Chapter-5

Practical Application of Wavelet Transform for PD Detection and Analysis
5.1 **INTRODUCTION** [50-55]

As discussed in the previous chapter, WT can be applied for any data extraction. The WT is mainly used to detect specified interested signals from the noisy signal that are PD pulses in current application. It is carried out with data acquisition, WT applicability check, WT analysis for different threshold methods and time domain signal analysis. WT analysis is carried out for both threshold value and threshold function determination. During analysis, it is observed that original time-domain signal analysis can be used for some kind of WT parameter selection. So, this is also covered in the thesis.

During data acquisition phase, data is acquired by Mtronics made PD data acquisition system. The Mtronics system software gives the sampled time-stamped values, which are used for further analysis.

WT suitability is checked by different type of pulses (with different time width and amplitude) with noise addition. The simulation restores PD signals from noisy simulated signal.

The signal is analyzed in two phases (1) original signal (define below) analysis and (2) WT analysis. The receiving signal during extensive testing of transformer is referred as original signal. In original signal analysis phase, the signal is separated in positive/negative samples and then analyzed separately. In WT analysis phase, the original signal is transformed to WT domain and is analyzed for WT threshold function selection method. Finally, a comparison is carried out between two analyses and relation is envisaged for WT threshold function selection based on original signal.
Block diagram of on line PD measurement is shown in figure-5.1. The PD measurements are carried out using Mtronix made Advanced Partial Discharge Measuring System MPD540.

![Block diagram of PD Measurement Setup](image)

**Figure-5.1 Block diagram of PD Measurement Setup**

This unit comprises of data acquisition unit (MPD540) and fiber optics controller (USB502). Former consist a Coupling unit (MPD540CPL) and data acquisition unit whereas later is USB based data transfer unit. MPD540CPL is connected to a high voltage coupling unit CPL542, also referred to as “quadripole”, which is connected to high voltage coupling capacitor. Figure-5.2 and Figure-5.3 show the practical PD measurement set up for 100 MVA, 220/132 kV transformer. The measured waveforms are stored in computer (at different time instance). The Mtronics software has data export feature, which converts recorded signal values to time stamped signal...
samples. Also, the extracted samples are stored in text file and further analysis is carried out.

Figure-5.2 Data acquisition Setup for PD Measurement

Figure-5.3 Power Transformer Setup as a Test Object
This text file data (reference data) is given to develop the program and further WT analysis is carried out to get PD pulses. WT has removed noise samples and has estimated PD pulses. PD test bandwidth is kept 300 KHz with PD test maximum voltage 2.45 KV as per IS standard. PD pulse & measurement value is obtained at different range of voltages with respect to time schedule on each phase of transformer. The test is performed as per standard IEC 60270 method. Before starting the measurement, the set-up is calibrated for 500 pC (as per the calibration criteria). Measurements are carried out at various voltages and durations as given in figure-5.4. Both quantities (PD and PD test voltage) are measured and set of data is recorded with software. This recorded data is used for WT analysis. PD measurements results (at various voltage and duration) during the experiment are recorded in Table-5.1.

![Figure-5.4 Measure Record Diagram]

A= 5 min., B=5min., C= test time, D= 30 min., E= 5 min.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Voltage → 212.18 kV</th>
<th>245 kV</th>
<th>212.18 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Samples</td>
<td>5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Duration</td>
<td>1 minute</td>
<td>5 second</td>
<td>3 minute</td>
</tr>
<tr>
<td>Sample No.</td>
<td>(pC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>260</td>
<td>505</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>280</td>
<td>-</td>
<td>500</td>
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<tr>
<td>3</td>
<td>290</td>
<td>-</td>
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<td>4</td>
<td>280</td>
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<td>2 /0</td>
<td>-</td>
<td>1500</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
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<tr>
<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>-</td>
<td>-</td>
<td>6782</td>
</tr>
</tbody>
</table>
5.3 **WT Suitability Check For PD Measurement** [55-56]

PDs are small electrical sparks resulting from the electrical breakdown of a gas contained within a void. If the void is within a solid or liquid, the PD will degrade the material and may eventually cause the failure of the insulation. The discharge in small void in insulation is extremely rapid event. In literature analysis of the PD events, it is found that PD events can occur from 1ns to few μs. S. N. Hettiwatte et al. has reported the propagation of PD pulse duration varying from 100ns-10μs. It is also reported that one PD pulse can be discriminated within 100μs for a 50Hz voltage and can be extensively analyzed on PD pulse pattern. Considering these references, it is necessary to carryout PD data acquisition, WT modeling (for suitability check) and WT analysis on acquired data.

Based on above reference, the simulation is carried out for four different PD pulse widths with two different amplitudes. So, total eight PD pulses are simulated and Gaussian noise is added in it. Finally, generated stream is applied for WT and PD pulses extraction. Block diagram of this Simulation is shown in figure-5.5.

![Figure-5.5 Block Diagram for PD Simulated Data](image-url)
5.4 **METHOD FOR ESTIMATING WT THRESHOLD FUNCTION**[^48,^51]

As discussed in earlier sections; PD data is acquired and analysis is carried out on various measurements. The analysis is carried out as per flow-5.6 given below. The work is carried out in two phases (1) Measurement and (2) signal acquisition and analysis.

![Flowchart](image)

**Figure-5.6 Flow of the Analysis**

Figure-5.7 shows block diagram of acquired signal analysis. Partial discharge signals are bidirectional in nature. Also, standard deviation and other statistical methods cannot be directly useful for signal analysis. So, the direct analysis is not viable for this signal and therefore signal has to separate between positive and negative samples. Further analysis is done separately on positive and negative samples & obtained result is compared with WT analysis signal.
Let $S_n$ is a signal having PD pulses. The sampled signal can be expressed as

$$S_n = S_{n_{pos}} + S_{n_{neg}} \quad \ldots (5.1)$$

Where $S_{n_{pos}}$ is total positive samples and $S_{n_{neg}}$ is total negative samples. A developed program separates positive and negative samples and their average is found out as

$$Avg_{n_{pos}} = \frac{\sum S_{n_{pos}}}{N_{pos}} \quad \ldots (5.2)$$

$$Avg_{n_{neg}} = \frac{\sum S_{n_{neg}}}{N_{neg}} \quad \ldots (5.3)$$

where, $Avg_{n_{pos}}$ and $Avg_{n_{neg}}$ are positive & negative samples’ average respectively and Similarly, $N_{pos}$ and $N_{neg}$ are the numbers for positive and negative samples individually. PD pulses estimation is carried out as per given below.

$$Avg_{est \_ pos \_ PD} = \sum (S_{n_{pos}} - Avg_{n_{pos}}) / N_{est \_ pos \_ PD} \cdot \text{if } S_{n_{pos}} > (p^{*} Avg_{n_{pos}})$$

$$= 0, \quad \text{if } S_{n_{pos}} \leq (p^{*} Avg_{n_{pos}}) \ldots (5.4)$$

$$Avg_{est \_ neg \_ PD} = \sum (S_{n_{neg}} - Avg_{n_{neg}}) / N_{est \_ neg \_ PD} \cdot \text{if } S_{n_{neg}} < (p^{*} Avg_{n_{neg}})$$

$$= 0, \quad \text{if } S_{n_{neg}} \geq (p^{*} Avg_{n_{neg}}) \ldots (5.5)$$
where, \( \text{Avg}_{\text{est\_pos\_PD}} \) is average of pulses which are above \( \text{Avg}_{\text{pos}} \), \( \text{N}_{\text{est\_pos\_PD}} \) is number of pulses whose value is above \( p \cdot \text{Avg}_{\text{pos}} \), \( \text{Avg}_{\text{est\_neg\_PD}} \) is average of pulses which are below \( \text{Avg}_{\text{neg}} \), \( \text{N}_{\text{est\_neg\_PD}} \) is number of pulses whose value is below \( p \cdot \text{Avg}_{\text{neg}} \) and \( p \) is the number which is used to estimate PD pulse amplitude. This analysis is carried out for different values of \( p \) that are 1, 1.5, 2 and 3. Here, \( p \) selects the signal level of comparison with respect to \( \text{Avg}_{\text{pos}} \) or \( \text{Avg}_{\text{neg}} \). However, for \( p=2 \) best result is achieved among all 13 data set files (each data set has more than 5000 samples).

A positive pulse ratio of estimated positive pulses and average positive signal samples determines positive PD pulse intensity and vice versa. These ratios are indicated by

\[
R_{\text{pos}} = \frac{\text{Avg}_{\text{est\_pos\_PD}}}{\text{Avg}_{\text{pos}}} \quad \ldots(5.6)
\]

\[
R_{\text{neg}} = \frac{\text{Avg}_{\text{est\_neg\_PD}}}{\text{Avg}_{\text{neg}}} \quad \ldots(5.7)
\]

Where \( R_{\text{pos}} \) and \( R_{\text{neg}} \) are ratios for positive and negative estimated PD pulses respectively. This ratio estimates PD pulses intensity on actual signal. \( R_{\text{pos}} \) high indicates that the signal has low noise contribution and high PD amplitude and vice versa. During the experiment, \( R_{\text{pos}} \) and \( R_{\text{neg}} \) ratios are found normally equal. Figure-5.8 and Figure-5.9 shows analysis results on data sets-1 and data set-13, respectively. This confirms that the signal is PD signal. Therefore these ratios are used for comparison by WT analysis.
Figure-5.8 Signal Analysis on Data Set-1 ($R_{pos}$ and $R_{neg}$ are High)

Figure-5.9 Analysis on Data Set-13 ($R_{pos}$ and $R_{neg}$ are Low)

Figure-5.10 shows block diagram for WT analysis to determine hard threshold function gain over soft threshold function. As discussed earlier, universal threshold
method decides threshold value for present analyses. WT is applied on signal with universal threshold value for hard and soft threshold function.

Flow chart for combing both the analyses (with different involved phases) and complete process is shown in figure-5.11.
Set-up for data acquisition

Run the Test

Store the data set (using Mtronix software)

Run Mtronix software and to get PD samples

Store the samples in text file

Open the text file for analysis

Is End-of-file?

Stop file read

Yes

No

Read the sample value and store in array

A1

B2

P1

Figure-5.11 Flowchart of signal analyses  Contd…
B2

Read the sample value

Is sample value $\geq 0$?

Yes

Determine Positive Average ($\text{Avg}_{\text{pos}}$)

Determine Negative Average ($\text{Avg}_{\text{neg}}$)

No

Are all samples taken?

No

Yes

Read the sample value

Is sample value $\geq 0$?

Yes

C2

No

D2

E2

Figure-5.11 Flowchart of signal analyses Contd.
Figure-5.11 Flowchart of signal analyses  Contd.
Figure-5.11 Flowchart of signal analyses
5.5 RESULTS

PD MODELING FOR SUITABILITY CHECK USING WT

This simulation is carried out with two amplitude sets with four varying pulse widths. Hence, total eight pulses are generated. Noise is also added with consideration of Gaussian in nature. Table-5.2 shows characteristics of simulated pulses.

TABLE-5.2 SIMULATED PULSE CHARACTERISTICS

<table>
<thead>
<tr>
<th>Simulated PD Pulse No</th>
<th>Peak Amplitude (mV)</th>
<th>Duration (uS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>20</td>
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<td>150</td>
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<td>7</td>
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<td>40</td>
</tr>
<tr>
<td>8</td>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>Noise</td>
<td>140 (mV) peak to peak</td>
<td>1 MHz frequency</td>
</tr>
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</table>

Figure-5.12 (a, b, c) shows simulated input PD signal with two different amplitudes, Noise and PD signal with addition of Noise respectively. Figure-5.12 (d and e) shows obtained PD signals with universal threshold and Minimax threshold.

Extracted PD signal is much definable and the reflected pulse can be clearly seen in comparison to the simulated noisy PD signal. In this analysis, signal is de-noised using level- approximation and Daubechies db2 wavelet.
Figure-5.12 Simulated PD pulses, noise and pulled out PD Pulses
WT Analysis on Data Acquired

PD measurements are recorded as per standard, which are with different time interval. During the measurement, waveforms are recorded for wavelet analysis. One of the recorded waveform is shown in figure-5.13. Stored waveform is referred to as data set in further theory. Summary of the WT analysis is shown in Table-5.3 and individual analysis on each data set (recorded at different time) are shown in Figure-5.14.
Figure 5.13 Recorded waveform using Mtronics software
<table>
<thead>
<tr>
<th>Data file No.</th>
<th>No of Samples</th>
<th>Universal Threshold (C)</th>
<th>Mean Value (C)</th>
<th>Positive Average (C)</th>
<th>Negative Average (C)</th>
<th>Average of Positive Samples Higher then Positive Avg ≠ 2 (C)</th>
<th>Average of Negative Samples Less then Negative Average ≠ 2 (C)</th>
<th>R_{ps}</th>
<th>R_{ng}</th>
<th>Absolute sum of Hard Threshold values (C)</th>
<th>Absolute sum of Soft Threshold values (C)</th>
<th>gain</th>
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<td>48.0394</td>
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<td>2</td>
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<tr>
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<td>1.88E-09</td>
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<td>-1.34E-11</td>
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<td>1.7617</td>
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Figure 5.14 (a) Effect of hard and soft threshold selection on data set-1
Figure-5.14 (b) Effect of hard and soft threshold selection on data set-2
Figure-5.14 (c) Effect of hard and soft threshold selection on data set-3
Figure-5.14 (d) Effect of hard and soft threshold selection on data set-4
Figure-5.14 (e) Effect of hard and soft threshold selection on data set-5
Figure-5.14 (f) Effect of hard and soft threshold selection on data set-6
Figure-5.14 (g) Effect of hard and soft threshold selection on data set-7
Figure-5.14 (h) Effect of hard and soft threshold selection on data set-8
Figure 5.14 (i) Effect of hard and soft threshold selection on data set-9
Figure-5.14 (j) Effect of hard and soft threshold selection on data set-10
Figure-5.14 (k) Effect of hard and soft threshold selection on data set-11
Figure-5.14 (l) Effect of hard and soft threshold selection on data set-12
Figure-5.14 (m) Effect of hard and soft threshold selection on data set-13
During PD analysis of transformer, 13 different data sets are stored separately at different time interval. Signal analysis and wavelet analysis are carried out on each data set.

Figure-5.14(a) shows the data set, where PD values are much higher than noise. Here, \( R_{pos} \) and \( R_{neg} \) are much higher. In this case, the PD signal derived using hard and soft threshold are nearly same. Figure-5.14(g) also shows the data set where PD values are small. Here, \( R_{pos} \) and \( R_{neg} \) are much less and the threshold function selection plays important role. At this sample data, the hard threshold function can detect PD signals.

Subsequently, other data sets are analyzed their comparison is shown in figure-5.15. It is envisaged that, when \( R_{pos} \) and \( R_{neg} \) are higher, then implementation of hard threshold gain is of less advantage. In other words, when acquired signal is containing less PD pulse and more noise contribution; then only hard threshold gives good results whereas in other conditions, both threshold functions gives nearly same results.

This analysis is performed on the data obtained from transformer (referred as X’mer-1) at TRIL (Transformer and Rectifier Industries Ltd.), Ahmedabad. Also, another sets of data is obtained from transformer (referred as X’mer-2) at AREVA T&E, Vadodara and similar analyses are performed on the various data sets. The final results for X’mer-2 are shown in figure-5.14 which complement with the earlier one (figure-5.13).
Gain (Hard threshold selection over Soft threshold selection) 
Vs. Actual signal parameters Rpos and Rneg (for p=2)

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Figure-5.15 Comparison of Hard threshold Gain with Actual Signal (for p=2) Available from X’mer-1
Gain (Hard threshold selection over Soft threshold selection) Vs. Actual signal parameters Rpos and Rneg (for p=2)

Figure-5.16 Comparison of Hard threshold Gain with Actual Signal (for p=2) Available from X’mer-2
5.6 CONCLUSION ON WT ANALYSIS

PD pulses de-noising is carried out using optimum WT, threshold function and threshold value selection. Wavelet transform can extract the PD signals effectively. Simulated PD signals are extracted by the Wavelet transform and the same method is applied to experimental data.

Simulated PD data has input of known PD pulses and noise whereas, test PD data has hidden PD pulses with noise. WT has successfully extracted PD samples, which match with simulated PD pulses.

The same WT method is applied on test data and extracted pulses. It is derived that extracted PD pulses (from testing data) are contains noise also and major noise is easily removed with this technique. It is concluded that WT technique can be utilized to de-noise the PD signals and thus enhance the detection sensitivity.

Later on, analysis is performed on acquired signal to determine in advance which threshold function is to be selected. Based on actual data and WT analysis, it is concluded that if the signal has low PD pulse intensity then hard threshold function selection has value, but when noise contribution is low compared to PD pulses then hard threshold function selection has marginal advantage over soft threshold function selection. So, based on amount of noise from surrounding environment at site, threshold function can be estimated in advance.