

Classification of Acoustic Emission Based Partial Discharge in Oil Pressboard Insulation System Using Wavelet Analysis

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Abstract—Insulation used in transformer is mostly oil pressboard insulation. Insulation failure is one of the major causes of catastrophic failure of transformers. It is established that partial discharges (PD) cause insulation degradation and premature failure of insulation. Online monitoring of PDs can reduce the risk of catastrophic failure of transformers. There are different techniques of partial discharge measurement like, electrical, optical, acoustic, opto-acoustic and ultra high frequency (UHF). Being non invasive and non interference prone, acoustic emission technique is advantageous for online PD measurement. Acoustic detection of p.d. is based on the retrieval and analysis of mechanical or pressure signals produced by partial discharges.

Partial discharges are classified according to the origin of discharges. Their effects on insulation deterioration are different for different types. This paper reports experimental results and analysis for classification of partial discharges using acoustic emission signal of laboratory simulated partial discharges in oil pressboard insulation system using three different electrode systems. Acoustic emission signal produced by PD are detected by sensors mounted on the experimental tank surface, stored on an oscilloscope and fed to computer for further analysis. The measured AE signals are analyzed using discrete wavelet transform analysis and wavelet packet analysis. Energy distribution in different frequency bands of discrete wavelet decomposed signal and wavelet packet decomposed signal is calculated. These analyses show a distinct feature useful for PD classification. Wavelet packet analysis can sort out any misclassification arising out of DWT in most cases.

Keywords—Acoustic Emission, Discrete Wavelet Transform, Partial Discharge, Wavelet Packet Analysis

I. INTRODUCTION

COMPETITIVE electricity market emphasizes a need for a better utilization of power apparatus with minimum downtime. Avoidance of unexpected failure of power apparatus is utmost important for reliable operation of power system. All these can be achieved by adopting condition monitoring of power apparatus [1]. Insulation failure is one of the major causes of power apparatus failure. Insulation of power apparatus deteriorates during service period and leads to final failure. This deterioration depends on many factors like moisture content, temperature & partial discharges.

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It is established that partial discharges enhance insulation deterioration, leading to catastrophic failure. Hence, online monitoring of partial discharges can reduce the risk of catastrophic failure of power apparatus [2]. There are different methods of partial discharge measurement like, electrical, optical, acoustic, opto-acoustic and UHF. Being non invasive and non interference prone, acoustic technique based partial discharge on-line monitoring is advantageous. PD produces acoustic pressure pulse which propagates to the tank surface. The piezoelectric sensor mounted on the tank surface converts this pressure pulse to electric signal, which is then amplified and stored on a data recorder for further analysis [3]-[5].

Partial discharges are classified according to the origin of discharges. Their effects on insulation deterioration are different for different types. PD classification is an important aspect for quality assessment of insulation. There are various tools available for PD classification [6]. Frequency domain or FFT analysis is conventionally used to classify the partial discharges using PDAE signal [7], [8]. Discrete Wavelet Transform is recently in use for the analysis of PDAE signal [9]. Frequency spectrum analysis is best suited for stationary type signal. For non stationary signal, like PDAE signal, wavelet analysis is more appropriate, compared to frequency spectrum analysis. Selection of mother wavelet and selection of number of decomposition level are important aspects in the application of wavelet transforms. There is no unique method for selection of mother wavelet and selection of number of decomposition level [10], [11]. So far, wavelet packet transform is not used for PDAE signal analysis, which is found to be advantageous for PD classification.

This paper reports experimental results and analysis for classification of partial discharges in oil pressboard insulation system typically employed in a transformer using acoustic emission signal. The experiments are conducted with (i) point-plane electrode system, (ii) plane-plane electrode system with pressboard insulation and (iii) rod-plane electrode system with pressboard insulation. These different electrode systems are employed to create PDs on conductor protrusions and PDs along barrier surface in oil pressboard insulation system. Discrete Wavelet Transform (DWT) analysis and Wavelet Packet Analysis are used for the analysis of measured AE signals. A comprehensive technique for selection of mother wavelet and selection of number of decomposition level are proposed, perhaps, for the first time. Energy distribution in different frequency bands of DWT decomposed signal and

wavelet packet decomposed signal is obtained. These parameters are used for classification of partial discharges. Wavelet packet analysis can sort out any misclassification arising out of DWT in most cases.

II. EXPERIMENTAL DETAILS

For online monitoring, AE sensors are mounted on transformer tank. PD produced inside the transformer is picked up by the sensor. For experimentation in the laboratory, a simulated situation is created by a model transformer tank filled with transformer oil. Tank dimensions are decided based on actual propagation distance of AE pulse in a transformer. Minimum propagation distance of an AE signal depends on the transformer size. The minimum distance of propagation being the least distance between conductor to tank surface, which is found to be around 10 cm for a typical 5 MVA, 33/11 kV transformer [12]. Maximum propagation distance for an AE signal depends on transformer size and perceptible sensitivity of AE sensor. The maximum source to sensor distance can be more than 1 m. It is seen from literature [13] and earlier simulations [14] that the AE propagation behavior is not linear for distances less than 30 cm. Further, data obtained with less than 30 cm propagation distance can not be extrapolated for longer distances. So for extrapolation to actual distances, some experimental results beyond 30 cm are necessary. In view of this, a model transformer tank of 60 cm X 60 cm X 60 cm is used for the experimentation. The tank thickness used is 5 mm, resembling with most common transformer tank thickness in practice. Employing this tank, experiments are conducted for source to sensor distances of 10 cm to 50 cm in steps of 2 cm.

Fig. 1 shows a schematic diagram of the experimental model. Here x indicates source to sensor distance. Fig. 2 shows the photograph of the experimental setup.

To simulate different types of PDs in transformer, different electrodes system are used [7]. Here, (i) PD on conductor protrusions in transformer and (ii) PD along barrier surface in transformer are studied. Point-plane electrode system is used to model the PD on protrusions. Plane-plane electrode system with pressboard insulation in between two electrodes is used to model surface discharge on uniform field and rod-plane electrode system with pressboard insulation in between two electrodes is used to model surface discharge on non-uniform field. Fig. 3 shows the schematic diagrams of different electrode systems employed. In plane-plane electrode systems, the upper or high voltage plane electrode is smaller in dimension than lower or grounded plane electrode. This is to confine the partial discharge in concentrated region while retaining the effect of plane.

Acoustic emission signals produced by PDs are picked up by the AE sensor mounted on the tank surface and stored on an oscilloscope. The reported maximum frequency of PDAE signal is up to 400 kHz [8]. So, it is planned in this work to set the recording device for signal frequency of 500 kHz. Hence, the sampling frequency of signal recording is kept at 1 MHz to get signal frequency up to 500 kHz. This stored signal is then fed to a computer for further analysis. For each electrode system and

for every sensor to source distance, 8 to 10 observations are recorded to avoid any statistical errors. A typical AE signal for a point plane electrode system with source to sensor distance of 10 cm is shown in Fig. 4. A 150 kHz resonant peak type AE sensor is used to pick up the PDAE signal. It is appropriate to mention here, that though the sensor is 150 kHz resonant peak type, the sensitivity of the sensor upto 500 kHz is good. The sensitivity of the sensor at 150 kHz is -62 db and that at 500 kHz is only -72 db.

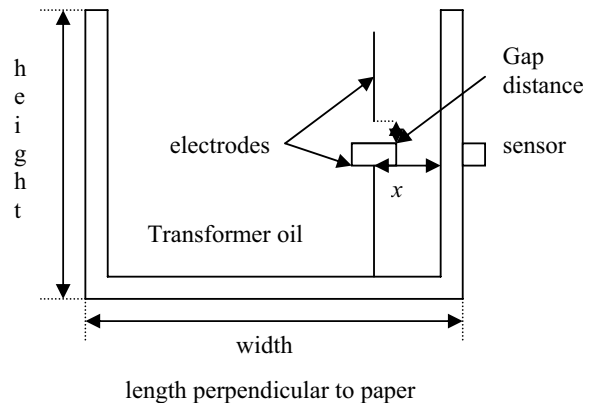


Fig. 1 Schematic diagram of experimental model



Fig. 2 Photograph of experimental setup viewing voltage source, model experiment chamber, sensors and recording device (digital storage oscilloscope)

III. RESULTS AND DISCUSSIONS

Experiments are conducted for different source to sensor distances and AE pulses are recorded for further analysis. A typical AE pulse is as shown in Fig. 4.

The PDAE signals are conventionally analyzed using FFT [7], [8]. The FFT is applicable to stationary and periodic signals. Since, it is based on the assumption that any signal can be decomposed into a series of sine and cosine waveforms. However, in reality, when the FFT is applied to irregular feature signals, such as PDAE signal, it presents serious limitation: energy spectra are invariant with respect to time shifts. Hence, this signal needs further investigation for characterization [15].

Discrete wavelet transform is useful to analyze non stationary signals like PDAE by decomposing into different frequency bands with time resolution [9]-[11], [16].

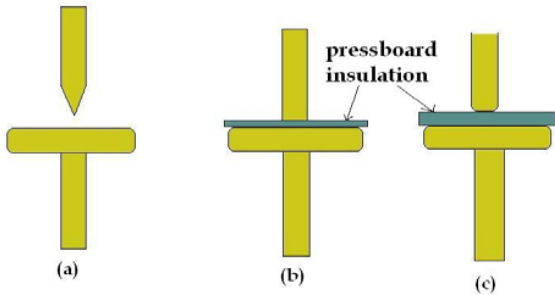


Fig. 3 Schematic diagram of electrode systems employed

- (a) point-plane electrode
- (b) rod-plane electrode with insulation.
- (c) plane-plane electrode with insulation.

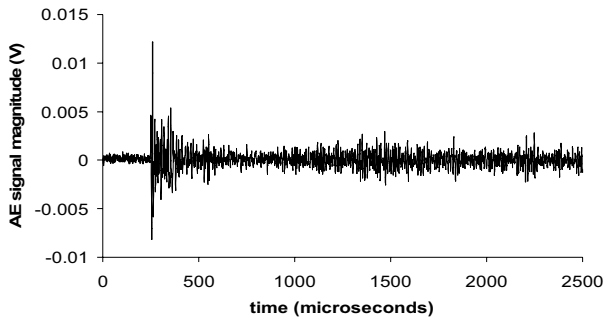


Fig. 4 Typical PDAE signal for a point plane electrode system with source to sensor distance of 10 cm.

1. DISCRETE WAVELET TRANSFORM (DWT)

A. Wavelet Decomposition of PDAE signal

Wavelet analysis is a very useful processing tool for time-frequency signals. Wavelet analysis represents a windowing technique with variable-sized region. Wavelet allows the use of long time intervals to extract more precise low frequency information and shorter regions to extract high frequency information. PDAE signal is non-stationary type time domain signal. The ability to do local analysis with wavelet is ideal for PD analysis and the technique is applied successfully to analyze PD signal [9]-[11], [16].

DWT (Discrete Wavelet Transform) is used for decomposition of PDAE signal. The frequency band of signal is decomposed into many layers. DWT decomposes the original signal into the approximate parts (low frequency) and the detail counterparts (high frequency) using complementary filters, namely a low pass and a high pass. The sampling rate of output is then halved. Then, the low pass output is decomposed again. Detail analysis is performed with a contracted, high frequency version of the mother wavelet, while approximate analysis is performed with a dilated, low frequency version of the same wavelet. Multistage filter bank implementation of DWT is as

shown in Fig. 5 [17]. The mathematical expression of one level of decomposition is as shown in (1).

$$\begin{aligned} Y_{high}[k] &= \sum_n x[n] \cdot g[2k - n] \\ Y_{low}[k] &= \sum_n x[n] \cdot h[2k - n] \end{aligned} \quad (1)$$

Where, Y_{low} is the approximate signal and Y_{high} is the detail signal to $x[n]$; $h[n]$ and $g[n]$ are low pass and high pass filters respectively.

As shown in Fig. 5, the DWT algorithm, signal $x[n]$ has frequency from $0 - \pi$ rad/s. In this work, π rad/s corresponds to 500 kHz. After passing through $g[n]$ and $h[n]$, the frequency of the output signal is $\pi/2 - \pi$ (detail) and $0 - \pi/2$ (approximation) respectively. Then it is down sampled by two, giving the output of first stage. $(2\downarrow)$ represents down sampling of the signal.

Selection of mother wavelet is an important aspect in the application of wavelet transforms. There is no unique method for selection of mother wavelet [10], [11]. Here, a comprehensive technique for selection of mother wavelet for PDAE signal analysis is proposed.

B. Selection of Mother Wavelet

The WT of a signal produces a wavelet coefficient distribution throughout the complete time scale of signal. More the similarity between the mother wavelet and the signal being analyzed, more will be the coefficients. This is similar to calculation of correlation between the signal and the mother wavelet in different time scales. Here, 20 nos. of AE signals are selected for each electrode configuration for wavelet decomposition using Symlet (sym2 to 9) and Daubecheis' (db2 to 9) mother wavelet and are decomposed up to 5th level. The reason for selection up to 5th level of decomposition becomes clear through the discussion in the next paragraph. The maximum coefficient of all the levels is noted. An average for 20 such signals is calculated and normalized. Fig. 6 shows the normalized maximum coefficient distribution for different mother wavelet for different electrode systems. Comparing the normalized maximum coefficient for a particular electrode system, it can be seen from Fig. 6, that the 'sym 7' mother wavelet is giving a maxima for point plane and plane plane (with insulation) electrode systems. The 'sym 5' mother wavelet is giving a maximum and the 'sym 7' is giving a second maximum for rod plane (with insulation) electrode system. In order to use only one type, best suited mother wavelet for all type of discharges, a comparative index is introduced. For each type of mother wavelet normalized maximum coefficient of three different electrode configurations are added and a comparative index is obtained as given in (2).

$$\text{comparative index} = \sum (\text{normalized maximum coefficient})_i \quad (2)$$

where, i is the electrode configurations.

Fig. 7 shows the comparative index distribution for different mother wavelets. The wavelet giving the maximum of this

index is considered for the analysis. It can be seen from Fig. 7, that the Symlet ('sym 7') is giving maximum comparative index and hence 'sym 7' is selected for the analysis in this work.

In DWT, Low frequency band (approximation) is decomposed further to get detail and approximation in the next stage and this is repeated in number of stages to get the detail and approximation in subsequent stages. In this paper, number of decomposition level is based on the requirement and observation of the frequency band and the explanation follows.

C. Selection of Number of Level for Decomposition

In this study, Maximum frequency of input PDAE signal, $x[n]$ is expected to be around 500 kHz. Accordingly, sampling frequency of signal $x[n]$ is kept at 1000 kHz (according to Nyquist criteria), corresponding to 1 μ s sampling time and is found to be adequate. Maximum frequency of decomposition is kept at 500 kHz. Number of decomposition levels is decided by the resolution needed at lower frequency. Table 1 lists the frequency bands of decomposed signal up to 5th level of decomposition. It can be observed from Table 1 that at fifth level, the frequency band of detail, D5 is 15.75 kHz to 31.25 kHz and the frequency band for approximate, A5 is 0 kHz to 15.75 kHz. Energy content of signal below 15.75 kHz is lower than 2% of total energy of AE signal. Most of the ambient noise is below 20 kHz [7]. So, frequency below 15.75 kHz is not significant in the AE signal and hence, not necessary to analyze. Based on the noise frequency and the energy of low frequency contents of signal, five decomposition levels are selected here.

AE signals obtained for different source to sensor distances and for different electrode systems are analyzed using DWT. Figs. 8, 9 & 10 show the discrete wavelet decomposition of typical AE pulses of different electrode systems using Symlet ('sym 7') wavelet up to 5th level of decomposition.

Percentage energy in each frequency band of decomposed level of AE signal is calculated. This is repeated for all the AE signals for each type of electrode system for different source to sensor distances. Energy distribution of all the measurements for each type of electrode system for different source to sensor distances shows similar patterns. The maximum standard deviation of peak energy of energy distribution is 8 to 12% for each type of electrode system. An average is taken for each frequency band and plotted in Fig. 11. Fig. 11 shows the energy distribution of AE signal in different frequency band of wavelet decomposed signal for different electrode systems. This energy distribution clearly shows distinct differences between the discharges and hence can be used as a classifier. Energy for discharge in point plane type electrode system shows up in the D2 and D3 range. Energy for discharge in plane plane electrode system (with insulation) shows up in D3 and D4 range, with a peak in D3. Energy for discharge in rod plane electrode system shows up in D3 and D4 range, with a peak in D4. Energy in D2 and D5 range is more than 10% for discharge in rod plane electrode system.

From Fig. 11, it can be seen that most of the energy is in D2, D3 and D4 bands for all types of discharges. To get the energy distribution in narrower frequency band and to see the

possibilities of getting the energy in a distinct frequency band for any type of discharges, wavelet packet analysis is used. Wavelet packet analysis decomposes the details as well as approximation to frequency bands of equal bandwidth.

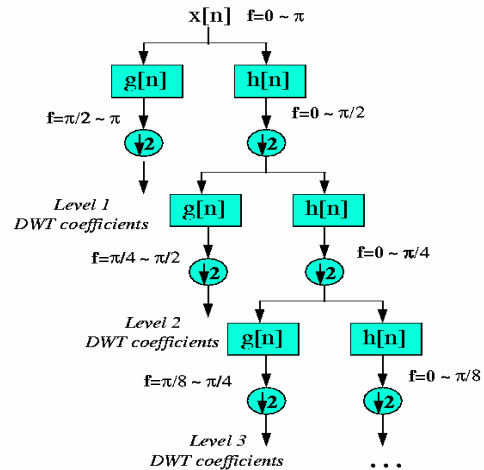


Fig. 5 Wavelet decomposition tree

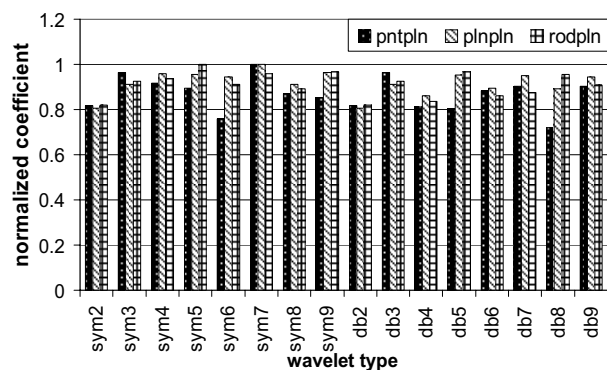


Fig. 6 Normalized DWT coefficient for different mother wavelet and for different electrode configuration

'pntpln' – point-plane electrode system
'plnpln' – plane-plane electrode system with insulation
'rodpln' – rod-plane electrode system with insulation

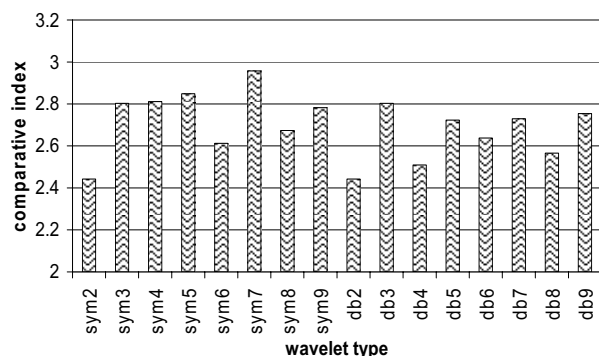


Fig. 7 Comparison of different mother wavelet for DWT through comparative index.

TABLE I FREQUENCY BAND OF DECOMPOSED SIGNAL	
Decomposition level	Frequency Band
D1	250 kHz to 500 kHz
D2	125 kHz to 250 kHz
D3	62.5 kHz to 125 kHz
D4	31.25 kHz to 62.5 kHz
D5	15.75 kHz to 31.25 kHz
A5	0 kHz to 15.75 kHz

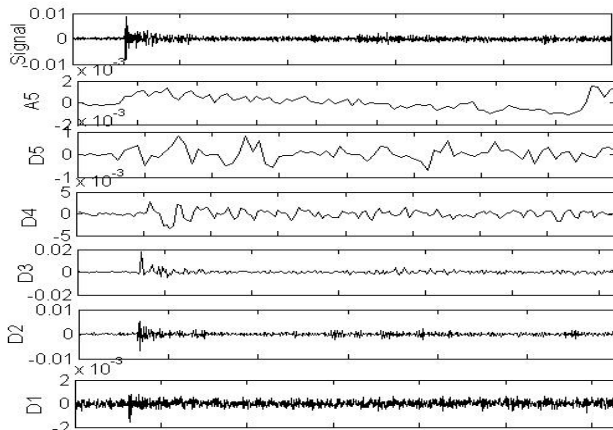


Fig. 8 DWT of typical PDAE signal for point plane electrode system

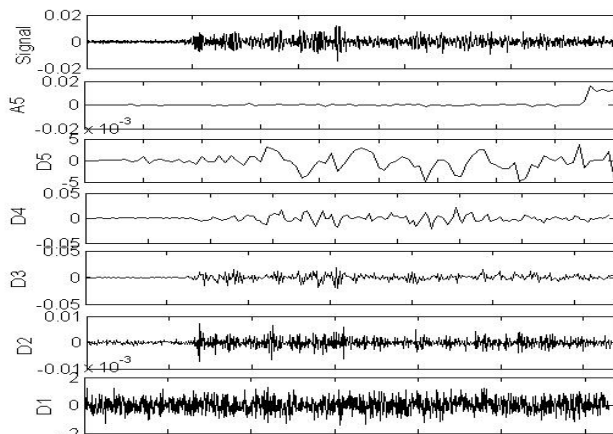


Fig. 9 DWT of typical PDAE signal for plane plane electrode system with insulation

2. WAVELET PACKET ANALYSIS

Discrete wavelet transform is used to analyze the signal by decomposing into different frequency bands [9], [16].

Wavelet packet decomposition is an extension of discrete wavelet transform. Wavelet packet analysis is a finer signal processing method. The frequency band of a signal is decomposed into many layers, the high frequency parts (details) of a signal, which is not further decomposed by DWT method, are also decomposed and the frequency bands are selected automatically, depending on characteristics of the signal. So wavelet packet transformation can make up the shortcoming of the DWT [18], [19].

In order to understand wavelet packet more easily, the wavelet packet decomposition tree, decomposed up to 3rd level is

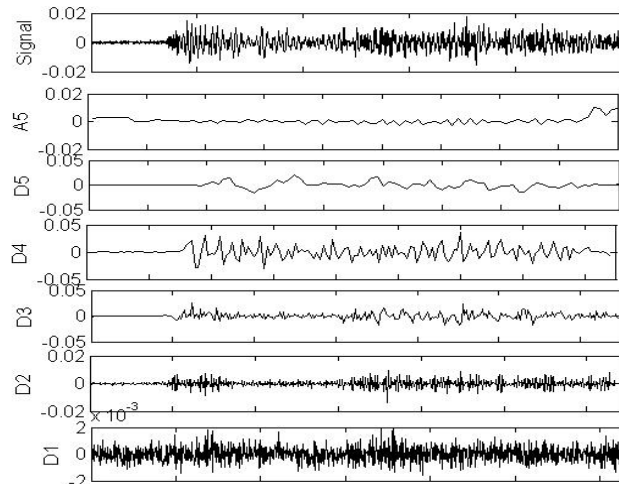


Fig. 10 DWT of typical PDAE signal for rod plane electrode system with insulation

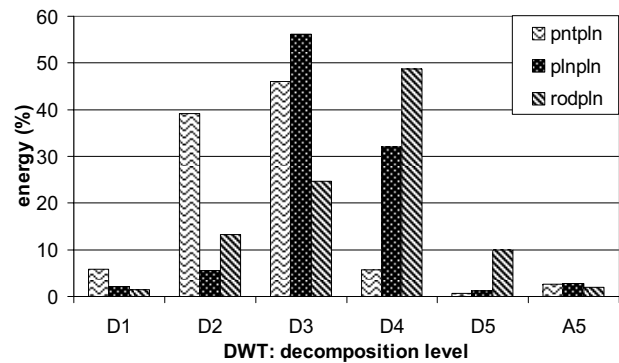


Fig. 11 Energy distribution of PDAE signal for different electrode system

'pntpln' – point-plane electrode system

'plnpln' – plane-plane electrode system with insulation

'rodpln' – rod-plane electrode system with insulation

shown in Fig. 12. Signals are decomposed into lower frequency and higher frequency band. Each decomposed signals are also decomposed into lower frequency and higher frequency band. This is continued up to the required level of decomposition.

The AE signal is decomposed up to 5th level using 'sym 7' as mother wavelet. Number of decomposed signal up to 5th level of decomposition is 32. All 32 decomposed signals have equal frequency band width. The frequency bands are starting from 0 kHz in steps of 15.625 kHz up to 500 kHz.

Percentage energy in each frequency band of decomposed level of AE signal is calculated. This is repeated for all the AE signals for each type of electrode system for different source to sensor distances. Energy distribution of all the measurements for each type of electrode system for different source to sensor distances shows similar patterns. The maximum standard deviation of peak energy of energy distribution is 8 to 12% for each type of electrode system. An average is taken for each

frequency band and plotted in Fig. 13(a). It can be observed from Fig. 13(a), energy beyond 16th decomposed signal (250 kHz) is negligible for all type of discharges. The same Fig. is redrawn upto 16th decomposed signal and presented in Fig. 13(b) for more clarity. The frequency band number used in Fig. 13(b) is listed in Table 2. This energy distribution shows distinct differences between the different type of discharges. Energy for discharge due to point plane type electrode system shows up in the band 5 and 13. Energy for discharge due to plane plane electrode system (with insulation) shows up in band 3, 4 and 7, with a peak in band 3. Energy for discharge due to rod plane electrode system shows up in band 3 and 4.

The results of DWT and wavelet packet analysis are compared. For point plane electrode system and plane plane electrode system (with insulation), peak is observed at D3 in DWT decomposition. Where as in wavelet packet decomposition peak is observed in band 5 for point plane electrode system and in band 7 for plane plane electrode system (with insulation). D3 in DWT corresponds to 5, 6, 7 and 8 band in wavelet packet decomposition.

For rod plane electrode system (with insulation) and plane plane electrode system (with insulation), peak is observed at D4 in DWT decomposition, where as in wavelet packet decomposition peak is observed in band 3 and 4 for rod plane electrode system (with insulation) and in band 3 for plane plane electrode system (with insulation). D4 in DWT corresponds to 3 and 4 band in wavelet packet decomposition.

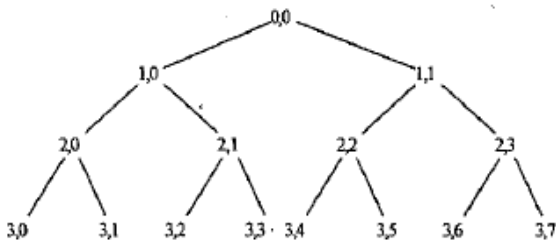


Fig. 12 The wavelet packet decomposition tree

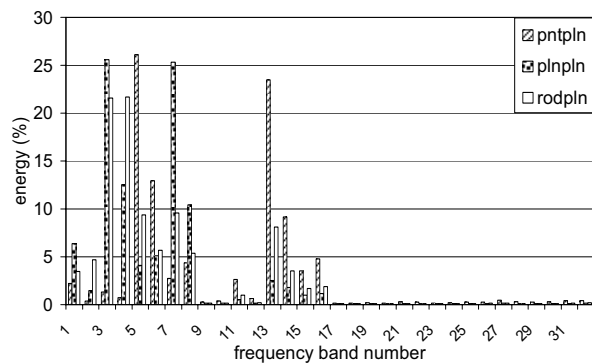
In DWT, peaks are observed in the same frequency band range with different relative magnitude for different electrode systems. In wavelet packet decomposition, peaks are observed more distinctly and clearly in different frequency band for different electrode systems. The classification results using DWT and wavelet packet analysis are summarized in Table 3. Wavelet packet analysis thus gives more clear PD classification with distinct variation of relative magnitude of energy of DWT decomposed signal in different decomposed level for different electrode system.

The PD phenomena and results can be explained as follows. Partial discharges of low energy create AE signal of higher frequency and high energy PDs produce lower frequency [4], [5]. Point plane electrode system gives non uniform field and PD at low energy and hence frequency contents are higher. Plane plane electrode system with insulation gives PD as breakdown of small oil gap between electrode and insulation as surface discharges. This gives higher energy discharges and hence frequency spectrum is having lower frequency

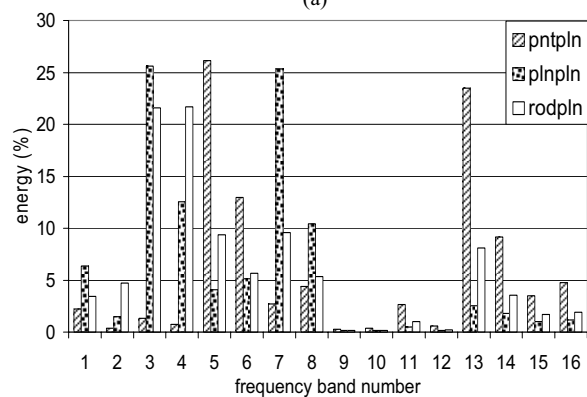
components. Rod plane electrode with insulation gives two frequency peaks. This can be explained as two simultaneous discharge events. One type of discharge is for higher frequency peak, similar to point plane electrode (on the sharp edges of rod) and other type is for lower frequency peak, on the surface of insulation i.e. surface discharges. Hence, it may be viewed as two simultaneous partial discharge activities having two dominant frequency regions.

TABLE II
FREQUENCY BAND NUMBER NOMENCLATURE

Frequency Band	Frequency band number	Frequency Band	Frequency band number
0kHz to 15.625kHz	1	125kHz to 140.625kHz	9
15.625kHz to 31.25kHz	2	140.625kHz to 156.25kHz	10
31.25kHz to 46.875kHz	3	156.25kHz to 171.875kHz	11
46.875kHz to 62.5kHz	4	171.875kHz to 187.5kHz	12
62.5kHz to 78.125kHz	5	187.5kHz to 203.125kHz	13
78.125kHz to 93.75kHz	6	203.125kHz to 218.75kHz	14
93.75kHz to 109.375kHz	7	218.75kHz to 234.375kHz	15
109.375kHz to 125kHz	8	234.375kHz to 250kHz	16



(a)



(b)

Fig. 13 Energy distribution of PDAE signal for different electrode system.

TABLE III
FREQUENCY BANDS FOR FIRST AND SECOND PEAK OF ENERGY DISTRIBUTION
OBTAINED USING DWT AND WAVELET PACKET ANALYSIS FOR DIFFERENT
ELECTRODE SYSTEMS

Type of electrode systems	Frequency bands in DWT (from Fig. 11)	Frequency bands in wavelet packet analysis (from Fig. 13(b))
Point plane electrode	D3 and D2	5 and 13
Plane plane electrode with insulation.	D3 and D4	3 and 7
Rod plane electrode with insulation.	D4 and D3	3 and 4

IV. CONCLUSIONS

This work presents the analysis of partial discharge acoustic signal. Three different electrode systems are used to simulate two different types of partial discharges. The partial discharge acoustic emission signal is analyzed using discrete wavelet transform and wavelet packet analysis. The most suitable mother wavelet for the analysis is determined and found to be symlet ('sym 7'). Energy level of decomposed signal, at 5th level of decomposition is found to be less than 4% for all types of discharges. Viewing this, it may be concluded that upto 5th level of decomposition for AE signal analysis is adequate. Energy distribution in decomposed frequency range of AE signal for different electrode systems can be used as PD classifier. Wavelet packet analysis shows a more precise energy distribution pattern and provides better classification than discrete wavelet transform analysis. Discharges associated with insulation are more harm full than protrusion or open conducting PD. So this analysis related to PD classification can help for severity analysis of PD for generating alarms.

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