 °C, resolution of 0.1 °C). The AC breakdown voltage (BDV) at various temperatures is measured with the test equipment manufactured by M/s BAUR Instruments, UK, with a separate test cell for conducting tests at elevated temperatures. The measured properties of the transformer oil with reference to the standards at standard test conditions are given in Table 3.4. The values of the transformer oil properties over the temperature range of 27 °C to 75 °C are listed in Table 3.5. The graphical representation of the experimentally measured oil parameters such as dielectric constant; dissipation factor, viscosity, specific resistance and BDV as a function of temperature are depicted in Figure 3.7, Figure 3.8, Figure 3.9, Figure 3.10 and Figure 3.11, respectively.

As shown in the Figure 3.7, dielectric constant almost remains constant over the temperature range of 30 °C to 75 °C with its magnitude being in the range of 2.05 to 2.1. Figure 3.8 indicates that the dissipation factor increases with temperature and shows a steep rise beyond 65 °C which was found to be a usual behavior. Similarly, Figure 3.9 indicates that viscosity has dropped with temperature, which is a usual behaviour of oil

(Musil et al. 1995). Figure 3.10 also indicates that specific resistance has dropped with temperature, which is also a usual behaviour of oil (Musil et al. 1995). Figure 3.11 indicates that BDV of the transformer oil has shown an increasing trend with temperature. The observed improvement in BDV values with temperature could be attributed to the lowering of moisture content in the oil (Musil et al. 1995 and Malik et al. 1998). The results obtained from the oil tests indicated that the transformer oil has shown normal behavior. Having understood the behavior of the oil, and having confirmed its characteristics, the same is used for the AE related experimentation.

Table 3.4: Measured properties of transformer oil under standard test procedures

Transformer oil property	Test standard	Measured value
Dielectric Dissipation Factor (tanδ) [90°C & RH 48%]	(IS-335 2005 and IS-1866 2000)	0.034
Specific Resistance(Ω-cm) [90°C& RH 48%]	IS-335 2005 and IS-1866 2000)	$7.4 \times 10^{+12}$
Specific Resistance(Ω-cm) [27°C& RH 48%]	IS-335 2005 and IS-1866 2000)	$1.38 \times 10^{+14}$
Dielectric Constant [90°C& RH 48%]	IS-335 2005 and IS-1866 2000)	2.14
Viscosity(cSt) [27°C& RH 48%]	IS-335 2005 and IS-1866 2000)	14.11
BDV(kV rms) [27°C& RH 48%]	IS-335 2005 , IS-1866 2000 and IEC-60156 1995	20

Table 3.5: Experimentally measured values of transformer oil properties at different temperatures

Temperature (°C)	Dielectric constant	Dissipation factor (tanδ)	Viscosity (cSt)	Specific resistance (Ω-cm)	BDV (kV)
27	2.111	9.00E-05	14.11	1.38E+14	18.90
35	2.097	2.50E-04	10.89	8.24E+13	26.90
40	2.088	3.20E-04	8.424	6.26E+13	29.30
45	2.098	4.10E-04	7.648	5.65E+13	49.50
50	2.092	5.10E-04	6.849	3.99E+13	54.30
55	2.078	5.50E-04	6.149	3.80E+13	63.10
60	2.053	7.90E-04	5.557	2.51E+13	66.20
65	2.055	9.30E-04	5.210	2.39E+13	69.50
70	2.045	1.28E-03	4.316	1.70E+13	76.60
75	2.078	2.95E-03	3.909	6.94E+12	78.00

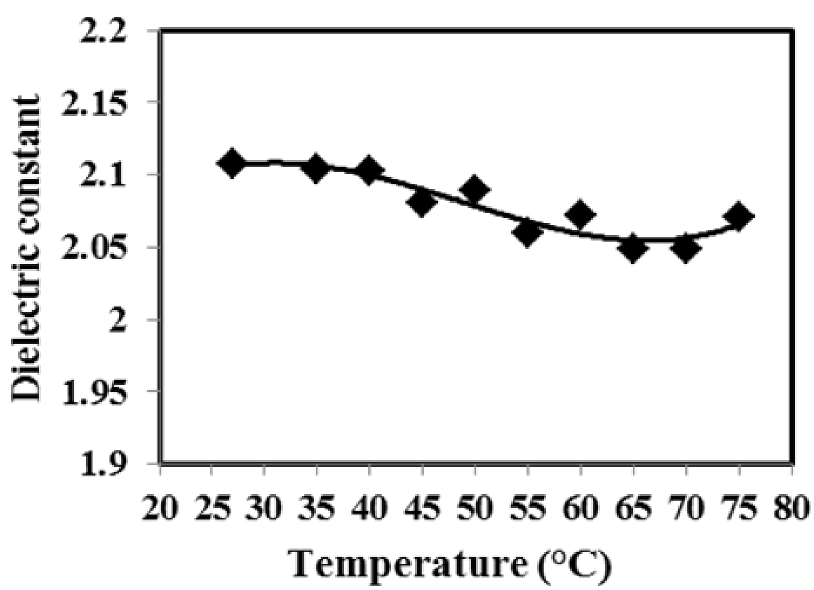


Figure 3.7: Dielectric constant as a function of temperature

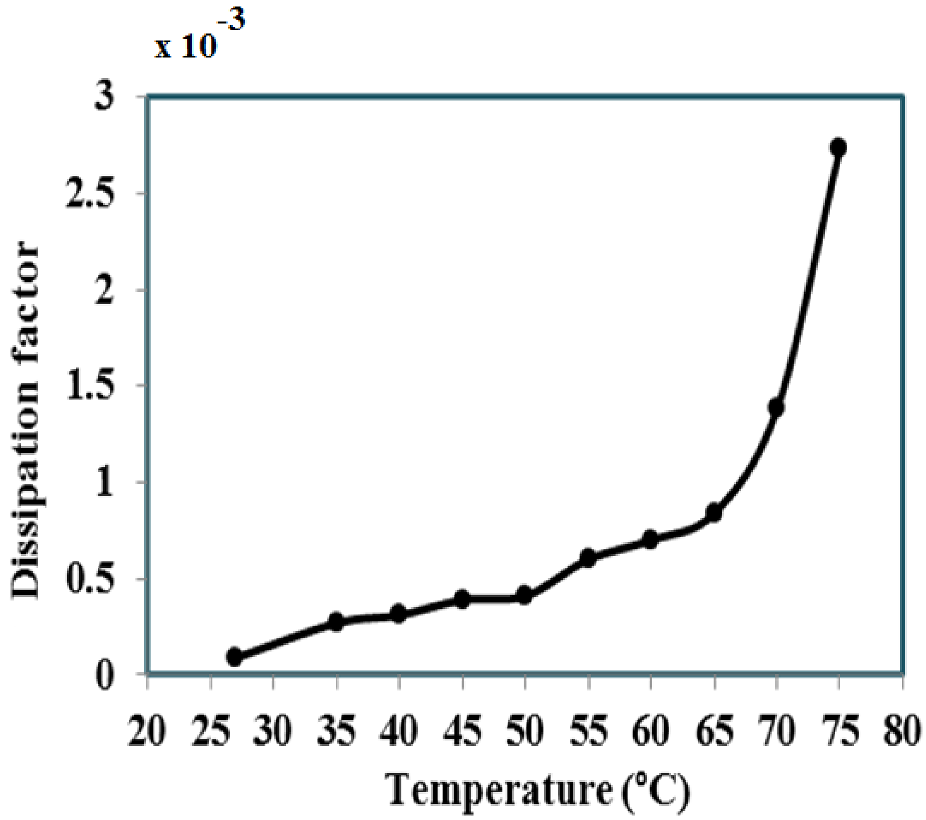


Figure 3.8: Dissipation factor as a function of temperature

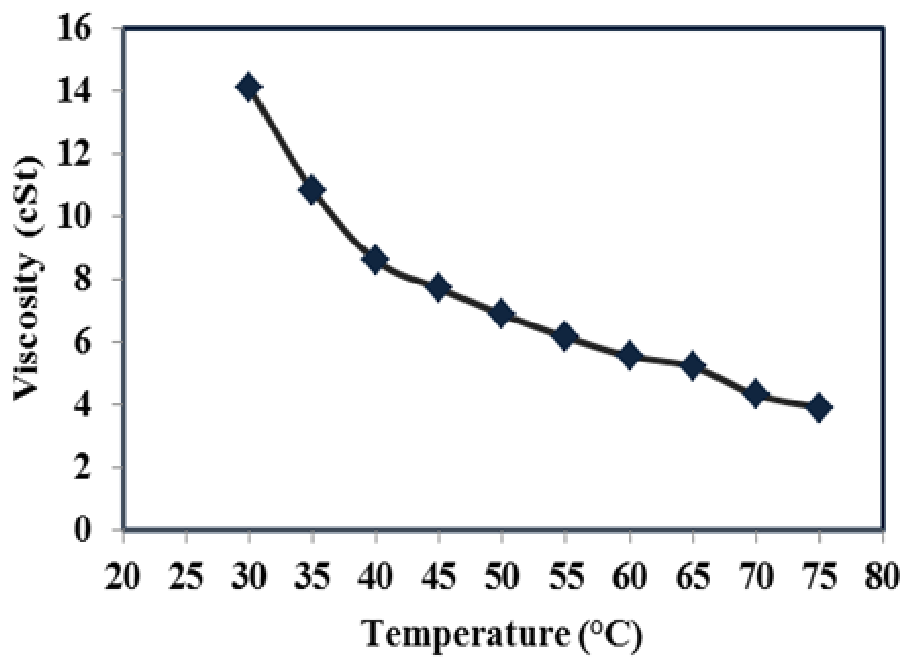


Figure 3.9: Viscosity as a function of temperature

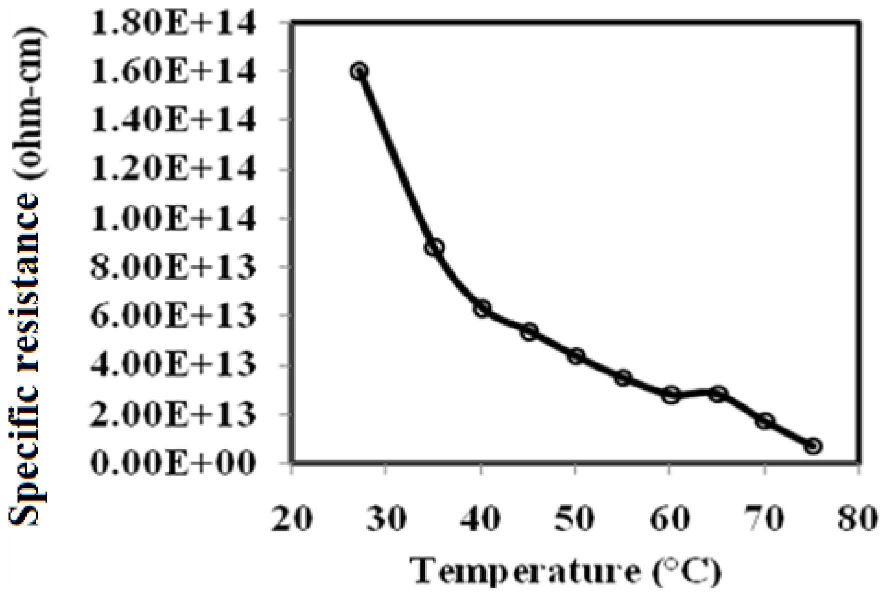


Figure 3.10: Specific resistance as a function of temperature

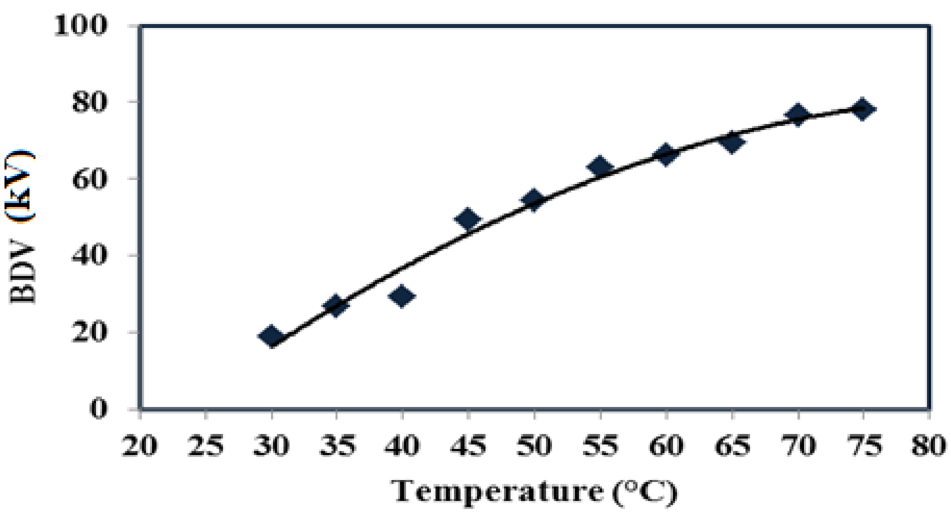


Figure 3.11: BDV as a function of temperature

3.6 SUMMARY

The laboratory experimental set-up and the instrumentation used for the simulation studies, the experimental procedure and the method of analysis of AE signal are discussed. The properties of the transformer oil used in the laboratory experimentation are also discussed in this chapter.

CHAPTER 4

ANALYSIS OF ACOUSTIC EMISSION SIGNALS FOR DEFECT CLASSIFICATION IN POWER TRANSFORMERS: EXPERIMENTAL/FIELD DATA

4.1 INTRODUCTION

The power transformers are important and vital components of ac power systems. It is essential to monitor the condition of these transformers periodically in order to ascertain the performance for continuous operation for its expected average life of 25-30 years. The defects in the power transformers lead to the deterioration of insulation and eventual premature failure. The deterioration of the insulation of the power transformers can be assessed by carrying out the condition monitoring tests periodically. The condition monitoring test techniques can be off-line or on-line. The off-line test techniques are being followed as given in IEEE Std. 62 (1995). These tests require the outage of the transformer, thereby causing interruption of the power supply. Whereas, the on-line test techniques do not require any outage. Hence, on-line diagnostic techniques have gained importance. The literature review shows the application of AE detection technique as a promising on-line tool for the condition monitoring/diagnosis of the power transformers. The general guidelines for the application of the AE technique for this purpose are outlined in IEEE Std. C57.127 (2007).

The PD is an electric discharge that occurs locally in the high stress regions of the insulation. Although the transformer insulations are designed to have stress within the limits, the high stress regions can occur in the transformers due to impurities and defects that develop in them with time. The PDs partially break the insulation between the two conductors. It has great influence on the reduction of insulation-life (Lundgaard 1992a and Stone1991). Even though the magnitude of these discharges is small, they can cause progressive deterioration of the insulation leading to ultimate failure of the insulation system. There are electrical, acoustic, optical and chemical methods for the PD detection. The AE technique has many advantages compared to the other PD detection methods (Lundgaard 1992b).

The power transformers are capital intensive equipment in the power system which needs attention in terms of monitoring their health in order to maintain the continuity of the power. Most of the utilities and the industries follow the maintenance protocols involving the off-line and the on-line monitoring techniques. The on-line techniques are being widely used as they do not interrupt the power supply (Lu 2000). The AE based PD detection technique is one of the relatively recent on-line techniques being employed to monitor the health of the oil-immersed power transformers (IEEE Std. 57.127 2007). Compared to the other on-line techniques, the AE based PD detection technique is amenable to real-time application in fault detection and identification.

The acoustic waves in the transformers are generated mainly due to the defects like PD and hot-spots. These signals, at times, can be due to the background noise. Both laboratory and field studies in understanding these AEPD signals can be cited from the literature (Lu 2000, Khawaja 2003 and Wei et al. 2016). The advantage of the AEPD technique is due to the non-invasive and the on-line detection features along with the possibility of identifying the fault location within the transformer body. Locating the region of fault is equally important from the point of view of initiating necessary corrective action for maintenance of the equipment (Veloso 2006, Nagamani et al. 2005, Fuping 2015, Kundu et al. 2009, Kundu et al. 2012, Arslan 2015, Hua 2016, Wasim et al. 2016).

Many efforts to extract and characterize the features of the AEPD signals, to understand the type of PD can be cited from the literature (Boczar and Zmarzly 2004, Boczar and Zmarzly 2003, Zheng 2006, Kundu et al., 2007, Lalitha and Satish 2000, Sharkawy 2007, Sharkawy 2008). Application of the wavelet analysis on the AEPD signals to differentiate the PD patterns (including the influence of the polarity of applied voltage) is attempted in the literature (Boczar and Zmarzly 2004, Boczar and Zmarzly 2003). The pattern recognition based on the experimentally generated AEPD signals is discussed in reference (Zheng 2006). The wavelet based fractal analysis of the AEPD signals is attempted and reported in the reference (Kundu et al., 2007). The efforts to classify the multisource PD using the artificial neural network from the multi resolution analysis (MRA) is also reported in the literature (Lalitha and Satish 2000). The suspended particle identification in the transformer oil using the AEPD pattern is attempted and discussed in the references (Sharkawy 2007 Sharkawy 2008, Ibrahim 2012). These studies (Boczar and Zmarzly 2004, Boczar and Zmarzly 2003, Zheng 2006, Kundu et al., 2007, Lalitha and Satish 2000, Sharkawy 2007 Sharkawy 2008, Ibrahim 2012) have been carried out to classify the type of the PD source, and to understand if it is from (1) PD in the oil, (2) PD in the void (3) PD on the surface (surface discharge) (4) PD due to the particles and (5) PD from the positive/negative polarity voltages. These are generally based on the laboratory generated AEPD signals by using the non-uniform field gaps.

The source of the AE signal in an oil immersed transformer can be due to PD and hot-spots apart from the noise signals. The core vibration and arcing can be the other possible source of AE signals which are not dealt in thesis. In the present study an attempt is made to differentiate the AEPD signals from the AE-heat-wave signals, using the FFT and DWT analysis. The laboratory experiment based results reported here are supported by the corresponding similar field-data. Thus the characterizing frequency range, and the peak frequency identified for the AE signals from these defects are validated. The focus is on the classification of defects from two different types of the sources of the AE signals. This is based on the analysis of the peak frequency (using FFT) and the analysis of the distribution of the energy over the different frequency ranges (using DWT).

4.1.1 AE signal and analysis

The AE signals are basically non-stationary signals with overlapping burst of unknown amplitudes. The main problem in the AE signal analysis is the estimation of the AE characterizing features. The multi resolution time-frequency analysis is required for the proper extraction of its features (Boczar and Zmarzly 2004, Boczar and Zmarzly 2003, Zheng 2006, Kundu et al., 2007, Lalitha and Satish 2000).

The basic limitation of the FT is that, the accurate information on the frequency spectrum of a signal can be obtained only when its run is known in an unlimited time range. Also, the signal has to be stationary in time. The STFT can provide the joint time-frequency representation of the signal, but the resolution is limited. In the case of STFT, the window length is fixed. A narrow window length gives a good time resolution and a poor frequency resolution and vice versa. When the signal requires more time resolution (or more frequency resolution) at some portions of the signal, the representation becomes inaccurate.

The wavelet analysis has emerged as a very powerful tool for the signal analysis (Boczar and Zmarzly 2004, Boczar and Zmarzly 2003, Zheng 2006, Kundu et al., 2007, Lalitha and Satish 2000). The wavelet analysis represents the windowing technique with the variable sized region. The wavelet allows the use of long time intervals to extract more precise low frequency information and shorter regions to extract high frequency information. This kind of wavelet signal analysis is ideal for the AE signals and the technique is applied successfully to classify the AE signals from the various defects. This is due to the discrete nature of the AE signal. The DWT captures both the frequency and the time information. The DWT is calculated by passing the signal through a series of filters. At first, the signals are passed through a high-pass filter and then through a low-pass filter. The output gives the detail-coefficients (from high-pass filter) and the approximation-coefficients (from the low-pass filter) (Zheng 2006).

4.1.2 Wavelet analysis of AE signals

In the present study, the 'Symlet' wavelet is opted for the DWT analysis of AE signal. When compared to the other wavelet family, the 'Symlet' wavelet has a closest approximation on a given level of decomposition (Boczar and Zmarzly 2004). The matlab toolbox is used for the purpose (Misti et al. 1996).The decomposition of AE signals into eight levels is carried out by using the 'Symlet-8' as the mother wavelet. The AE signals within the frequency range of 0-500 kHz are considered. The duration of each signal considered is of 1023 μs. The Table 4.1 shows the frequency range of each level in the 'Symlet-8' based decomposition process. The details related to this decomposition process and analysis is given in 3.4.2.

Table 4.1: The frequency ranges of detail-coefficients and the approximation-coefficients in the eight level decomposition using 'Symlet-8' mother wavelet.

Details and Approximations	Frequency range (kHz)
D1	250 - 500
D2	125 - 250
D3	62.5 - 125
D4	31.2 - 62.5
D5	15.6 - 31.2
D6	7.81 - 15.6
D7	3.90 - 7.81
A7	0.00 - 3.90

The AE signals are captured by using the piezo-electric sensors. The energy distribution of the signals is computed over the different frequency ranges given in Table 4.1 by adopting DWT. These results are compared with those of DGA. Hence the relevant topics of DGA based analysis and fault identification is given in the sequel.

4.1.3 DGA analysis for fault identification

The DGA is a test used as a diagnostic and maintenance tool for oil filled apparatus. Under abnormal electrical or thermal stresses insulating oils break down to liberate small quantities of gases. The regular monitoring of dissolved gases can provide useful information about the condition of the transformer and prior information of the faults. The DGA test commonly evaluate the concentration of hydrogen (H_2), methane (CH_4), ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2) and oxygen (O_2). The chemical analysis by gas chromatography remains the backbone of DGA. The results thus obtained can be interpreted using key gas methods. Key gas method involves plotting all the Total Dissolved Combustible Gas (TDCG) as a percentage of their total in a histogram. Each fault type will give a distinctive pattern characterized by a key gas, which is generally the most abundant. Different gases can serve as markers for different type of faults. In-service transformers always have some fault gases dissolved in their oil. A fault is suspected only when these levels exceed some threshold value. Table 4.2 shows the permissible concentration of hydrogen and methane (for normal condition) in oil as given in IEEE Std. C57.104 (2008) and the type of fault identified using these gases.

Table 4.2: Permissible concentration of hydrogen and methane in oil (μL/L) and the type of fault identified using these gases

Key gas	Permissible concentration (ppm)	Type of fault
Hydrogen	100	PD
Methane	120	Overheated oil

4.2 THE LABORATORY EXPERIMENTATION

The experimental studies have been performed in the laboratory employing the transformer tank model of size 1.1 m x 1.1 m x 1.1 m, with the wall thickness of 5 mm, made up of mild steel, and it is filled with the transformer oil. The transformer oil was heated with the help of the heaters of suitable rating immersed in the oil. The oil circulation arrangement was made for ensuring the uniformity of the oil temperature. The temperature of the oil is set to a particular temperature and is controlled by a temperature controller. The PD in the laboratory model is simulated by a needle electrode of 0.03 mm diameter suspended from the top cover of the tank. The top cover of the tank is made up of an insulating sheet (Hylam sheet of 8 mm thickness). The details of this laboratory test set up are given in section 3.2.3.

In order to eliminate the AE signals due to the background noise, it is a general practice to have a threshold of 35 dBae, so that the AE signals below this magnitude are not acquired by the data acquisition system. Even with this, some AE signals above the threshold set (35 dBae) were observed during the experimentation without the application of HV to the needle electrode (no AE due to simulated PD defect), with oil being at the ambient temperature (no AE due to simulated heat-wave defect). These AE signals are grouped as noise signals in this report.

The AE signals generated by the two defects (PD and hot-spots) are captured by employing 16 sensors made up of the piezo-electric material with the integrated pre amplifier. These sensors are strategically mounted on the transformer tank with the help of magnetic holders. The layout of the sensors is as given in section 3.2.3. The signals within the frequency range of 0-500 kHz are captured for the sake of analyses.

Several laboratory experiments were carried out to capture (1) AE signals generated due to PD (2) AE signals due to hot-spots, and (3) noise signal. The characteristics of the AE signals due to PD, hot-spots and noise are studied by using both the FFT and the DWT analysis.

4.2.1 Case-1: AE Signals due to PD in transformer tank model

The PD in the oil filled tank is generated using the needle electrode with the bottom of the tank acting as plane electrode. The distance between the tip of the needle and the ground plane is 0.418 m. The schematic of the laboratory test transformer along with the electrode arrangement is as shown in Figure 3.2. The AE signals due to the PD (simulated defect) in the oil have been captured by applying the HV, at a power frequency of 50 Hz, to the needle electrode. This experiment is carried out at the oil temperature of 30 °C (room temperature).

4.2.2 Case-2: AE Signals due to hot-spots (heat-waves) in transformer tank model

The AE heat-wave signals (due to the simulated defect) are captured by switching-on the heaters immersed in the oil. The schematic of the laboratory test transformer along with the heater arrangement is as shown in Figure 3.3. The experiment was conducted with the oil temperature set to 60 °C. This is with no application of HV to the needle electrode.

4.3 THE FIELD STUDY

The diagnostic laboratory at CPRI, India, is involved in providing the field measurement and service to utilities in the AEPD detection. More than 200 power-transformers in power-stations / generating-stations from all over India have been tested, over the last 8-10 years, on the invitation of the power-station authorities as a part of their periodic maintenance program. From this vast data, having diagnosed the defects, the following three specific case studies associated with the power transformers are discussed and analyzed. Of the three, the first two cases (namely, case-3 and case-4) deals with the transformers that had predominantly PD activity in it and the last case (case-5) deals with the transformer that had predominantly hot-spots in it. These in-situ studies are described in the following subsections. The characteristics of these AE signals for these transformers are further analyzed by using the FFT and the DWT analysis.

4.3.1 Case-3: AE Signals due to PD in a transformer (GT-Y)

This is a study related to a GT (GT-Y) of rating 11 kV / (220/√3) kV, 43.33 MVA, (1-Phase transformer) in one of the Hydro-Power plants in India. The DGA of the transformer oil was also carried out to find the presence of the defects like PD, hot-spots and the deterioration of the insulation properties. The DGA and oil Break Down Voltage (BDV) test results conducted on this transformer oil are given in Table 4.3. The DGA of this transformer oil had shown presence of higher amount of hydrogen indicating the presence of PD (IEEE Std. C57.104 2008). The measured hydrogen gas content was 537 ppm (more than 100 ppm). Based on the permissible concentration of key gas hydrogen content (see Table 4.2) it is inferred that type of fault in this case would be due to PD. The AE signals were collected for this transformer in the field. The load condition of the transformer while the AE tests were conducted is summarized in Table 4.4.

Table 4.3: DGA and BDV test results for GT (GT-Y)

Test	Dissolved gas type	Quantity
DGA	Methane (ppm)	1
	Ethane (ppm)	Not Detected
	Ethylene (ppm)	1
	Acetylene (ppm)	Not Detected
	Hydrogen (ppm)	537
	Oxygen (ppm)	36507
	Nitrogen (ppm)	59454
	Carbon Monoxide (ppm)	Not Detected
	Carbon Dioxide (ppm)	694
BDV	Break Down Voltage (kV rms)	52

Table 4.4: Load condition of transformer while capturing AE signal for GT (GT-Y)

PARAMETER	VALUE
Power	37.93 MW
Reactive power	9.3 MVAR
HV side Voltage	218 kV
LV side Voltage	10.88 kV
HV Current	338 A
LV Current	6160 A
Power Factor	0.98
Frequency	49.9 Hz
Oil temperature	45 ºC
Winding temperature	58 ºC

4.3.2 Case-4: AE Signals due to PD in a transformer (ICT-Y)

This is a study related to an Inter Connecting Transformer (ICT-Y) of rating 400 kV / 230 kV / 33 kV, 250 MVA, (3-phase transformer) in one of the thermal power stations in India. The DGA and the oil BDV test results conducted on this transformer oil are given in Table 4.4. The DGA of this transformer oil had shown presence of higher amount of hydrogen indicating the presence of PD (IEEE Std. C57.104 2008). The measured hydrogen gas content was 357 ppm (more than 100 ppm). Based on the permissible concentration of key gas hydrogen content (see Table 4.2) it is inferred that type of fault in this case would be due to PD. The AE signals were collected for this transformer in the field. The load condition of the transformer while the AE tests were conducted is summarized in Table 4.6.

Table 4.5: DGA and BDV test results for interconnected transformer (ICT-Y)

Test	Dissolved gas type	Quantity
DGA	Methane (ppm)	5
	Ethane (ppm)	1
	Ethylene (ppm)	Not Detected
	Acetylene (ppm)	Not Detected
	Hydrogen (ppm)	357
	Carbon Monoxide (ppm)	12
	Carbon Dioxide (ppm)	135
BDV	Break Down Voltage (kV rms)	52

Table 4.6: Load condition of transformer while capturing AE signal for the interconnected transformer (ICT-Y)

PARAMETER	VALUE
Power	184 MW
Reactive power	78 MVAR
HV side Voltage	398 kV
LV side Voltage	224 kV
HV Current	315 A
LV Current	420 A
Power Factor	0.94
Frequency	49.7 Hz
Oil temperature	50 ºC
Winding temperature	56 ºC

4.3.3 Case-5: AE Signals due to hot-spots in a transformer (GT-Z)

This is a study related to a 3-Phase Generator-transformer of rating 20 kV / 230 kV, 370 MVA in a power-station which was in operation for less than 3 years. The DGA and oil BDV test results conducted on this transformer oil are given in Table 4.7. The DGA of this transformer oil was showing methane gas content higher than the permissible limit (IEEE Std. C57.104 2008). The measured methane gas content was 155 ppm (more than 120 ppm). The winding temperature was also high. Based on the permissible concentration of key gas methane content (see Table 4.2) it is inferred that type of fault in this case would be due to hot-spots. The AE signals were collected for this transformer in the field which would be due to heat-wave. The load condition of the transformer while the AE tests were conducted is summarized in Table 4.8.

Table 4.7: DGA and BDV test results for GT (GT-Z)

Test	Dissolved gas type	Quantity
DGA	Methane (ppm)	155
	Ethane (ppm)	284
	Ethylene (ppm)	40
	Acetylene (ppm)	Not Detected
	Hydrogen (ppm)	Not Detected
	Carbon Monoxide (ppm)	23
	Carbon Dioxide (ppm)	246
BDV	Break Down Voltage (kV rms)	58

Table 4.8: Load condition of transformer while capturing AE signal for the GT (GT-Z)

PARAMETER	VALUE
Power	315 MW
Reactive power	87 MVAR
HV side Voltage	222 kV
LV side Voltage	19.9 kV
HV Current	820 A
LV Current	9140 A
Power Factor	0.98
Frequency	49.8 Hz
Oil temperature	55 ºC
Winding temperature	75 ºC

The AE signals corresponding to the above cases are studied by using the DWT analysis and the results are discussed in the following section. An attempt to correlate the

AEPD signals and the AE heat-wave signals obtained from laboratory and field studies are also carried out in the next section.

4.4 RESULTS AND DISCUSSION

The AE signals acquired corresponding to the laboratory and the field studies explained in section 4.2 and section 4.3 are with a sampling rate of 1 MSPS. A large number of AE waves are collected in each of these tests over a period ranging from 30 s to 5 minutes. The duration of each AE wave analyzed is 1023 μs. These waves are analyzed by using the FFT and the DWT. 'Symlet-8' is used as the mother wavelet for DWT analysis with 8 level frequency decomposition (Zheng 2006). The energy content in these discrete eight frequency ranges is analyzed.

4.4.1 Case-1: AE Signals due to PD in transformer tank model (Experimental results)

A number of laboratory experiments to capture the AE signal due to the simulated PD are conducted. A typical AE signal due to simulated PD, captured by the sensor is shown in Figure 4.1. The peak frequency can be identified using the FFT analysis. The FFT analysis of a typical AEPD-wave in the transformer oil is given in Figure 4.2. The first twenty AE signals captured by the sensors are subjected to the FFT analysis and the peak frequency for each signal is given in Table 4.9. From Table 4.9 the average frequency is calculated for these twenty signals and it is seen that, the average peak frequency for an AEPD signal is 134.54 kHz. But the minimum to maximum peak frequency for these signals vary over a wide range of 0.42 kHz to 177. 12 kHz. The peak frequency for the twenty signals with the average peak frequency is shown in a bar graph given in Figure 4.3.

The DWT analysis is also carried out to find the energy distribution over different frequency ranges. The DWT analysis of a typical AEPD-wave in the transformer oil, by using 'Symlet-8' as the mother wavelet, is given in Figure 4.4. The maximum energy content is seen in the D2 range. In one such experimental result having a total of 346 AE-waves, 320 AE-waves are found to have maximum energy in the frequency range of

125 kHz - 250 kHz (D2). Thus, for the case of the AE signals, it is inferred that, due to the PD, the DWT analysis shows that the energy content is maximum in the D2 range.

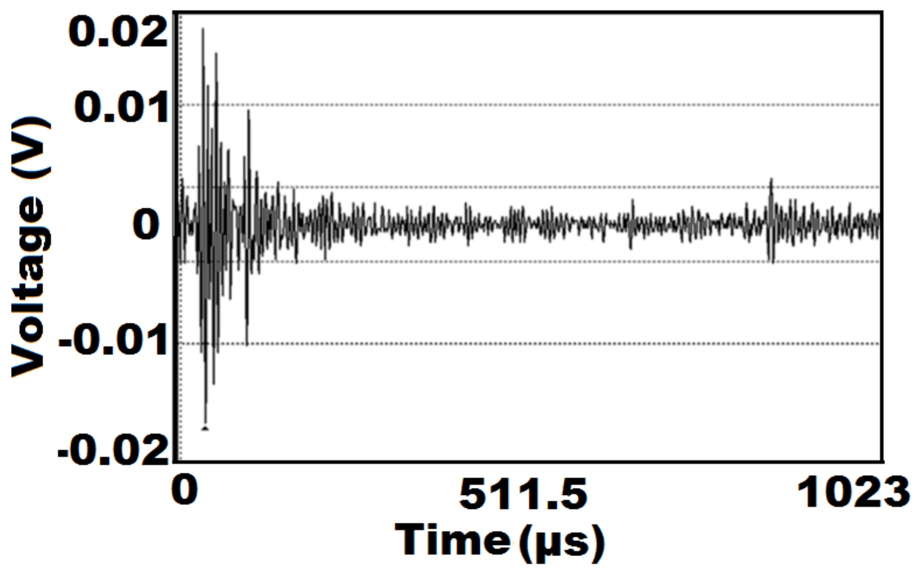


Figure 4.1: A typical AE signal due to simulated PD captured by the sensor (case-1)

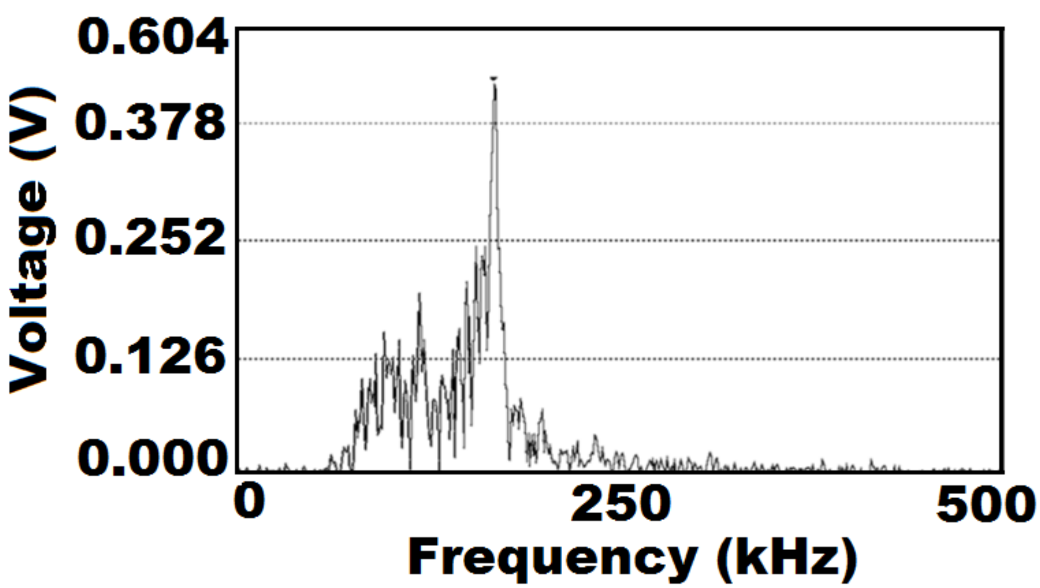


Figure 4.2: The FFT analysis of a typical AEPD wave (case-1)

Table 4.9: The peak frequency for twenty signals (case-1)

Signal number	Frequency (kHz)	Signal number	Frequency (kHz)	Signal number	Frequency (kHz)	Signal number	Frequency (kHz)
1	168.22	06	0.4240	11	167.8	16	121.89
2	165.93	07	126.28	12	107.63	17	176.27
3	145.73	08	168.64	13	169.92	18	163.81
4	126.42	09	129.66	14	125.17	19	156.80
5	123.31	10	177.12	15	0.4240	20	169.49

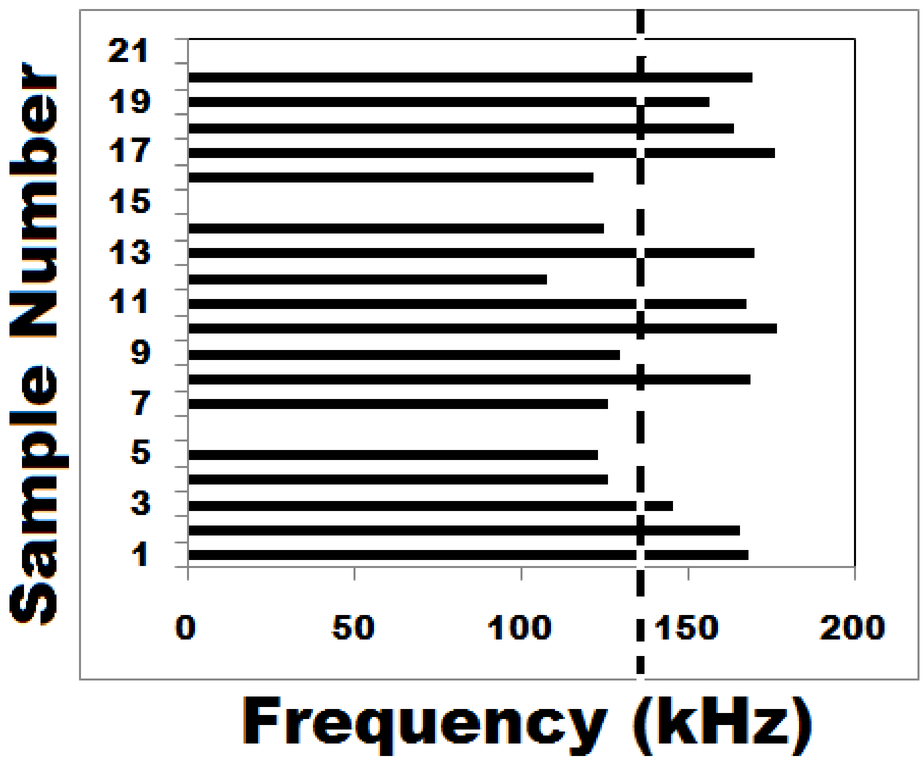


Figure 4.3: The bar graph showing the peak frequency at for twenty signals (case-1) The average frequency is marked with broken line.

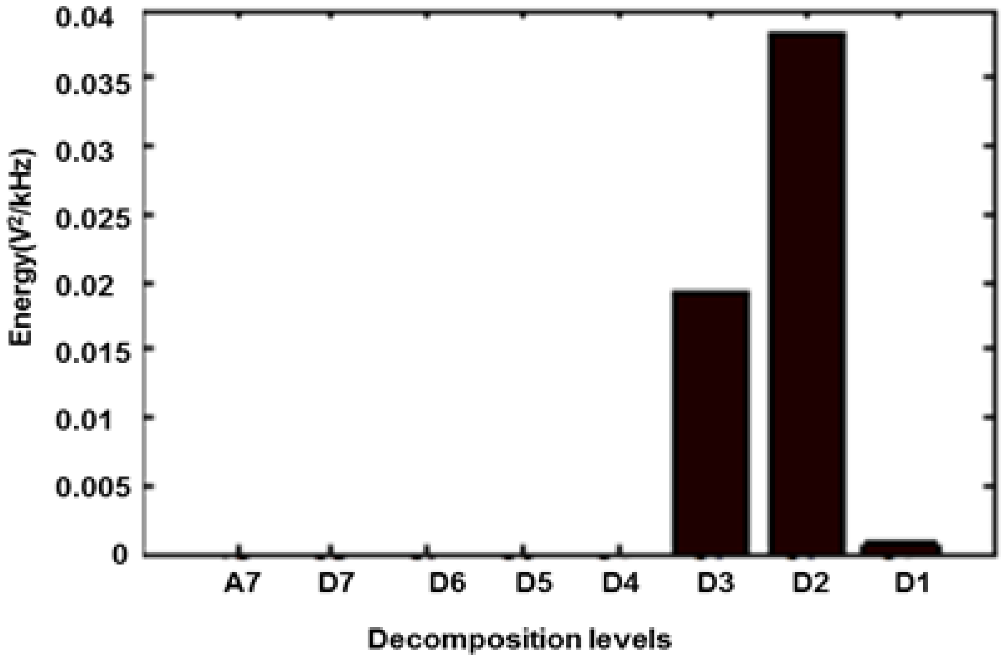


Figure 4.4: The DWT analysis of a typical AEPD wave (case-1)

4.4.2 Case-2: AE Signals due to hot-spots in transformer tank model (Experimental results)

A number of laboratory experiments to simulate the AE signal due to the hot-waves simulating hot-spots are conducted. A typical AE signal due to simulated heat-wave, captured by the sensor is shown in Figure 4.5. The peak frequency of an AE signal can be identified using the FFT analysis. The FFT analysis of a typical AE heat-wave in the transformer oil is given in Figure 4.6. The first twenty AE signals captured by the sensors are subjected to the FFT analysis and the peak frequency for each signal is given in Table 4.10. From Table 4.10 the average frequency is calculated for these twenty signals and it is seen that, the average peak frequency for an AEPD signal is 101.96 kHz. But the minimum to maximum peak frequency for these signals vary over a wide range of 94.49 kHz to 115.25 kHz. The peak frequency for the twenty signals with the average peak frequency is shown in a bar graph given in Figure 4.7.

The DWT analysis is also carried out to find the energy distribution over different frequency ranges. The DWT analysis of a typical AE heat-wave in the transformer oil, by using ‘Symlet-8’ as the mother wavelet, is given in Figure 4.8. The maximum energy content is seen in the D3 range. In one such experimental result having a total 550 AE-waves, 534 AE-waves are found to have maximum energy in the frequency range of 62.5 kHz - 125 kHz (D3). Thus, for the AE signal, it is inferred that, due to the heat-waves, the DWT analysis shows that the energy content is maximum in the D3 range.

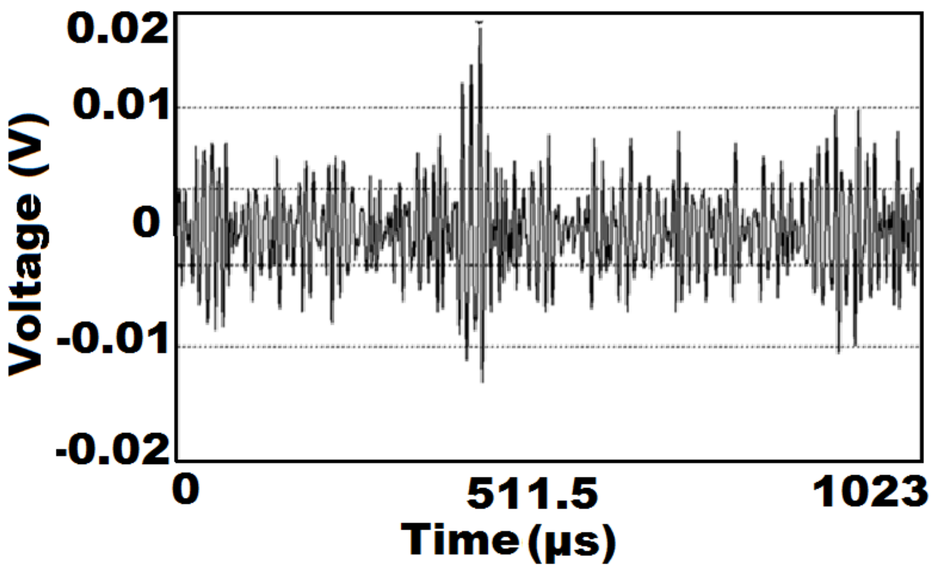


Figure 4.5: A typical AE signal due to simulated heat-wave captured by the sensor (case-2)

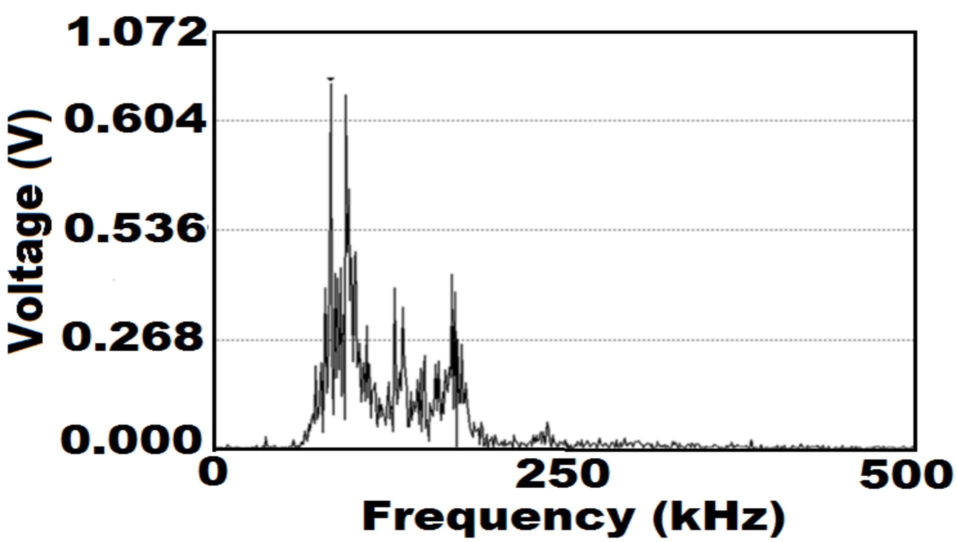


Figure 4.6: The FFT analysis of a typical AE heat-wave (case-2)

Table 4.10: The peak frequency for twenty signals (case-2)

Signal number	Frequency (kHz)	Signal number	Frequency (kHz)	Signal number	Frequency (kHz)	Signal number	Frequency (kHz)
1	94.92	6	111.02	11	98.31	16	100.42
2	111.86	7	98.31	12	102.12	17	97.46
3	100.85	8	94.49	13	94.49	18	101.27
4	115.25	9	112.71	14	101.27	19	107.67
5	100.42	10	98.19	15	94.49	20	103.81

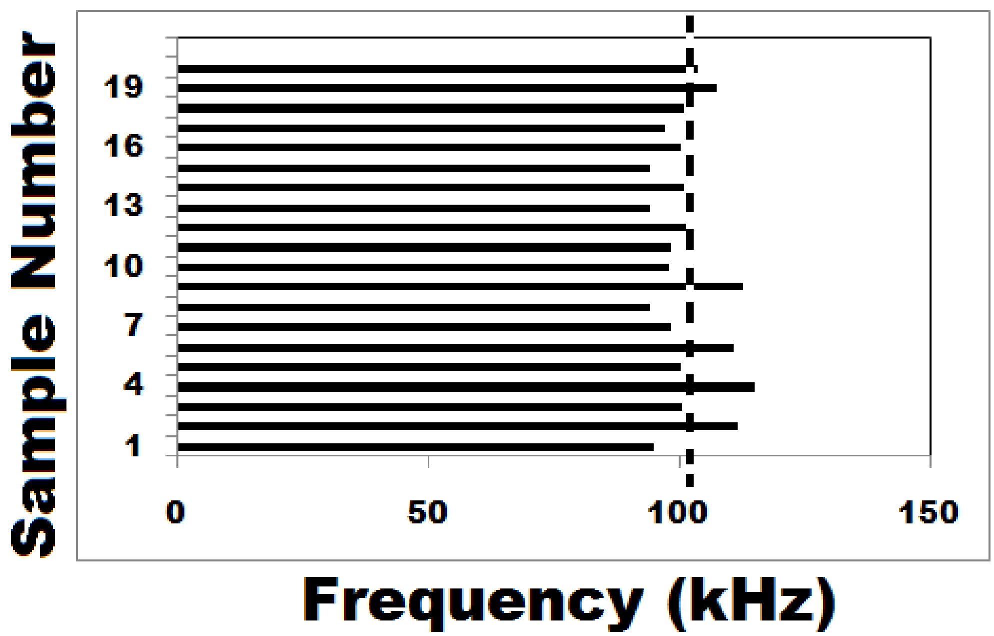


Figure 4.7: The bar graph showing the peak frequency for twenty signals (case-2). The average frequency is marked with broken line.

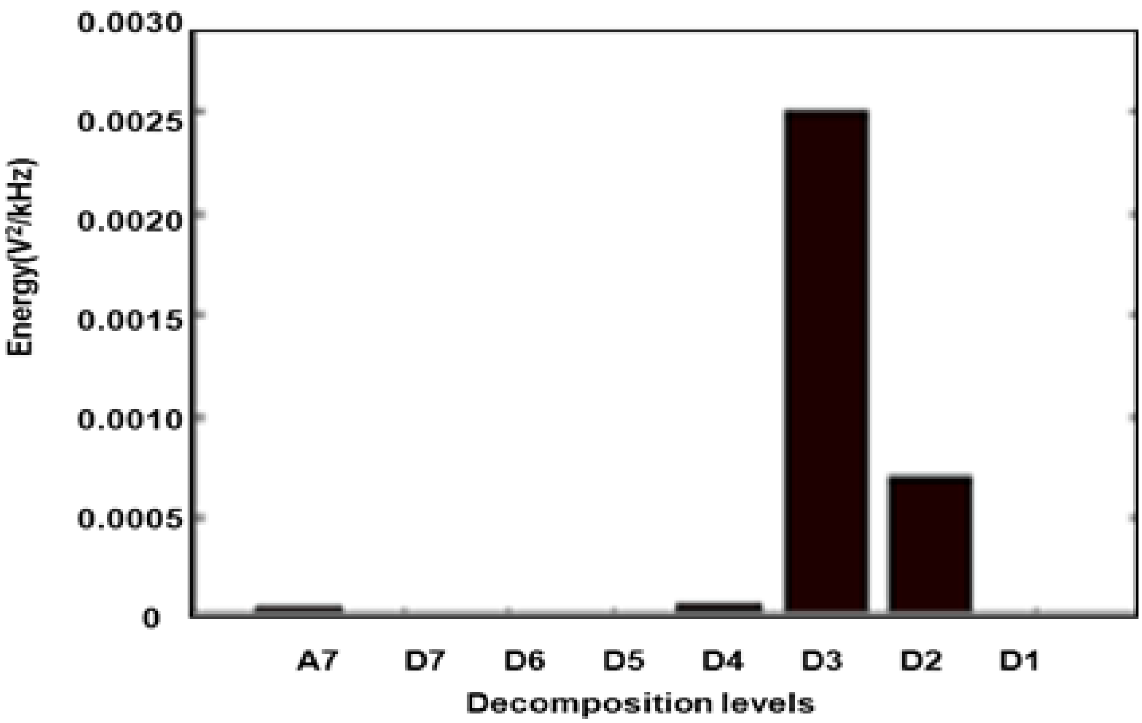


Figure 4.8: The DWT analysis of a typical AE heat-wave (case-1)

4.4.3 Laboratory experiments: Noise signal

While carrying out experiments to simulate AEPD waves and AE heat-waves, it was observed that AE signals were captured by the AE detection system even without applying the voltage to the needle electrode (source of PD signals) and the heaters not being switched-on (source of heat-wave signals). These signals thus captured by AE detection system are grouped under noise-category, their magnitude being low (generally < 40 dBae). However, these signals are also captured and studied to understand their dominant frequency range. A typical noise signal captured is shown in Figure 4.9. The results of the FFT and DWT analysis of a typical noise signal are given in Figure 4.10 and Figure 4.11. From Figure 4.10, it can be seen that the peak frequency is less than 3 kHz. Figure 4.11 shows the energy distribution of the AE signal over the different frequency range. The maximum energy content is seen in the A7 range. In one such experimental result having 35 AE-waves, 33 AE-waves are found to have maximum energy in the frequency range of 0 kHz - 3.90 kHz (A7). These are some of the incidental results and may not have greater significance if the noise signal magnitudes are below the threshold set (generally 35 dBae).

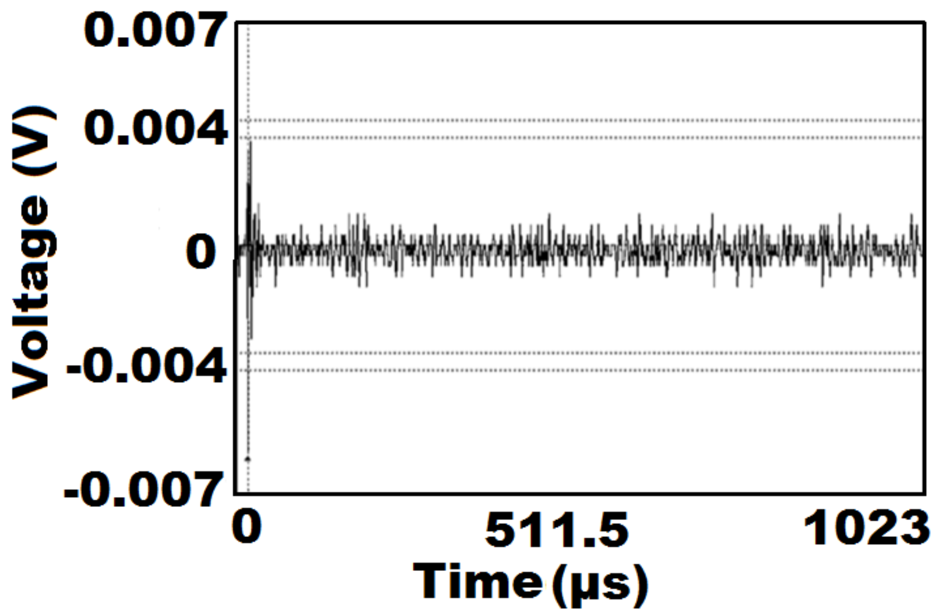


Figure 4.9: A typical AE signal due to noise captured by the sensor

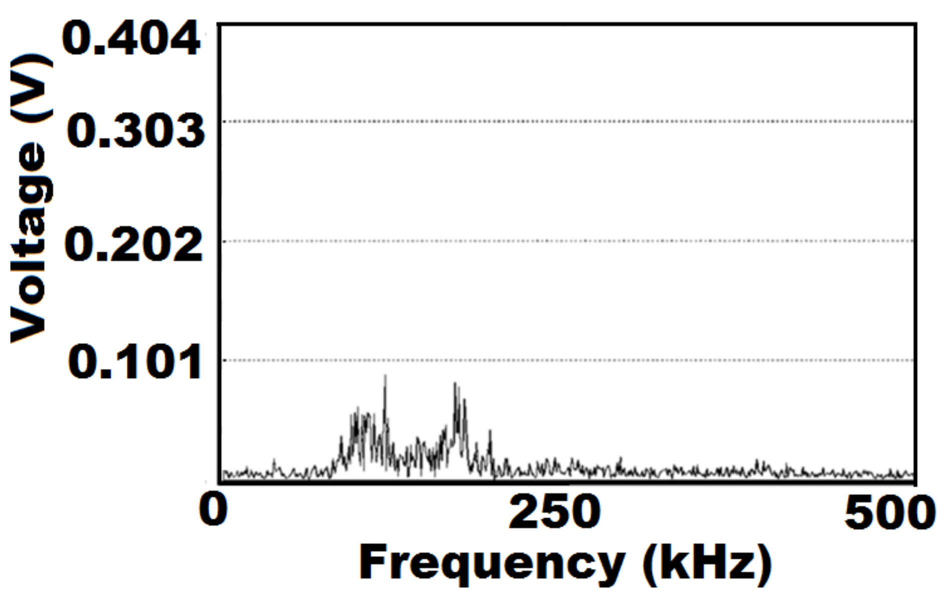


Figure 4.10: The FFT analysis of a typical AE wave due to noise

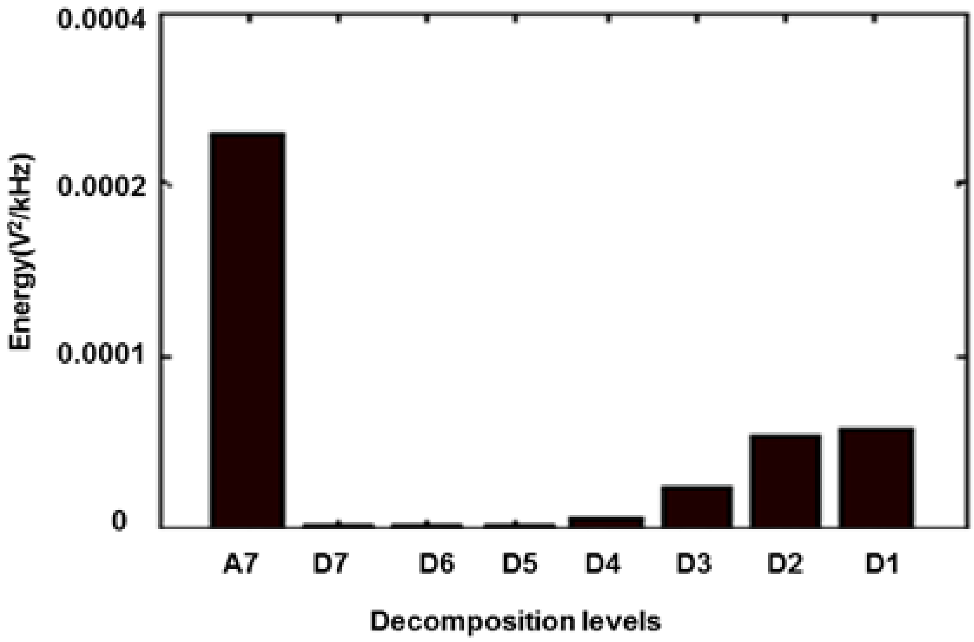


Figure 4.11: The DWT analysis of a typical AE-wave due to noise

4.4.4 Summary of laboratory experiments

The FFT and the DWT analysis of the AE-waves with PD, hot-spots and noise as source of AE are carried out. From the FFT analysis it is inferred that the peak frequencies are approximately 135 kHz, 102 kHz and less than 3 kHz for AEPD wave, AE heat-wave and AE noise, respectively. From the DWT analysis, it is inferred (characterized) that the maximum energy content of the AE signals is in the frequency range of D2, D3 and A7, for PD, hot-spots and noise, respectively. The FFT analysis helps in identifying the peak frequency. But this frequency may vary from signal to signal. So, it is difficult to decide these frequencies for characterizing the individual defects. Therefore, it would be desirable to go for identification of a range of frequencies for the classification and characterization of individual defect. Hence DWT analysis, which gave the range of frequency having the maximum energy content of the signal, is adopted for identification of fault type. Further attempt is made to correlate this with those of the field studies.

4.4.5 Case-3: AE Signals due to PD in transformer GT-Y (Field results)

The DGA of this transformer oil (transformer details are given in section 4.3.1) had shown presence of higher amount of hydrogen indicating the presence of PD (IEEE Std. C57.104 2008). The measured hydrogen gas content was 537 ppm. The online AE test (in-situ) was also carried out capturing 1357 AE- waves for this transformer. A typical AE wave captured in the field is shown in Figure 4.12. The amplitude of the AE signals captured by the 16 channels of the AE-detection system is depicted in Figure 4.13. From Figure 4.13, it can be seen that the maximum amplitude of the AE signal is above 60 dBae indicating abnormal condition in the transformer. The DWT analysis is carried out to find the energy distribution over different frequency ranges. The DWT analysis of a typical AE wave in the transformer oil, by using 'Symlet-8' as the mother wavelet, is given in Figure 4.14. The maximum energy content is seen in the D2 range. All the 1357 AE-waves of this transformer are analyzed. The percentage of the total AE-waves having their maximum energy content in the frequency ranges D2, D3 and A7 are grouped and are given in the bar graph (Figure 4.15).

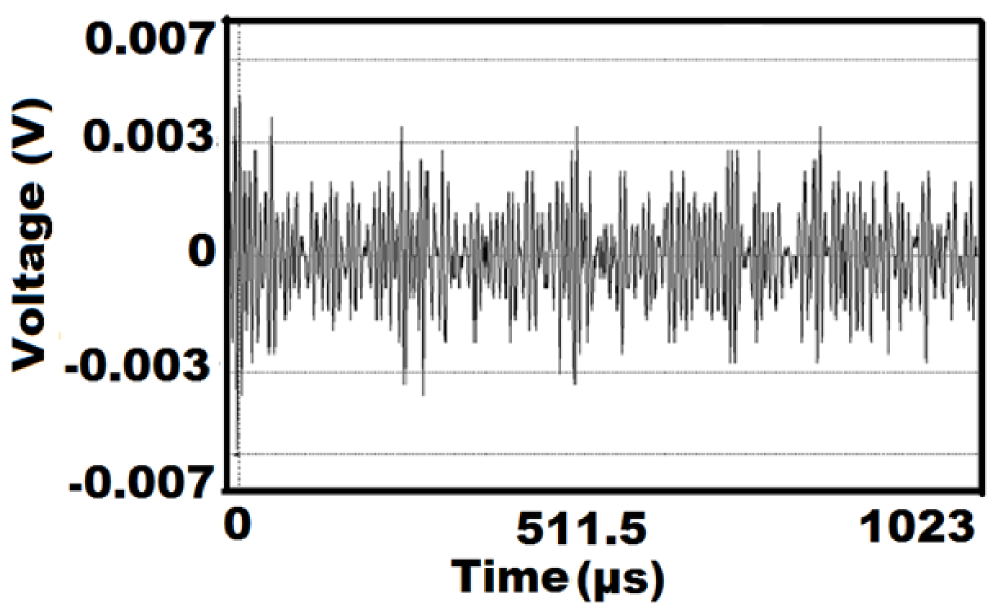


Figure 4.12: A typical AE signal from transformers GT-Y (case-3)

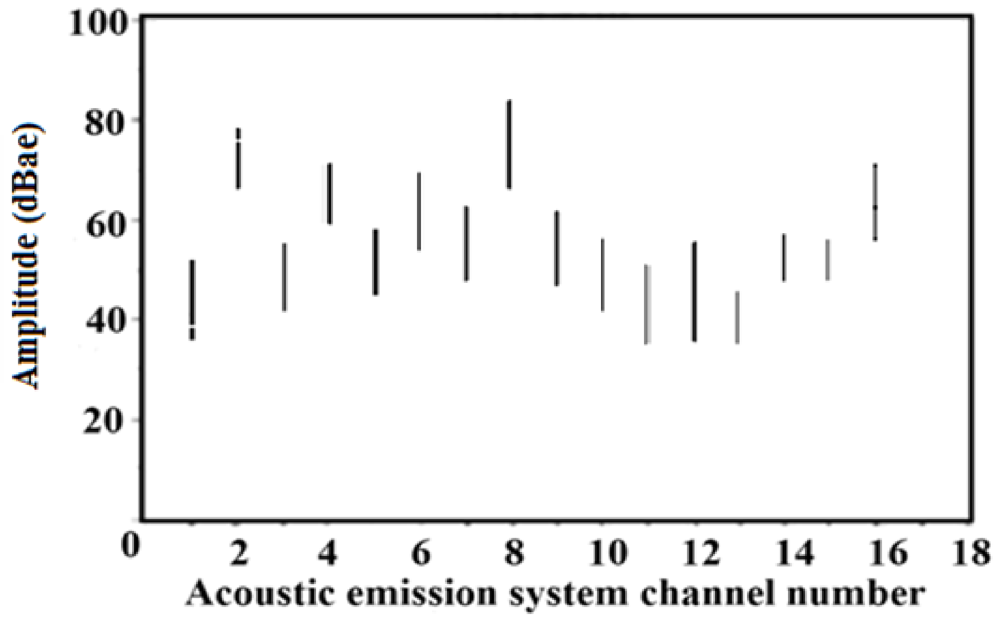


Figure 4.13: AE Amplitude for 16 AE channels recorded for transformer GT-Y (case-3)

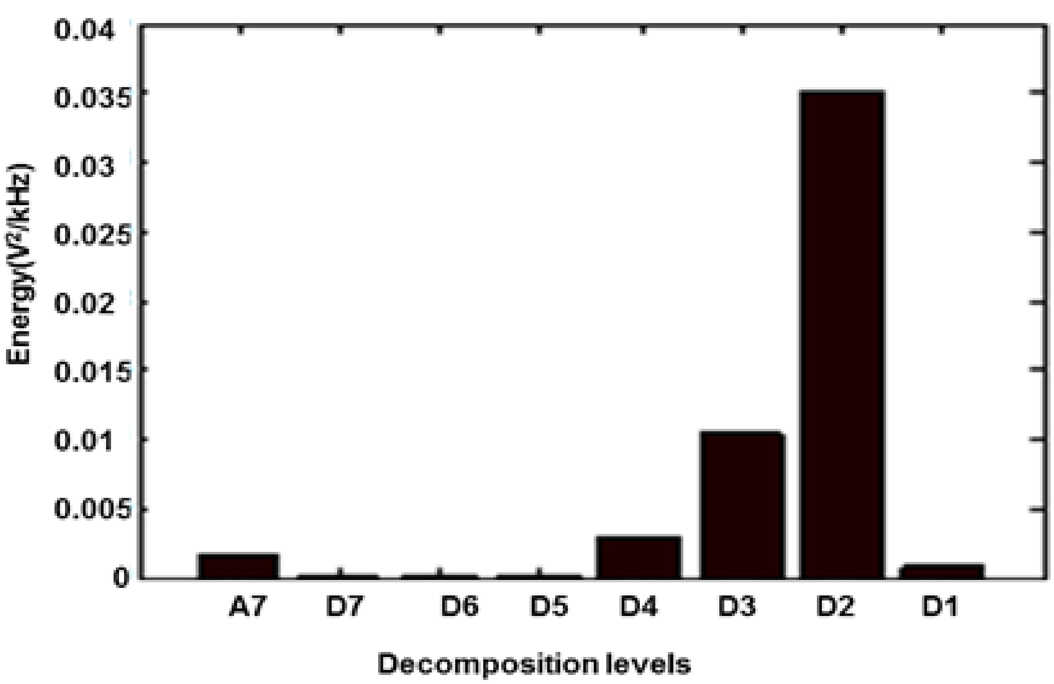


Figure 4.14: The DWT analysis of a typical AE wave from transformer GT-Y (case-3)

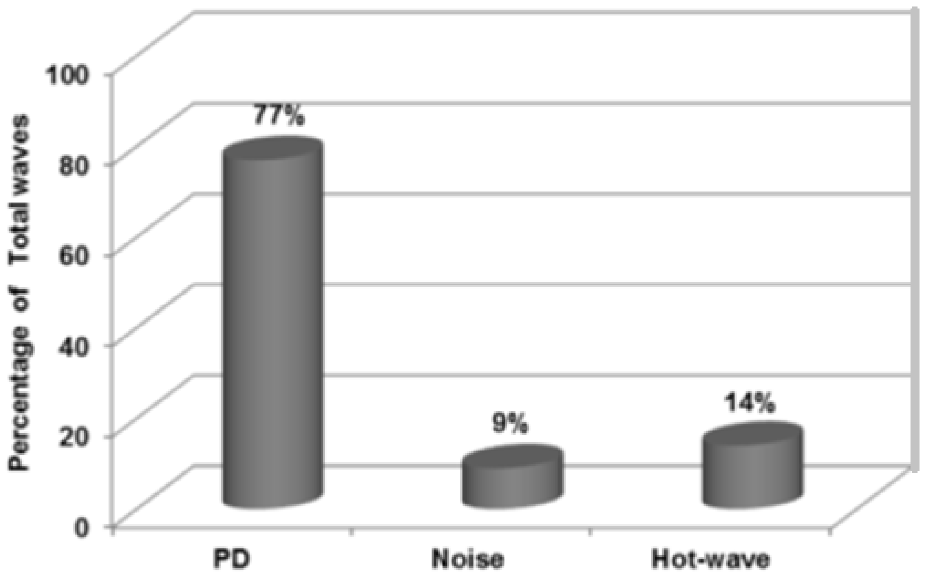


Figure 4.15: Percentage distribution of total AE waves having their maximum energy content in the PD (D2), hot-wave (D3) and noise (A7) frequency ranges obtained by DWT based decomposition of 1357 AE-waves captured for the transformer GT-Y (case-3)

The results obtained from the DWT analysis of the AE signals given in Figure 4.15 confirm the presence of predominant PD activity. These results reaffirm the PD characterizing frequency range to be D2, as summarized in section 4.4.1.

4.4.6 Case-4: AE Signals due to PD in transformer ICT-Y (Field results)

The DGA of this transformer oil (transformer details are given in section 4.3.2) had shown presence of higher amount of hydrogen indicating the presence of PD (IEEE Std. C57.104 2008). The measured hydrogen gas content was 357 ppm. The online AE test (in-situ) was also carried out capturing 88078 AE- waves for this transformer. A typical AE wave captured in the field is shown in Figure 4.16. The amplitude of the AE signals captured by the 16 channels of the AE-detection system is depicted in Figure 4.17. From Figure 4.17, it can be seen that the maximum amplitude of the AE signal is around 60 dBae indicating abnormal condition in the transformer. The DWT analysis is carried out to find the energy distribution over different frequency ranges. The DWT analysis of a typical AE wave in the transformer oil, by using 'Symlet-8' as the mother wavelet, is given in Figure 4.18. The maximum energy content is seen in the D2 range. All the 88078 AE-waves of this transformer are analyzed. The percentage of the total AE-waves having their maximum energy content in the frequency ranges D2, D3 and A7 are grouped and are given in the bar graph (Figure 4.19).

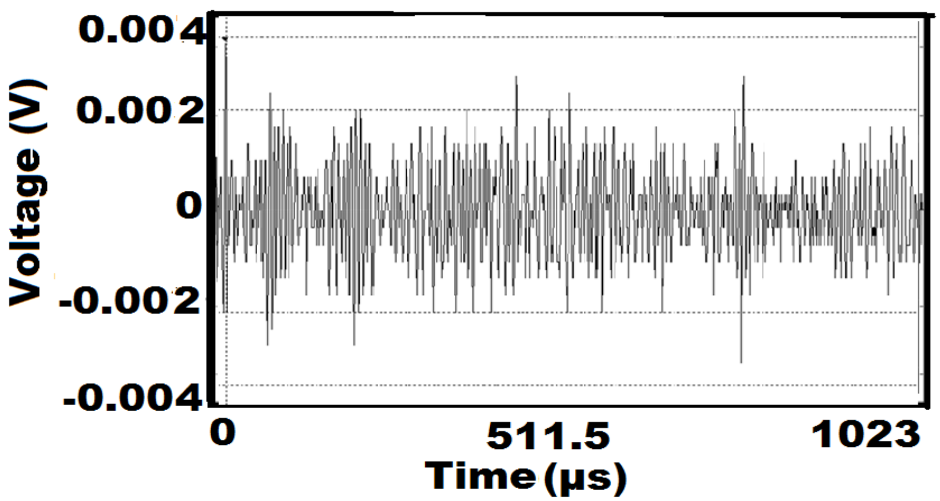


Figure 4.16: A typical AE signal from transformer ICT-Y (case-4)

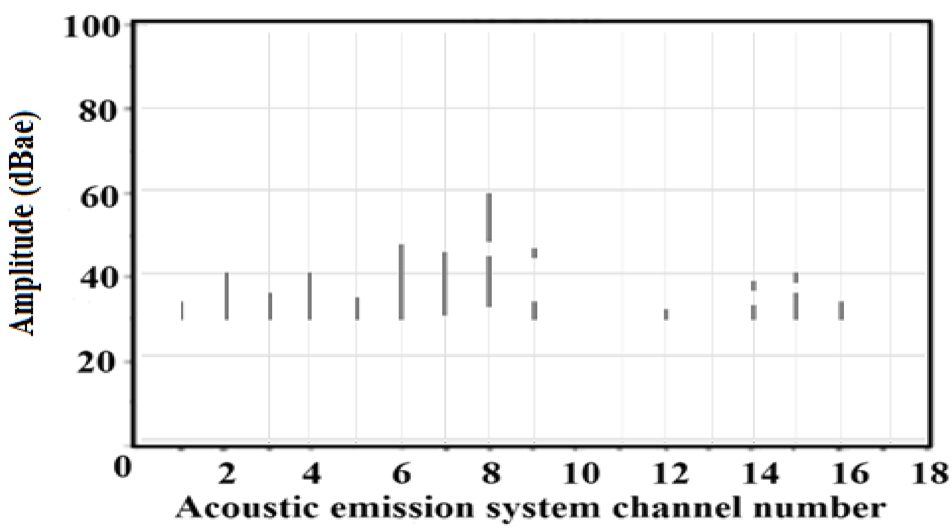


Figure 4.17: AE Amplitude for 16 AE channels recorded for transformer ICT-Y (case-4)

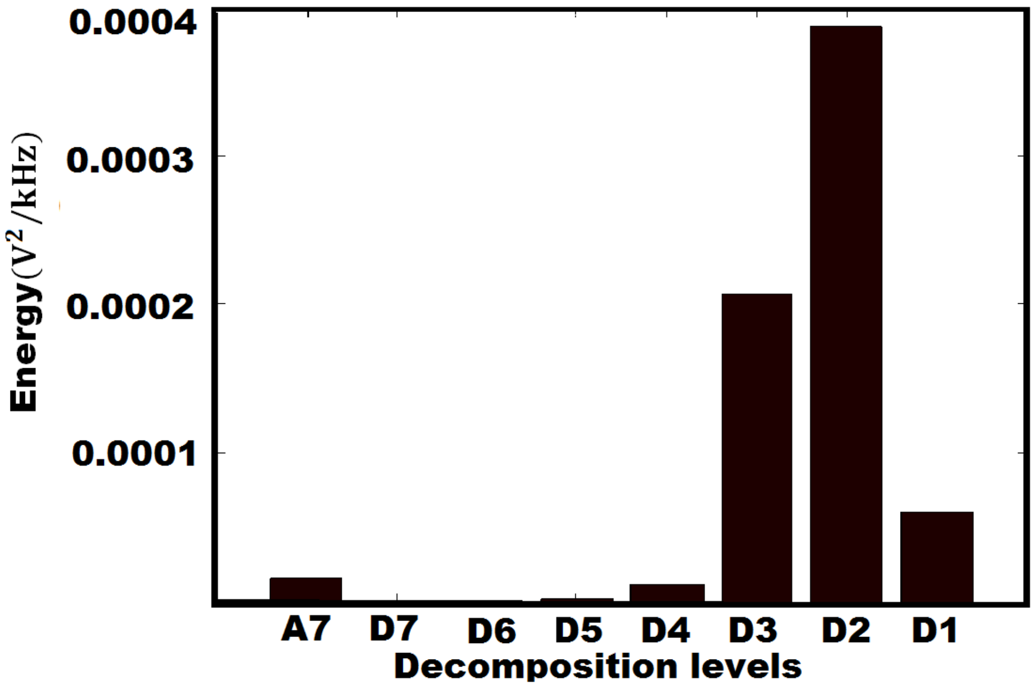


Figure 4.18: The DWT analysis of a typical AE-wave from transformer ICT-Y (case-4)

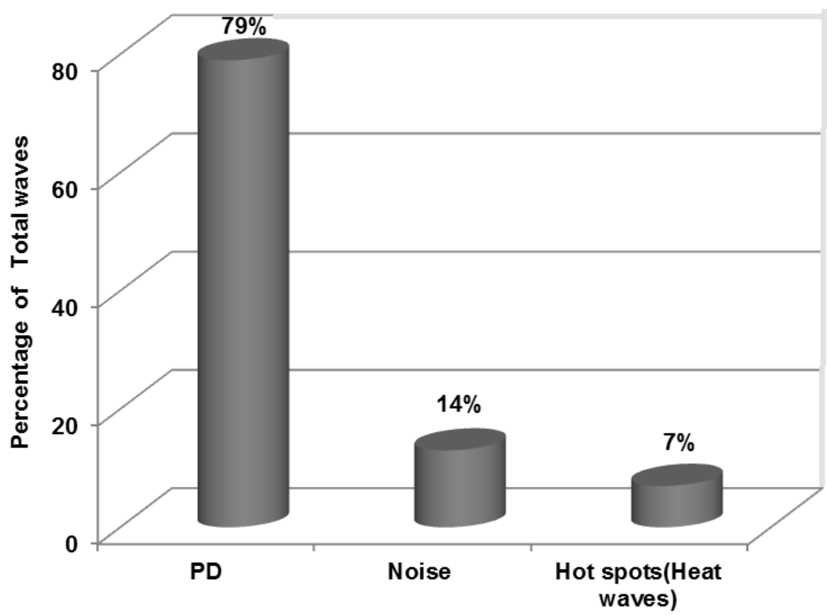


Figure 4.19: Percentage distribution of total AE waves having their maximum energy content in the PD (D2), hot-wave (D3) and noise (A7) frequency ranges obtained by DWT based decomposition of 88078 AE-waves captured for the transformer ICT-Y (case-4).

Results obtained from the DWT analysis of the AE signals given in Figure 4.19 confirm the presence of predominant PD activity. These results reaffirm the PD characterizing frequency range to be D2, as summarized in section 4.4.1.

4.4.7 Case-5: AE Signals due to hot-spots in transformer GT-Z (Field results)

The DGA results of the transformer oil (transformer details are given in section 4.3.3) had shown the presence of methane gas indicating localized overheating due to presence of hotspots (IEEE Std. C57.104   2008). The measured methane gas content was 155 ppm (above permissible limit of 120 ppm). The online AE test (in-situ) was also carried out capturing 84225 AE-waves for this transformer. A typical AE wave captured in the field is shown in Figure 4.20. The amplitude of the AE signals captured by the 16 channels of the AE-detection system is depicted in Figure 4.21. From Figure 4.21, it can be seen that the maximum amplitude of the AE signal is above 60 dBae indicating abnormal condition in the transformer. The DWT analysis is carried out to find the energy distribution over different frequency ranges. The DWT analysis of a typical AE wave in the transformer oil, by using Symlet-8 as the mother wavelet, is given in Figure 4.22. All the 84225 AE-waves of this transformer are analyzed. The percentage of the total AE-waves having their maximum energy content in the frequency ranges D2, D3 and A7 are grouped and are given in the bar graph (Figure 4.23).

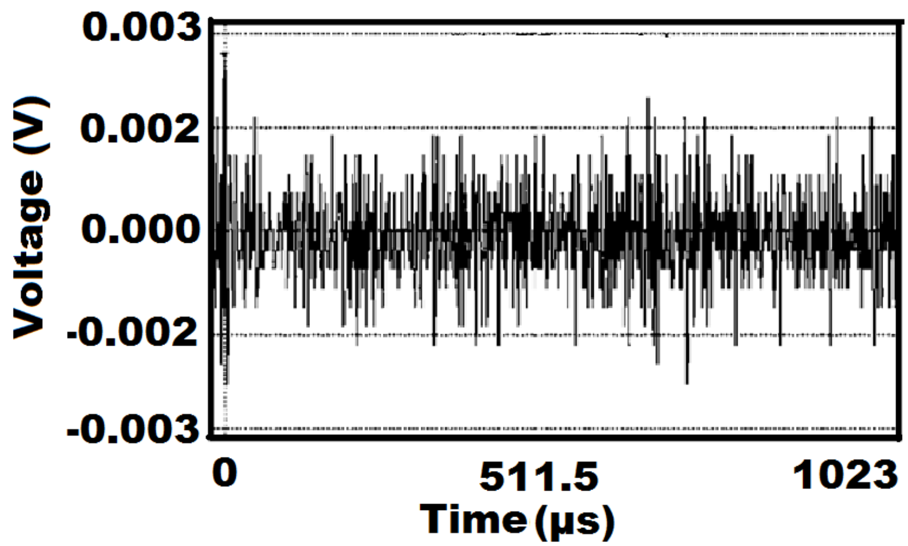


Figure 4.20: A typical AE signal from transformer GT-Z (case-5)

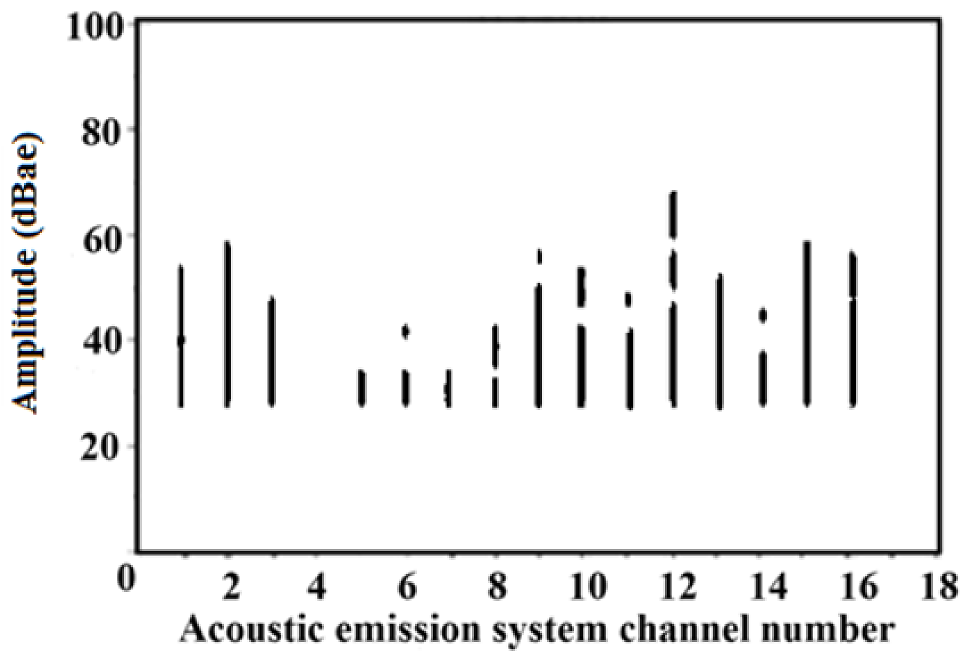


Figure 4.21: AE Amplitude for 16 AE channels recorded for transformer GT-Z (case-5)

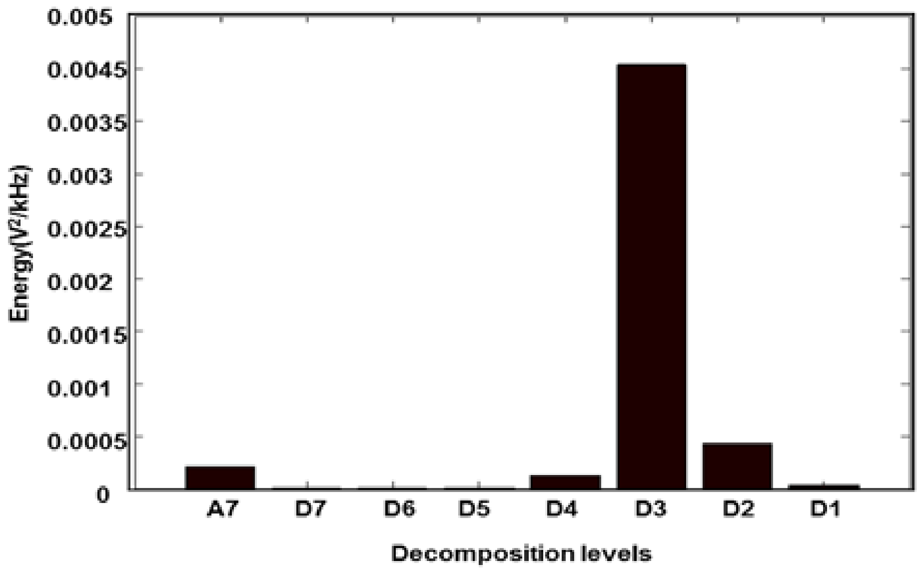


Figure 4.22: The DWT analysis of a typical AE wave from transformer GT-Z (case-5)

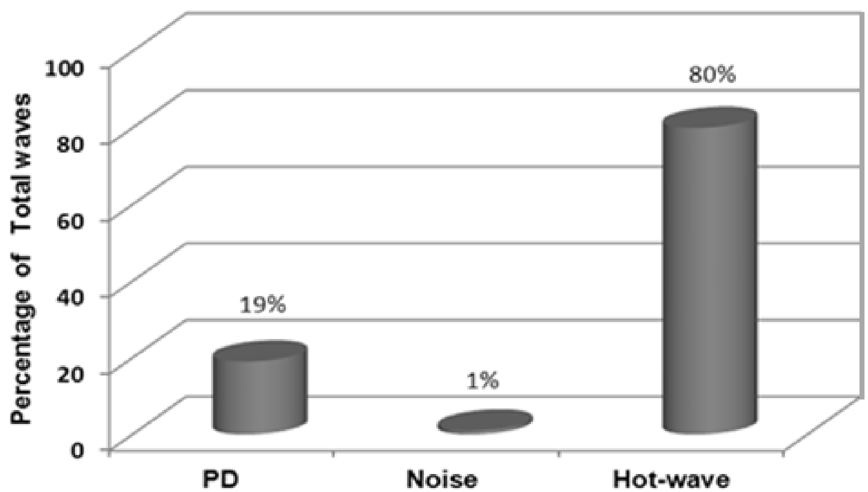


Figure 4.23: Percentage distribution of total AE waves having their maximum energy content in the PD (D2), hot-wave (D3) and noise (A7) frequency ranges obtained by DWT based decomposition of 84225 AE-waves captured for the transformer GT-Z (case-5).

The results obtained from the DWT based analysis of the AE signals given in Figure 4.23 confirm the presence of predominant heat-wave activity. These results reaffirm the hot-spot characterizing frequency range to be D3, as summarized in section

4.4.2. Overheating of transformer was confirmed as the winding and oil temperatures were 75 ºC and 55 ºC, respectively.

4.5 SUMMARY

- The FFT and DWT analysis of the AE signals captured from the individual defects (PD and hot-spot) simulated in the laboratory experimental studies are carried out. The peak frequency identified by using the FFT analysis falls in the range of the class of frequencies (with maximum energy of AE signal in the decomposition level) identified through DWT analysis for the individual defects.
- The FFT analysis helps in identifying the peak frequency. But this frequency may vary from signal to signal. So it is difficult to decide these frequencies for the individual defects. Therefore, it would be better to go for identification of a range of frequencies for the classification and characterization of individual defect. Hence DWT analysis, which gave the range of frequency having the maximum energy content of the signal, is adopted for fault classification.
- The AE signals obtained in the laboratory set-up and their DWT analysis indicate the characterizing dominant frequency range of (i) PD to be 125-250 kHz and (ii) hot-wave to be 62.5-125 kHz.
- The AE signals obtained from the transformers working in the field and their DWT analysis also confirms that the characterizing dominant frequency range of (i) PD to be 125-250 kHz and (ii) hot-wave to be 62.5-125 kHz.
- The DGA results pertaining to the transformers used in the case studies also substantiate the presence of the PD (high hydrogen content) or the hot-spots (high methane content) in the respective cases. Also, DGA results corroborate with those of the proposed DWT based AE classification.
- Thus DWT analysis can be adopted for analyzing the AE signal and for the online diagnosis to infer if the transformer has PDs or hot-spots. This would be a better substitute for DGA based analysis as AE based analysis can be carried out in real-time.

CHAPTER 5

BEHAVIOUR OF ACOUSTIC EMISSION PD SIGNALS IN TRANSFORMER OIL AT DIFFERENT TEMPERATURES

5.1 INTRODUCTION

The AE based PD detection technique is one of the recent methods for the on-line diagnosis of oil filled power transformers. The PD in a power transformer generates acoustic signals for which transformer oil acts as a medium for propagation. The AEPD detection technique makes use of AEs associated with PD signals in detection and location of faults in power transformers (Lundgaard 1992a, Lundgaard 1992b, Harrold 1985 and Boczar 2001). Experimental results showing the effect of temperature on AEPD signals over a limited range of 25 °C to 40 °C is reported in one of the earlier studies Wang et al. (2005) have studied the shift in acoustic energy of the acoustic signals/waves generated by PD in transformer oil at temperatures of 25 ºC and 40 ºC. These authors have analyzed the AE signal data with FFT and their findings have shown that the acoustic energy at 40 ºC is larger than that at 25 ºC.

As the oil temperature of transformer in service may exceed 40 ºC, it was found appropriate to study the behavior of AEPD signals in the temperature range beyond 40 ºC. The laboratory experiments have been carried out to study the behavior of AEPD signals at temperatures of 30 °C to 75 °C. Some of the important AEPD signal quantities (PAC 2003), namely, discharge amplitude and peak frequency were considered for the study. The properties of transformer oil such as dissipation factor, dielectric constant, viscosity, specific resistance and breakdown voltage (BDV) have also been measured at temperatures of 30 °C to 75 °C (given in section 3.5) for correlating with the AEPD signal quantities.

5.2 EXPERIMENTAL STUDY

Laboratory experiments are carried out making use of a mild steel tank with wall thickness of 5 mm and size of 1.1 m x 1.1 m x 1.1 m, filled with transformer oil (Nagamani et al. 2005). The PDs are generated in the oil medium with a point electrode having a tip of 0.03mm diameter and electrode gap as 0.418 m. Considering the volume of the oil in the laboratory experimental tank, it was observed that transformer oil is required to be heated to 8 hours to get a stable temperature over the entire volume of oil. This duration of heating is required for the transformer oil to stabilize (1°C/hr) (IS-8623 Part-1 1993). Only after obtaining the stable condition AEPD signal measurements are taken. The AEPD signal quantities such as discharge magnitude and peak frequency have been measured at voltages of 15 kV rms, 16 kV rms and 17 kV rms in the temperature range of 30 °C to 75 °C in steps of 5 °C. The temperature measuring accuracy was ±1 °C and resolution is 0.1 °C. The AE signals generated from the PD in oil were captured with piezoelectric sensor (model DT15I of M/s PAC, USA) having an operating temperature ranging from -45 °C to+85 °C and sensitivity of ±2 dBae. The sensor was mounted on the outer surface of the tank at a distance of 0.60 m from the tip of the electrode.

In order to understand the behavior of AEPD signal quantities in transformer oil, the properties of transformer oil like dielectric constant, dissipation factor, viscosity and specific resistance have been measured at temperatures ranging from 30 °C to 75 °C in steps of 5 °C, using relevant procedures of Indian standards (IS-335 2005, IS-1866 2000). BDV was measured as per IEC 60156 (1995) using M/s BAUR Instruments, UK, by heating the oil to the required temperature. The oil temperature was measured with a temperature indicator of M/s Fluke, USA make (accuracy of ±0.5 °C, resolution of 0.1 °C).

5.3 RESULTS & DISCUSSION

The measured values of the AEPD magnitude (dBae)for temperatures ranging from 30 °C to 75 °C are depicted in Figure5.1 at 15 kV rms, 16 kV rms, and 17 kV rms. At each experimental condition, three readings were taken with a time gap of 600 s, in order to check the repeatability of the measurements. The AEPD magnitude (dBae) measured at 15 kV rms, 16 kV rms, and 17 kV rms for temperatures ranging from 30 °C to 75 °C for the three trials are shown in Table 5.1. The AEPD magnitude has increased in the temperature range from 30 °C to 40 °C and thereafter remained stable (within ±5 dBae) up to 65 °C, at all the three voltages, 15 kV rms, 16 kV rms and 17kV rms. Beyond 65°C, a substantial reduction in the AEPD magnitude has been observed. A considerable increase in AEPD magnitude has been observed at 17 kV rms in the temperature range of 45°C and 65 °C as compared to 15 kV rms and 16 kV rms. As expected, with increase in voltage the AEPD magnitudes have increased.

The peak frequency is the frequency at which peak amplitude occurs (PAC 2003). The FFT of the AEPD signal was carried out to obtain the peak frequency. The peak frequencies measured at various temperatures are given in Table 5.2. For brevity, peak frequencies measured at different temperatures have been depicted in Figure 5.2 for 17 kV. A considerable shift in the peak frequency (from 105 kHz to 168 kHz) has been observed at temperatures 35 °C and 40 °C. From 40 °C to 65 °C, not much change in the peak frequency (within 10 kHz) has been observed. A decrement in peak frequency was observed above 65 °C, which is same with the AEPD magnitude.

The properties of transformer oil such as dissipation factor, dielectric constant, viscosity and breakdown voltage (BDV) have also been measured at temperatures of 30 °C to 75 °C (given in section 3.5). Dielectric constant has not shown much variation with temperature (Figure 3.7). The dissipation factor, as expected, has increased with temperature, showing a steep rise beyond 65 °C (Figure 3.8). The viscosity has dropped with temperature (Figure 3.9), which is a usual behavior of the oil. The specific resistance has also dropped with temperature, which is a usual behaviour of oil (Figure 3.10). The BDV of the transformer oil has shown an increasing trend with temperature (Figure 3.11).

Table 5.1: The AEPD discharge magnitude (dBae) measured at 15 kV rms, 16 kV rms, and 17 kV rms for temperatures ranging from 30 °C to 75 °C for the three trials

Discharge magnitude (dBae) at 15 kV rms											
Temp (°C)		30	35	40	45	50	55	60	65	70	75
Trial number	1	44	48	52	53	53	52	52	52	47	44
	2	43	45	50	50	50	49	51	51	45	43
	3	43	46	48	50	50	48	48	47	44	42
Discharge magnitude (dBae) at 16 kV rms											
Temp (°C)		30	35	40	45	50	55	60	65	70	75
Trial number	1	46	50	55	55	56	55	54	54	48	44
	2	46	49	56	54	55	56	55	53	46	43
	3	45	50	55	56	54	57	55	55	48	45
Discharge magnitude (dBae) at 17 kV rms											
Temp (°C)		30	35	40	45	50	55	60	65	70	75
Trial number	1	53	56	68	67	69	65	65	64	52	47
	2	53	54	67	68	67	66	64	65	50	48
	3	54	57	70	69	68	64	65	64	51	46

Table 5.2: The Peak frequencies of AEPD signals measured at temperatures ranging from 30 °C to 75 °C

Temperature (°C)	Peak frequency (kHz)
30	109
35	111
40	168
45	173
50	170
55	168
60	166
65	165
70	127
75	97

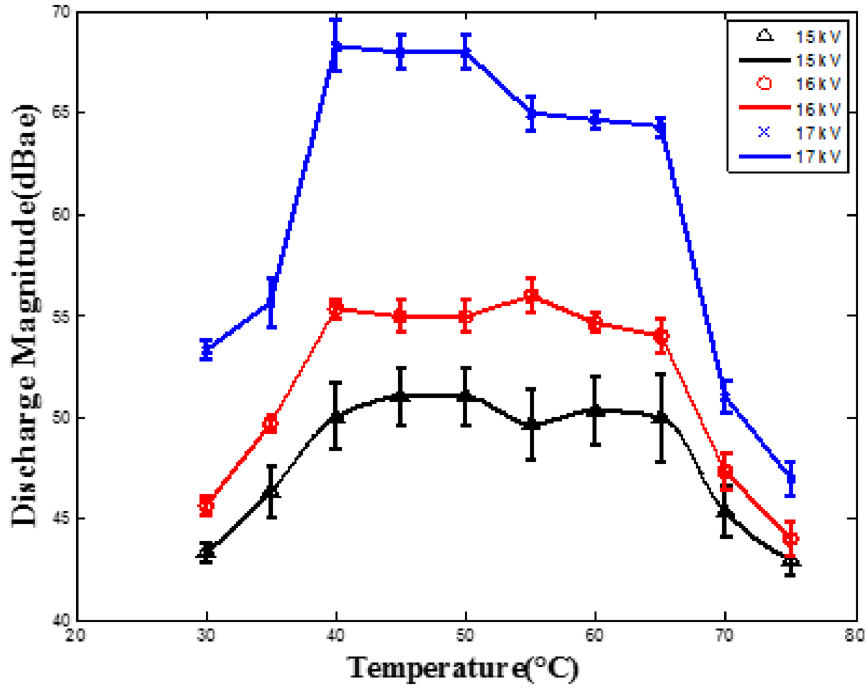


Figure 5.1: Discharge amplitude(dBae) versus temperature at 15 kV rms, 16 kV rms & 17 kV rms

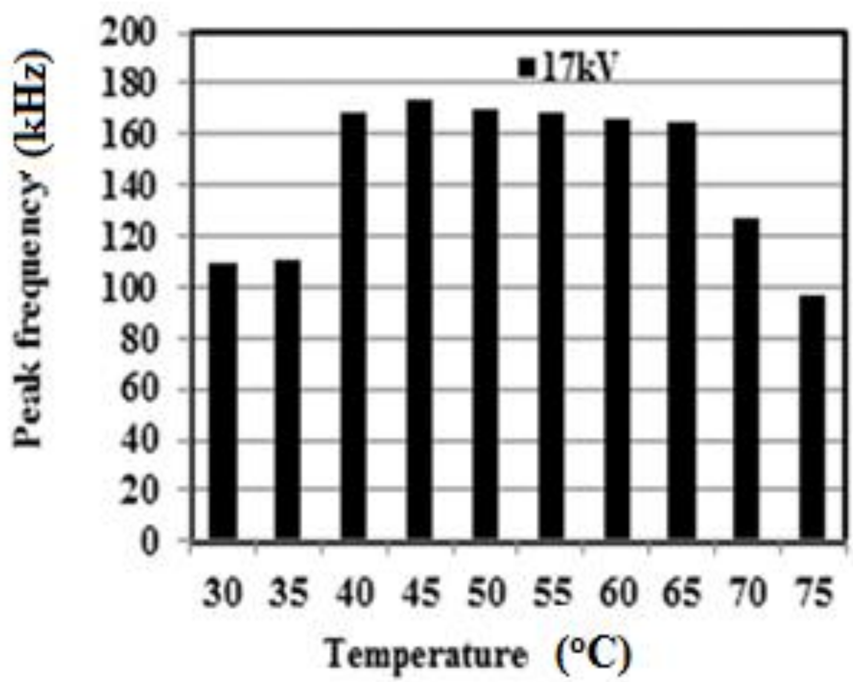


Figure 5.2: Peak frequencies versus temperature with applied voltage of 17 kV rms.

AEPD has shown a normal behavior of increased PD activity up to certain temperature (from 30 °C to 50 °C) and has exhibited a strange behavior of reduction in AEPD signal quantities beyond 65 °C. At 70 °C, AEPD signal quantities have reduced to almost equal to those of at 30 °C. One of the possible reasons for the reduced AEPD signals in transformer oil after a particular temperature can be attributed to and could be due to the increase in BDV of the oil. This explanation seems to help explain the reduction in AEPD signal magnitudes at higher temperatures beyond 55 °C. Increase in BDV of the transformer oil is equivalent to increase in its intrinsic strength. This increased intrinsic strength implies corresponding reduction in PD activity (with gap separation and non-uniformity remaining the same). The observed improvement in BDV values with temperature could be attributed to lowering of moisture content in the oil (Musil et al. 1995 and Malik et al. 1998). At lower temperatures (30 °C to 40 °C) the reduction in AEPD magnitudes could be due to changes in the viscosity of the oil with temperature. As seen from the figure 3.9 viscosity of the transformer oil reduces with increase in temperature. Acoustic signal strength and velocity are affected by the viscosity of the oil. It is expected that at higher viscosities the strength of the AE signals will be lower.

Since there is correlation between temperature with BDV and viscosity of the transformer oil, an attempt is made to relate BDV and viscosity with AEPD magnitude by curve fitting.

By curve fitting technique, a correlation equation is found to explain the effect of BDV and viscosity on AEPD magnitude is attempted. The empirical relation relating AEPD magnitude (α) with BDV (β) and viscosity (γ) is given by equation 5.1. Both β and γ vary as function of temperature (θ).

$$\alpha = 125.7372 - (7.7310 * \gamma) - (1.2965 * \beta) + (0.1788 * \gamma * \beta) \qquad (5.1)$$

The experimental results showing the variation of viscosity, BDV and AE discharge magnitudes as a function of temperature is given in Table 5.3. The predicted values of AEPD magnitudes can be compared with those of the experimentally measured values (comparing data in column 4 and 5).

Table 5.3: Variation in AEPD magnitudes (at 17 kV rms), viscosity and BDV as function of temperature of the transformer oil

Temperature (θ) in °C	Viscosity (γ) in cSt	BDV (β) in kV	AEPD discharge magnitude (α) in dBae	
			Measured @ 17 kV rms	By curve fitting
30	12.7	23.1	53.3	50.1
35	10.9	26.9	55.7	59.0
40	8.42	29.3	68.3	66.8
45	7.65	49.5	68.0	70.1
50	6.85	54.3	68.0	68.9
55	6.15	63.1	65.0	65.8
60	5.56	66.2	64.7	62.7
65	5.21	69.5	64.3	60.1
70	4.32	76.6	51.0	52.2
75	3.91	78.0	47.0	48.9

The strange behavior of reduction in AEPD magnitude (α) with increase in temperature can be explained by the combined effect of changes in BDV (β) and viscosity (γ). As the combination of effect of both viscosity and BDV variation with temperature, a hump in the AEPD magnitudes as function of temperature could be explained.

5.4 SUMMARY

- Study of transformer oil properties such as dielectric constant, specific resistance, dissipation factor, viscosity and BDV at various temperatures ranging from 30 ºC to 75 ºC is carried out to find the suitability of the transformer oil for carrying out laboratory experiments, and the results were found to be normal.
- The AE signal parameters due to the PD are measured over the entire working temperature range (30 °C to 75 °C) of the transformer and are reported. Beyond 65 °C, a substantial reduction (35%) in AEPD discharge magnitude has been

observed. This peculiar behavior of reduction in AEPD signal quantities is attributed to the changes in other parameters of the transformer-oil such as BDV and viscosity. An attempt is made to relate these quantities by an empirical relation.

- A shift in the peak frequency from 105 kHz to 168 kHz (an increase of 63 kHz) has been observed at temperatures 35 °C and 40 °C which were found in line with the work carried out by Wang et al. (2005) published in their paper.
- A decrement in frequency at peak amplitude (165 kHz to 97 kHz at 17 kV) is also observed from 65 °C to 75 °C which was a peculiar behaviour being reported probably for the first time.

CHAPTER 6

CONCLUSIONS AND SCOPE FOR FURTHER STUDY

6.1 SUMMARY OF THE WORK

In the present study, one of the on-line diagnostic techniques such as AE detection technique is adopted to study the most probable defects such as PDs and hot-spots (heat-waves). The field case studies involving the on-line condition assessment of power transformers based on the amplitude of the detected acoustic signals are discussed. The laboratory experimental studies carried out to simulate, capture and characterize AE signals from the most probable defects like PDs and hot-spots (heat-waves) are reported. The analysis of the laboratory results and the field data are correlated for the characterization of the defects (PD and hot-spots). The effect of temperature on the AEPD signals, especially the AE signal parameters like discharge magnitude and peak frequency, over the working range of transformer oil i.e., 30 ºC to 75 ºC is studied.

6.1.1 Field case studies based on maximum amplitude of AE Signals

The on-line AE detection technique was adopted to assess the internal condition of the GTs at various power stations in India. The identical transformer data and time-based monitoring data of the AE test further help to analyze the rate of insulation degradation via comparison. One should also be aware of other probable causes (other than defects in transformers) that can result in AE signals from the transformers which may be otherwise misleading.

6.1.2 Classification of defects (PD and hot-spots) based on AE signal analysis

The probable defects like PD and Hot-spots (heat-waves) resulting into AE signals in a power transformer were simulated in the laboratory experimental set-up. The AE signals in the frequency range of 0-500 kHz are captured with the AE workstation. The AE signals from these defects were analyzed using both FFT and DWT. The peak frequency of the AE signal can be identified by using FFT. The DWT analysis helps in identifying the distribution of energy over the different frequency ranges. Since the DWT analysis is found to be advantageous for analysis of the AE signals, it is adopted in field studies.

The typical case studies involving AE signals due to PD and hot-spots (heat-wave) for the in-situ on-line diagnosis of power transformers are also reported.

Two case studies (i) related to a GT of rating 11 kV / (220/√3) kV, 43.33 MVA, 1-Phase transformer in one of the Hydro-Power plants in India (ii) related to an interconnected transformer (ICT-Y) of rating 400 kV / 230 kV / 33 kV, 250 MVA, (3-Phase transformer) in one of the thermal power stations in India, are carried out. The DGA of these transformers had shown presence of higher amount of hydrogen indicating presence of PD (IEEE C57.104 2008). The measured hydrogen gas content was more than 100 ppm. The online AE test was also carried out in both the transformers, capturing large number of AE-waves. The analysis of these AE signals are carried out using DWT based decomposition.

Another case study related to a 3-phase Generator-transformer of rating 20 kV / 230 kV, 370 MVA, 3-Phase, in a power station which was in operation for less than 3 years. The DGA of this transformer was showing methane gas content (155 ppm) higher than the permissible limit (IEEE C57.104 2008). The winding temperature was also high. The overheating of transformer was confirmed as the winding and oil temperatures were 75 ºC and 55 ºC, respectively. The online AE test was also carried out capturing large number of AE-waves. The analysis of these AE signals are carried out using DWT based decomposition.

The characterization of the defects like PD and hot-spots (heat-waves) obtained from the laboratory experimental studies were correlated with the AE signals captured from various transformers working in the field.

6.1.3 Study of transformer oil properties and AEPD-signals at elevated temperatures.

Laboratory study of AEPD signals is carried out over the entire working temperature range of the transformers in-service. The results are viewed with reference to other transformer oil parameters. The effort is made to understand and explain the changes seen in the AEPD signals with the increase in temperature of the transformer oil.

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6.2 IMPORTANT CONCLUSIONS OF THE PRESENT STUDY

6.2.1 Conclusion from field case studies

- The DGA data and the AEPD test data can supplement each other. So it is important to take into account the DGA results when interpreting the AE data.
- 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.
- The problematic areas can be pinpointed by identifying the AE sensor which receives the signal with maximum AE amplitude.
- The periodic monitoring using the AE technique and the implementation of corrective measures have revealed improvements in the condition of transformer insulation.
- The operation of the cooling system pumps and the OLTCs can also result in higher magnitude of AE signals and this should not be misunderstood as a defect in the transformer.

6.2.2 Correlating Laboratory and field data for the classification of PD and hot-spots

- The FFT and DWT analysis of the AE signals captured from the individual defects (PD and hot-spot) simulated in the laboratory experimental studies are carried out. The peak frequency identified by using the FFT analysis falls in the range of the class of frequencies (with maximum energy of AE signal in the decomposition level) identified through DWT analysis for the individual defects.
- The FFT analysis helps in identifying the peak frequency. But this frequency may vary from signal to signal. So it is difficult to decide these frequencies for the individual defects. Therefore, it is desirable to go for a range of frequencies for the classification and characterization of individual defect. Hence DWT analysis, which gave the range of frequency having the maximum energy content of the signal, is adopted for the fault classifications.
- The AE signals obtained in the laboratory set-up and their DWT analysis indicate the characterizing dominant frequency range of (i) PD to be 125 kHz - 250 kHz and (ii) hot-wave to be 62.5 kHz - 125 kHz.
- The AE signals obtained from the transformers working in the field and their DWT analysis also confirms that the characterizing dominant frequency range of (i) PD to be 125 kHz - 250 kHz and (ii) hot-wave to be 62.5 kHz - 125 kHz.
- The DGA results pertaining to the transformers used in the case studies also substantiate the presence of the PD (high hydrogen content) or the hot-spots (high methane content) in the respective cases.
- Thus DWT analysis can be adopted for analyzing the AE signal and for the online diagnosis to infer if the transformer has PDs or hot-spots. This would be a better substitute for DGA based analysis as AE based analysis can be carried out in real-time.

6.2.3 Effect of temperature on AEPD signal parameters

- Study of transformer oil properties such as dielectric constant, specific resistance, dissipation factor, viscosity and BDV at various temperatures ranging from 27 ºC to 75 ºC is carried out to find the suitability of the transformer oil for carrying out laboratory experiments, and the results were found to be normal.
- The AE signal parameters due to the PD are measured over the entire working temperature range (30 °C to 75 °C) of the transformer and are reported. Beyond 65 °C, a substantial reduction (35%) in AEPD discharge magnitude has been observed.
- A shift in the peak frequency from 105 kHz to 168 kHz (an increase of 63 kHz) has been observed at 35 °C and 40 °C which were found in line with the work carried out by earlier researchers.
- A decrement in frequency at peak amplitude (165 kHz to 97 kHz at 17kV) is also observed from 65 °C to 75°C which is a peculiar behavior probably reported for the first time.
- This peculiar behavior of reduction in AEPD signal quantities is attributed to the changes in other parameters of the transformer-oil such as BDV and viscosity.

6.3 CONTRIBUTIONS

The contributions of the present study reported in the thesis are as follows:

- Some of the field experiences with AE based transformer condition monitoring have been discussed by reporting the results of few case studies. The AE detection technique was also found to be useful in identifying the problems with cooling pump systems (other than internal defects). The operation of OLTC resulted in high magnitude of AE signals. Hence, caution has to be exercised while handling these situations as the maximum magnitude of AE signals should not be misinterpreted as the defects in the transformers.

- In the laboratory set-up built for the purpose, the AE signal parameters due to PD are measured over the entire working temperature range (30 °C to 75 °C) of the transformer and are reported (probably for the first time).
- Beyond 65°C, a substantial reduction (35%) in AEPD discharge magnitude has been observed. This peculiar behavior of reduction in AEPD signal quantities is attributed to the changes in other parameters of the transformer oil such as BDV and viscosity.
- A decrement in peak frequency (165 kHz to 97 kHz at 17kV) is also observed from 65°C to 75°C (this observation is probably being reported for the first time).
- Classification of the AE signals obtained in the laboratory experiments from simulated defects namely, PD and hot-spots (heat-waves) are carried out by using DWT with 8 level (D1-D7 and A7) decomposition.
- The large percentage of AE signals due to PD when decomposed lies in the frequency range of 125 kHz - 250 kHz; D2.
- The large percentage of AE signals due to heat-wave when decomposed lies in the frequency range of 62.5 kHz - 125 kHz; D3.
- The typical case studies involving AE signals due to PD and hot-spots (heat-wave) for the in-situ on-line diagnosis of power transformers are reported. The DWT analysis of these signals corroborate well with the frequency range of PD and heat-waves found in the laboratory experiments from the simulated defects. Thus this proposed technique would be a better substitute for DGA based analysis as AE based technique can be adopted in real time.

6.4 SCOPE FOR FURTHER STUDY

Laboratory simulation studies may be carried out for simulating other defects like core vibration and arcing with suitable laboratory models in relation to the actual transformers. Capture the AE signals from these defects and analyze the signals for the classification of these defects. The results of DWT based analysis can be further compared and correlated with the other DGA based techniques like gas ratio method etc.

The temperature dependant correction for the AEPD signals based detection may be suggested for the field applications. Analysis of AE signatures of different types of PDs, corona in oil, surface discharge, void discharge due to floating particles, etc. can be considered for further study. The effect of solid barriers present inside the transformer on the AE signals can also be studied. The time-frequency representation of AE signals using wavelet analysis and combining the lower frequency ranges for higher resolutions can be considered for further study.

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List of Publications based on Research Work

Sl.No.	Title of the paper	Authors (In the same order as in the paper. Underline the Research Scholar's name)	Name of the Journal/ Conference/ Symposium, Vol., No., Pages	Month & Year of Publication	Category*
1.	Acoustic Emission Partial Discharge Detection Technique Applied to Fault Diagnosis: Case Studies of Generator Transformers	T.BhavaniShanker, H.N.Nagamani, GururajS.Punekar	Serbian Journal of Electrical Engineering Vol.13, No.2, June 2016, pp. 189-202. **DOI:10.2298/SJEE1602230045 (SCOPUS INDEXED)**	June 2016	Journal Paper, Full paper reviewed(1)
2.	On-line Diagnosis of Power Transformer Insulation System-Experience of CPRI,India	H. N. Nagamani, T. BhavaniShanker,	The Journal of CPRI, Vol. 8, No.1, March 2012, pp 17-24. **ISSN: 0973-0338**	March 2012	Journal Paper, Full paper reviewed(1)
3.	Acoustic Emission Technique for Condition Monitoring of Power Transformers: A Case Study on Identical Units	T.BhavaniShanker, Gururaj S Punekar, H.N.Nagamani, A. Sudhindra	IEEE-3rd International Conference on Power Electronics and Intelligent Transportation System, Shenzen, China, 20-21November 2010, pp 23-26. **ISBN 978-1-4244-9162-9** **Number of Citations: 01**	November 2010	Conference paper, full paper Reviewed(3)
4.	Condition Monitoring of Power Transformer Insulation by Acoustic Emission Technique-Case studies	T.BhavaniShanker, Gururaj S Punekar, H.N.Nagamani, A. Sudhindra	International Conference on Condition Monitoring, Vizag, India 24-25 Feb.2011,pp. 185-189	February 2011	Conference paper, full paper Reviewed(3)
5.	Thermal effects on acoustic emission based PD in transformer oil: A study	T.BhavaniShanker, H.N.Nagamani, GururajS.Punekar	IEEE - International Conference on Properties and Applications of Dielectric Materials (ICPADM)-2012, 24-28 July 2012, pp. 1-4. **DOI:10.1109/ICPADM20126318957** **Number of Citations: 02**	July 2012	Conference paper, full paper Reviewed(3)
6.	Acoustic emission signal analysis of On-Load Tap Changer(OLTC)	T.BhavaniShanker, H N Nagamani, Gururaj S Punekar	IEEE-International Conference on Condition Assessment techniques in Electrical Systems – IEEE - CATCON-2013, 6-8 Dec 2013, pp. 347-352. **DOI:10.1109/CATCON20136737525** **Number of Citations: 01**	December 2013	Conference paper, full paper Reviewed (3)

List of Publications based on Research Work

Sl.No.	Title of the paper	Authors (In the same order as in the paper. Underline the Research Scholar's name)	Name of the Journal/ Conference/ Symposium, Vol., No., Pages	Month & Year of Publication	Category*
7.	Comparison of Performance of Mother wavelets in Discrete Wavelet Transform Analysis with Acoustic Emission Partial Discharge signals	Athira S Menon, Gururaj S Punekar, T.BhavaniShanker, H.N. Nagamani.	National Conference on New Tends in Electronics, Computing and Communication(NTECC-14), 25-26 April 2014, Kerala, India	April 2014	Conference paper, full paper Reviewed (3)
8.	On-line acoustic emission technique for monitoring relative performance for partial discharges from 400kV hydro generator transformers-case studies	T. BhavaniShanker, Gururaj S Punekar, H.N.Nagamani	International Conference on High Voltage Engineering &Technology (ICHVET-2015), Hyderabad,India 29-30 January 2015, pp. 15-22	January 2015	Conference paper, full paper Reviewed (3)
Some other related publications:					
9.	Some aspects of Location identification of PD source using AE signals by iterative method	Gururaj S Punekar, PriyankaJadhav, T.BhavaniShanker, H.N. Nagamani	IEEE-International Conference on Properties and Applications of Dielectric Materials (ICPADM)-2012, 24-28 July 2012, pp. 1-4. **DOI:10.1109/ICPADM2012631957** **Number of Citations: 01**	July 2012	Conference paper, full paper Reviewed (3)
10.	Genetic algorithm in location identification of AEPD source: Some aspects	Gururaj S Punekar, Deepthi Antony, T.BhavaniShanker, H.N. Nagamani, N. K..Kishore	IEEE-International Conference on Condition Assessment techniques in Electrical Systems-IEEE-CATCON-2013, 6-8 Dec 2013, pp 386-390. **DOI:10.1109/CATCON20136737533**	December 2013	Conference paper, full paper Reviewed (3)

*Category: 1: Journal paper, full paper reviewed 2: Journal paper, Abstract reviewed
3: Conference/Symposium paper, full paper reviewed 4: Conference/Symposium paper, abstract reviewed
5: others (including papers in Workshops, NITK Research Bulletins, Short notes etc.)
(If the paper has been accepted for publication but yet to be published, the supporting documents must be attached.)

Research Scholar
Name & Signature, with Date

Research Guide (from NITK)
Name & Signature, with Date

Additional Guide (From CPRI)
Name & Signature, with Date

List of Papers Communicated after Thesis submission based on Research Work

Sl.No.	Title of the paper	Authors (In the same order as in the paper. Underline the Research Scholar's name)	Name of the Journal/ Conference/ Symposium, Vol., No., Pages	Month & Year of Publication	Category*
1.	Effects of Transformer-oil Temperature on Amplitude and Peak Frequency of Partial Discharge Acoustic Signals	T.BhavaniShanker, H.N. Nagamani, Deepthi Antony, Gururaj S Punekar.	IEEE-Power Engineering Letters **(SCI Indexed)**	Under review with **favourable response**	Journal Paper, Full paper reviewed(1)
2.	Acoustic emission signals from sources other than partial discharges in power transformers: Field studies	T. BhavaniShanker, H.N.Nagamani, Gururaj S Punekar, Deepthi Antony.	Journal of Applied Acoustics (Elsevier) **(SCI Indexed)**	Under review	Journal Paper, Full paper reviewed(1)
3.	Transformer Fault Diagnosis using Dissolved Gas Analysis: Case Studies	T.BhavaniShanker, H.N. Nagamani, Deepthi Antony, Gururaj S Punekar.	International Conference on Condition Assessment Techniques in electrical systems, CATCON 2017.	Under review	Conference paper, full paper Reviewed (3)

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3: Conference/Symposium paper, full paper reviewed 4: Conference/Symposium paper, abstract reviewed
5: others (including papers in Workshops, NITK Research Bulletins, Short notes etc.)
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Research Scholar
Name & Signature, with Date

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9.	**MEMBERSHIP OF PROFESSIONAL SOCIETIES**	:	• Chairman, ET-29-BIS- Sectional Committee of Power Capacitors of Bureau of Indian Standards. India. • Member of Technical Committee of NPL, New Delhi • Member of Condition Monitoring Society of India (CMSI), NSTL, Visakhapatnam • Member of WG-13, IEC-TC 33: "Power capacitors and applications" • NDT Level I Certified Engineer for Acoustic Emission testing as per American Society for Non-destructive testing (NDT).
10.	**TECHNICAL PUBLICATIONS**	:	• More than 25 technical papers in National and International Conferences, Workshops and Seminars
11.	**AWARDS/ SPECIAL ACHIEVEMENTS**	:	• Second Best Paper Award for the paper on "Experience of CPRI in Performance Evaluation of Power Capacitors Of Unit Rating Up To 1000 Kvar" presented at the 7th International Seminar on Capacitors (CAPACIT 2010), Organized by IEEMA during 20-21 Jan 2010 at Mumbai. • Best Paper Award for the paper on "New test facility for Discharge current test on Series Capacitors as per IEC 60143" presented at the 6th International Seminar on Capacitors (CAPACIT2005), October 2005, • Second Best Paper Award for the paper titled "Detection & Location of Multiple PD sources Employing Acoustic Emission Detection Technique" presented at the 7th International Seminar on Electrical & Electronic Insulating Materials & Systems, organized by IEEMA at Mumbai on 20-21, Jan 2005.
12.	**OVERSEAS ASSIGNMENTS (DEPUTED BY CPRI)**	:	• Member of the team for Testing and pre-dispatch Inspection of Parallel Resonance Transformer Test System of rating 6800 KVA, 50 kV, at the works of M/s. High Volt, Dresden, Germany during July 2004. • Testing and pre-dispatch Inspection of 35kV, 1.1Amps HVDC Power Supply, at the works of M/s. FuG Elektronik GmbH, Rosenheim, Germany during June 2011. • As Chairman of BIS-ET-29, represented the Indian National committee in the Meetings of IEC-TC-33 " Power Capacitors and Applications" held at Milan, Italy, during 12-16 November 2016

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14. **CONFERENCES AND WORKSHOPS**	:	• Organizing secretary IEEE- International Conference on Condition assessment techniques in Electrical systems(IEEE-CATCON-2015), CPRI, BANGALORE • Member of organizing team for organizing IEEE-ICPADM-2012 and IEEE- PEDES- 2012 • Organizing workshop on" Capacitors for Reactive Power Compensation" from 2011 • Conducted Training Program On" LV and HV Capacitors specific to National and International Standards" in 2010