PARTIAL DISCHARGE LOCATION WITHIN A TRANSFORMER WINDING USING PRINCIPAL COMPONENT ANALYSIS

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Abstract: Partial discharge (PD) may occur in a transformer winding due to ageing processes, operational over stressing or defects introduced during manufacture. The presence of PD does not necessarily indicate imminent failure of the transformer but it will lead to serious degradation and ageing mechanisms which can be considered as a precursor of transformer failure. A necessary step is required in order to prevent degradation due to PD activity which may ultimately lead to failure. PD might occur anywhere along the transformer winding, the discharge signal can propagate along the winding to the bushing and neutral to earth connections. As far as maintenance and replacement processes are concerned, it is important to identify the location of PD activity so any repair or replace decision is assured to be cost effective. Therefore, identification of a PD source as well as its location along the transformer winding is of great interest to both manufacturers and system operators. The proposed method for locating PD sources in windings is based on wavelet filtering and principal component analysis. An experiment has been developed based on a high voltage winding section that has been used to produce PD measurement data and to investigate the feasibility of the proposed approach.

1 INTRODUCTION

The evolution of maintenance strategies of high voltage transformers in the electrical industry have developed over recent years. There are several maintenance strategies employed for transformers which depend any given problem. Basically, corrective and time based preventive maintenance strategies have been practiced over many years [1]. The corrective strategy involves implementation of maintenance once the plant has failed to operate. The advantage of this type of maintenance is that it does not require any decision tools. However, using this approach will cost the utility company a significant amount to replace the asset. Time-based preventive maintenance is another approach that can be implemented and is better than corrective strategies because it is performed periodically regardless of asset condition. There are several disadvantages associated with this kind of strategy: 1) it may incur high costs due to unnecessary maintenance, 2) failure may still occur if maintenance is not well scheduled, 3) there is no establish method to predict the future condition of high voltage plant in operation 4) some degradation indicators such as partial discharge activity within a winding are difficult to detect as they depend on a large number of internal and external factors. PD activity when detected is a clear indication of insulation degradation within the transformer. Detection of PD for maintenance needs additional decision tools which are required to provide information to allocate the appropriate maintenance process. Traditional transformer monitoring techniques are being slowly replaced by online condition monitoring systems. The condition monitoring techniques are replacing traditional asset management methods because new methods of condition monitoring offer increased accuracy, continuous cost reduction and technological advances via sensor development and technology, data acquisition, information technology and intelligent diagnostic software [2, 3]. For a detailed survey on transformer condition monitoring see [4].

Partial discharge (PD) is a common phenomenon which may occur in high voltage transformers. The term “Partial discharge’’ (PD) is defined by IEC 60270 [5] as a localized electric discharge that only partially bridges the dielectric insulator between conductors when the electric field exceeds a threshold value. At the moment, there are numbers of PD measurement techniques which can be subdivided with respect to information acquired from many sources such thermal, chemical, acoustic, optical and electrical means and these are described thoroughly in several papers [6-8]. Although, partial discharge in a transformer may occur anywhere inside the transformer tank; this paper is concerned about PD which occurs somewhere within the transformer winding. Such an event will cause propagation of the discharge signal along the winding and can be detected at the bushing tap and neutral to earth connections. Hence from these measurements it may be possible to locate the PD source in the transformer winding. Previous work at Southampton has proposed a method for locating PD sources based on analysis of analytical solutions of partial differential equations with estimation of unknown parameter coefficients to model the propagation of discharge signal along the winding from the source to measurement points. Then a comparison of the simulation and real data is made in order to identify the most likely location of a PD source [9]. Unfortunately, due to the fact that complexity of the transformer winding structure as well as the parameters of the winding are unknown and may are change over time this may result in errors of location of the PD source.

This paper is concerned with the development of a new approach for locating PD sources in transformer windings by using signal processing methods that only use the features of the captured data. Data is obtained using radio frequency current transducer (RFCT) sensors at both the bushing tap and neutral to earth connection measurement points. The theory behind the proposed method is described in the next section. In section three, the artificial PD source used is described and this is followed by a description of the experiment procedure in the next section. Results obtained from the analysis are then detailed. Finally, after a short discussion, conclusions and further work are discussed.

2 DATA PROCESSING METHODS

Before further analysis on PD data can be developed using signal processing techniques, experimental PD data that have been captured by an RFCT was pre-processed in order to find and match an exact pair of PD pulses which were measured at different measurement points. The idea is to use comparison based on the nearest pulse location and time of flight of PD signal from site to measurement points. This method is applied to a group of pulses containing hundreds of pulses from each measurement point (i.e. bushing tap and neutral to earth connections) that were obtained by continuously recording over ten cycles of applied voltage. This process was repeated five times to create a data set of PD activity over 50 cycles.

2.1 Discrete Wavelet Decomposition

The initial stage of the algorithm involves applying a discrete Wavelet decomposition to individual PD pulses. The discrete wavelet transform is used rather than the continuous Wavelet transform because it helps to reduce computation time. The discrete Wavelet transform is formed by passing the PD signal through a series of quadrature filters consisting of a high pass and a low pass filter as shown in Figure 1a. Wavelet decomposition produces an 'approximation', A, as the output of the low pass filter and a 'detail', D, as the output of the high pass filter. This decomposition process is iterative because A, the approximation coefficient for the previous level is then used as the new input for the next level of the decomposition process as shown in Figure 1b. In order to apply wavelet decomposition within PD analysis, it is important that the most suitable Mother Wavelet is selected. In this paper, the 'Daubechies' (db) family order of 8 was chosen as it has previously been shown to be the suitable for PD analysis [10, 11]. However, the choice of the mother wavelet is arbitrary and there are no general rules to apply. The number of decomposition levels can be pre-determined by a user and in this case the individual pulses were decomposed into 9 detail levels and an approximation.

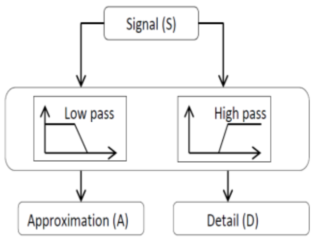
Wavelet filtering is used as to improve the signal to noise ratio (SNR) in many applications, details on de-noising method can be found in [12], however, in this work it is used to identify the distribution of signal energies in both the time and frequency domains. The distribution of signal energy in each decomposition level can be defined as [13]:

$$E_{Di} = \frac{\sum_{j=1}^{Nci} Cd_{i_j}^2(t)}{\sum_{i=1}^{n}\sum_{j=1}^{Nci} Cd_{i_j}^2(t) + \sum_{j=1}^{Ncn} Ca_n^2(t)} \cdot 100 \qquad (1)$$

$$E_{An} = \frac{\sum_{j=1}^{Ncn} Ca_n^2(t)}{\sum_{i=1}^{n}\sum_{j=1}^{Nci} Cd_{i_j}^2(t) + \sum_{j=1}^{Ncn} Ca_n^2(t)} \cdot 100 \qquad (2)$$

Where n is the decomposition level, E_{An} and E_{Dn} are the energy levels for approximation and detail levels respectively, while Ca is the approximation decomposition coefficients and Cd is the detail decomposition coefficients. The measured PD pulse energy distribution is believed to be determined not only by the type of discharge event but also the particular propagation path that the signal traverses between source and sensor. Therefore the use of these energy levels can be another technique to develop a method of locating PD sources along a transformer winding.

(a)



(b)

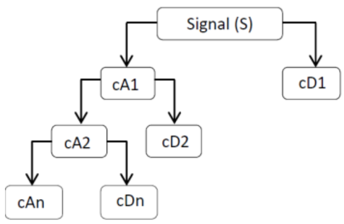


Figure 1: The fundamental of the Discrete Wavelet decomposition a) High and low pass filters b) iterative process of multilevel decomposition.

2.2 Principal Component Analysis (PCA)

Wavelet decomposition generates a distribution of 10 relative energies at 9 levels of decomposition. As such the pulse can be represented by a vector of these 10 variables (or a single point in 10 dimensional spaces). PCA was used reduce 10 dimensions of 10 relative energy into 3 dimensions to create plot a 3-D representation. Principal component analysis is a non-parametric statistical method that is used widely and is the most popular for dimensional reduction technique for large data sets and also can reveal hidden patterns inside data [13]. Initially, a matrix for each measurement point represented by B at bushing tap and N for neutral to earth connection is created where each column in the matrix is the relative energy distribution of the pulse (hence the matrices have 10 columns) while number of row in the matrix indicates number of PD pulse. Each column of 10 dimensions matrix is standardized to ensure the column data has zero mean and a unity variance. The covariance matrices are determined as follows:

$$B_1 = Cov[B] = \frac{B \cdot B^T}{9}\ ,\ N_1 = Cov[N] = \frac{N \cdot N^T}{9} \quad (3)$$

The eigenvalues (λ) with its corresponding eigenvectors (v) are determined for each matrix and the original matrices are transposed using the eigenvectors such that:

$$B_2 = V_{B1}^T \cdot B\ ,\ N_2 = V_{N1}^T \cdot N \quad (4)$$

Finally, the first 3 columns of B_2 and N_2 which represent the highest variances in decreasing order is selected thus creates a 3-D point that is best represents the 10-D data of B and N. Thus, the dimensional reduction is achieved.

3 ARTIFICIAL PD SOURCE

Partial discharge was simulated inside the transformer winding by using an artificial source which is produces data similar to a void in oil as shown in Figure 2. In order to create this type of source, a hollow stainless steel sphere was used as the upper electrode. An air bubble was trapped within the sphere and had dimensions of 4.73 in diameter and 10.30mm in length. A rectangular Perspex block of length 139mm, width 200mm and thickness 7.53mm was inserted between the pair of electrodes. The whole artificial PD source arrangement was immersed in transformer oil.

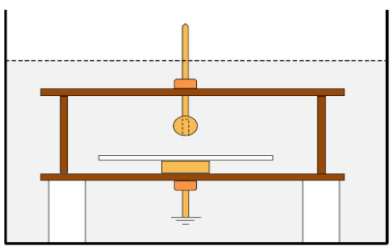


Figure 2: Artificial void in oil PD source

4 EXPERIMENT

The experiment is based on a high voltage transformer winding section, manufactured by Alstom and is detailed in Figure 3. The winding has connections from the disc pairs that allow the injection of PD signals. The injected signals propagate in both directions and can be detected at the two winding ends. The winding section is immersed in an oil filled tank filled with oil of specification BS148:1998 class 1. The experimental model contains interleaved and plain discs and there are 7 disc pairs for each winding section. Each section is separated by end plates similar to both bottom and upper of the winding section. A 60 kV transformer bushing is connected at the top of the winding and any high frequency components of the propagated discharge signal can be detected via a RFCT placed at the bushing tap-point. The whole design is discharge free for applied ac voltages up to 30 kV. In order to inject PD signal into the winding section, the bottom electrode of the external PD source was connected at one of the terminals along the winding section. In this experiment, there are two RFCTs which have a measurable frequency range of up to 200 MHz placed at bushing tap and neutral to earth connection. Capture signals are displayed, analysed and stored in the digital storage oscilloscope with a sampling rate of 500 MS/s. A commercial PD detector was used to detect PDs in the winding and quantifies the discharge magnitude; prior to any measurement the PD detector was calibrated. Figure 3 shows an experiment diagram which used to simulate partial discharge and to produce measurement data for method proposed in this paper.

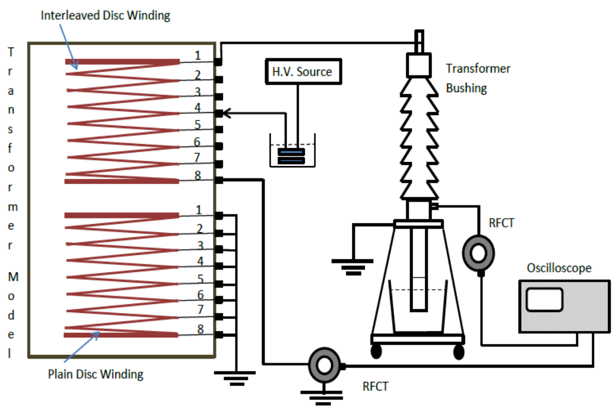


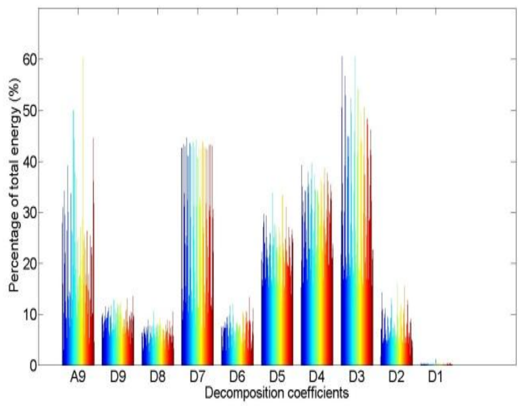
Figure 3: Experiment for simulating PD signals into the interleaved winding section and measure at both ends.

5 RESULTS

The distribution of energy within a PD signal was found to be an effective method to visualise the PD pulse characteristic rather than considering the Wavelet decomposition coefficients and has the advantage of identifying the most significant

Wavelet decomposition levels. A histogram showing the percentage of energy at different composition levels for different PD pulses at the same injection point is shown in Figure 4. Comparison between different injection locations and different measurement terminals either bushing tap or neutral to earth connections is relatively straightforward (compare Figure 4 with Figure 5 say). Figure 4a and 4b show a percentage of total energy from bushing and neutral to earth terminals respectively for PD pulses injected at terminal 1 and Figure 5a and 5b show results for PD pulses injected at terminal 8. Comparison of Figure 4 and Figure 5 shows that the distribution of energy associated with each set of Wavelet decomposition levels at different PD locations along the winding is significantly different.

(a)



(b)

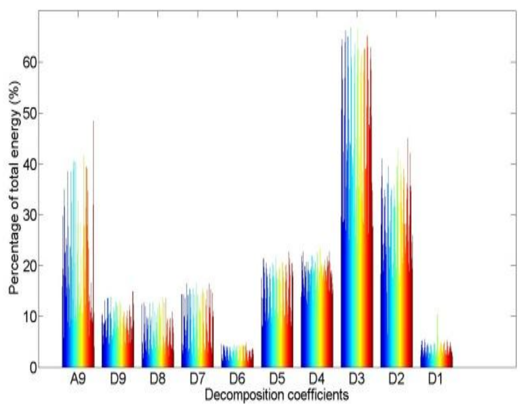
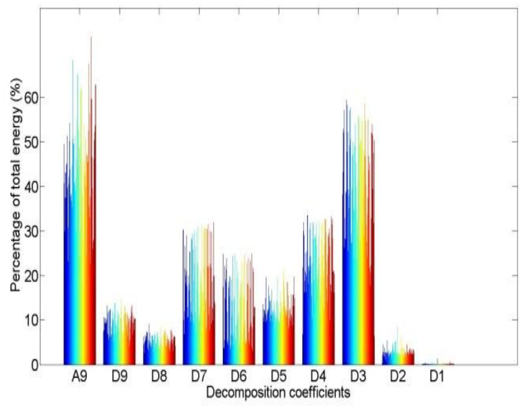


Figure 4: Distribution of Energy Histogram a) Pulses measured at bushing, b) Pulses measured at neutral. Signals injected at same terminal.

The implementation of PCA allows a further reduction of 10 energy levels into a 3 dimensional representation for visual inspection of the cluster pattern and separation between clusters. From this reduced dataset, it may be possible to determine the location of a PD source.

(a)



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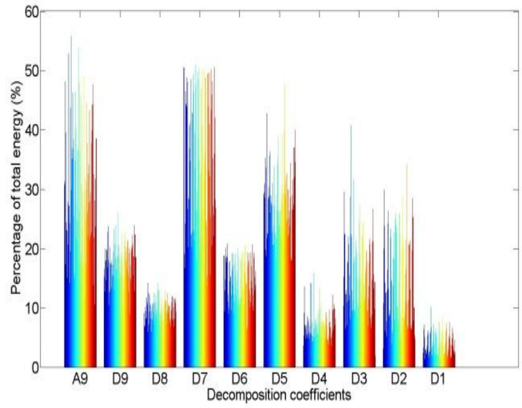

Figure 5: Distribution of Energy Histogram a) Pulses measured at bushing, b) Pulses measured at neutral. Signals injected at same terminal.

For any pulse, the main energies which are most significant are identified using PCA and used to form the 3-D plot as shown in Figures 6 and 7. Referring to both Figures, there are two different groups of clusters separated from each other; the red cluster represents the bushing while the blue cluster represents the neutral.

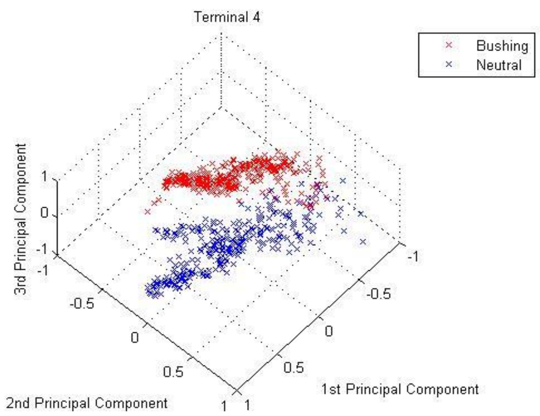

Figure 6: The 3-D plot representing the principal components of the wavelet coefficient energies.

It is clearly possible to separate the clusters for pulses measured at different points as shown in Figures 6 and 7. Hence, a mean centre of gravity, Cg, within the three coordinate systems (xyz) can be determined for each cluster, X, using:

$$Cg = 1/n \sum_{i=1}^{n} Xi \qquad (4)$$

Where X_i is a single 3-D data point, the separation distance (D) between two clusters was calculated using Cg such that:

$$D = \sqrt{(x2 - x1)^2 + (y2 - y1)^2 + (z2 - z1)^2} \qquad (5)$$

Where Cg_1 is defined as (x_1,y_1,z_1) and Cg_2 as (x_2,y_2,z_2). The separation distance (D) between clusters in the 3-D PCA plot may be used as the approach to identify the location of PD event along the winding. The assumption has been made to this approach is different PD locations would give different values of separation distance between the clusters obtained from the two measurement points at opposite ends of the winding. However, the value of the separation distance was yet to be fully analysed or investigated. Figure 7 shows a larger separation distance between two groups of clusters for a signal injected into terminal 5, thus reinforcing the assumption that different PD source locations will produce different separation distance when analysing the distribution of signal energies and using dimension reduction techniques.

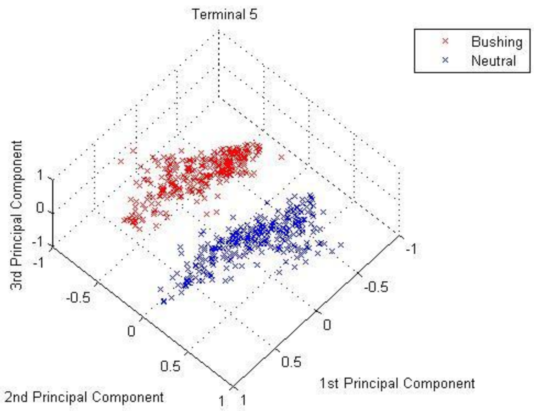

Figure 7: The 3-D plot obtained from PCA applied for data injected at terminal 5

Table 1 show an exact value for separation distance measured using the experimental winding and Figure 8 is a plot of the separation distance between the two clusters for all the injection terminals along the winding. The pattern shown in Figure 8 indicates the separation distance increases from terminal 1 to terminal 8 however, between terminals 5 and 6 there is a decrease in distance between clusters. This may have been caused by excessive noise for example as seen in Figure 6, where the resulting cluster has greater spaced and is less dense.

Terminals	Separation Distance
1	2.8737
2	3.1641
3	3.2868
4	3.4193
5	3.3697
6	3.1213
7	3.3539
8	3.5011

Table 1: The separation distance for all different injection terminals along the transformer winding

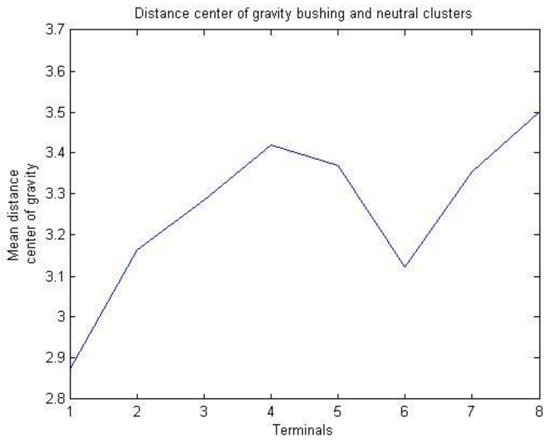

Figure 8: Pattern of separation distance of all terminals

6 CONCLUSION

RFCT sensors located at both the bushing tap and neutral end can detect discharge signals and it is possible to record and store these PD signals over 50 cycles of applied ac voltage. Application of Wavelet discrete decomposition is a useful pre-processing technique that can produce a feature vector that represents the distribution of signal energy in both the time and frequency domains. This information can be further reduced and visualised in 3 dimensions using principal component analysis (PCA). This results in the formation of clusters of data, the separation distance between clusters may be indicative of the location of PD. These are initial results and for experiments and further work on the analysis of the clusters of data produced needs to be undertaken, it is important that noise levels are reduced before any analysis to improve the accuracy of identifying source location. Early results indicate that this new approach has promise and maybe determine the location of PD within a transformer winding without the need for transformer winding parameter estimation, modelling or offline measurements.

7 REFERENCES

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