Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 30, No. B6, pp 655-666
Printed in The Islamic Republic of Iran, 2006

INVESTIGATION OF PARTIAL DISCHARGE PROPAGATION AND LOCATION IN MULTIPLE-α AND SINGLE- α TRANSFORMER WINDINGS USING OPTIMIZED WAVELET ANALYSIS*

MOHAMMAD S. NADERI[1**], M. VAKILIAN[1], T. R. BLACKBURN[2], T. B. PHUNG[2] AND MEHDI S. NADERI[3]

[1] School of Electrical Engineering, Sharif University of Technology, Tehran 11365-9363, I. R. of Iran
Email: salaynaderi@hotmail.com
[2] School of Electrical Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[3] School of Electrical Engineering, Amirkabir University of Technology, Tehran 15914, I. R. of Iran

Abstract– Partial discharges (PD) are recognized as the main cause of the inner insulation deterioration process in power transformers. Therefore, the optimum inner insulation design is one of the challenges a transformer designer is faced with. Transformer strength, especially during transient conditions, is a criterion for transformer insulation designers. This challenge has made designers initiate and employ other types of winding, for example, rather than ordinary layer and disc windings employ the multiple-α windings. Multiple-α windings have a more complicated structure and are comprised of various parts with different physical structures and electrical characteristics. Typical partial discharge signals cover a wide frequency range from DC up to hundreds of MHz and different frequency components propagate through the winding depending upon the winding structure in different modes. Partial discharge propagation in single-α winding is more predictable compared to multiple-α winding. A 66 kV / 25 MVA interleaved winding, which has 19 fully interleaved discs, plays the role of a single-α winding. When this main winding is connected to the tap winding with a different structure and magnitude response, a multiple-α winding is constructed. Two terminal current signals are detected by the application of two home-made high frequency current transformers (HF-CT). The signals were amplified and fed into a 500 MHz digital storage oscilloscope. Home-made sensors are designed to provide maximum sensitivity in the desired frequency range. In order to evaluate the partial discharge signal accurately, a method for selecting the optimal wavelet is introduced to reduce the noise effects. This method is based on the capability of the chosen mother wavelet for generating coefficients with maximal values. The wavelet based de-noising method proposed can be employed in extracting the PD pulses from the measured signal successfully to provide enhanced information and further infer the original site of the PD pulse through the capacitive ratio method..

Keywords– Power transformer, partial discharge, wavelet analysis, PD location, PD propagation, multiple-α winding, single-α winding

1. INTRODUCTION

Failure of the inner insulating systems of HV equipment, including transformers, can lead to a catastrophic failure of the equipment with serious environmental and economic consequences. Partial Discharge monitoring and diagnosis is essential to identify the nature of insulation defects causing discharge.

Monitoring means mainly data acquisition, sensor development, data collection, and development of methods for the condition measurement of a power transformer. Diagnostics contain the interpretation of off-line and on-line measured data [1]. In this sense, during the monitoring in an AC system or off-line

*Received by the editors January 4, 2006; final revised form April 4, 2006.
**Corresponding author

measurements, interferences and disturbances affect the measurement data in noisy conditions and the PD signal is buried in the noise.

Noise can be defined as any unwanted signal that is not related to the input signal. The primary sources of random, unpredictable noise are from radio waves, electrostatic discharges (ESD), power utility transients, corona and lightning, and thermal noise. During the last decades, interference from noise sources has been a persistent problem, which has increased with the advent of solid state power switching electronics [2].

Despite the advances achieved during past decades in measuring instruments, partial discharge detection circuits, e.g., the ultra wide-band detectors coupled to the real-time oscilloscopes of very wide band-width, and a sophisticated analytical tool to post-process PD data has yet to be developed [3].

The wavelet and its associated transforms [4-6] represent a powerful signal processing with a wide variety of applications. The main reason for this growing activity is the ability of the wavelet transform not only to decompose a signal into its frequency components, but also to provide a non-uniform division of the frequency domain, whereby it focuses on short-time intervals for high-frequency components and long intervals for low frequencies. This attribute to tailor frequency resolution can greatly facilitate signal analysis and the detection of signal features.

2. STRUCTURAL DIFFERENCES BETWEEN MULTIPLE-α AND SINGLE-α WINDINGS

In order to make the most efficient use of the inner insulation system provided within the transformer, it is imperative to design the windings in such a way as to eliminate, or at least to slash, both the initial voltage concentration at the line end, and also subsequent high oscillatory voltages in the body of the winding. Any improvement in the initial distribution will also decrease the divergence between the initial and final response of the winding; thus it will also reduce the magnitude of the subsequent oscillations. It is also sufficient to concentrate solely on improving the initial voltage distribution in the windings.

Up to a few years ago, transformer windings were designed uniformly from the line end to the neutral end; thus the material and geometry of the insulation all in the winding body, was the same. With some simplification, a uniform transformer winding may be represented by a uniform circuit of series inductance, together with shunt and series capacitances. When a unit-function voltage is applied to this equivalent circuit, the initial distribution of voltage is determined entirely by the capacitive network.

Previously, it was found [7] that for some windings, especially interleaved windings regardless of whether they are multiple-α or single-α type windings, there exists a range of frequencies within which the signal components do not change phase when traveling through the winding.

As a theoretical rule, for a winding to be presented as a capacitive network, at least two requirements must be satisfied. Firstly, in the frequency range to be considered, the transfer function should have a nearly constant magnitude. Secondly, its phase shift must be very small. If considered in the time domain, the wave shape of output at one end should be similar to that of the input at another end and the ratio should be constant with respect to time [7, 8].

Figure 1 demonstrates the simplified capacitive circuit of a uniform transformer winding. In this figure, C'_S is the series capacitance of one individual element and C'_g is the earth capacitance of each element.

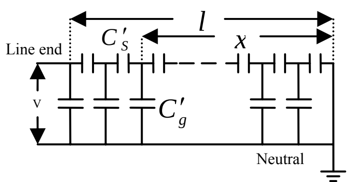


Fig. 1. Simplified capacitive circuit of a uniform transformer winding

If C_g is total capacitance of the winding to earth, C_S is series capacitance measured from end to end of the winding, *l* is total winding length and the neutral is solidly earthed, then the voltage at a point, which has a distance of *x* from the neutral end of the winding (theoretical capacitive distribution) is given by [8]:

$$v(x) = \frac{V\, sinh(\alpha x/l)}{sinh(\alpha)} \tag{1}$$

Where

$$\alpha = \sqrt{\frac{C_g}{C_S}} \tag{2}$$

α is the initial impulse voltage distribution coefficient and it can be seen as a single number for a uniform winding. The lower this coefficient is, the better linear voltage distribution along the winding is achieved. A lower coefficient is available through reduction of the earth capacitance C_g, or nullifying its effect by electrostatic shields, or alternatively, by increasing the series capacitance C_S.

In practice, to reduce earth capacitance, the transformer dimensions should increase, which is not acceptable for manufacturers and also customers. Choosing disc type coils and then interleaving the windings yield an increase in the series capacitance.

Nowadays, to get better results in large power transformers, windings are designed to be non-uniform; then winding can be considered by various sections with different structural data. These series of windings are known as multiple-α windings, which are complicated to design, analyze the behavior in normal and stressful conditions, and they also lessen accuracy in partial discharge location methods.

3. VALIDITY OF PD PROPAGATION AND LOCATION MODELS

The identification of the partial discharge location and its propagation obviously has the advantage that the fault can be quickly rectified and also the time lost due to outage will be minimal.

Depending on the severity and location of a discharge, the transformer will either be taken out of service immediately or at a convenient time, or will be kept in service with an increased monitoring service. Early work [7] on partial discharge location assumed that the transformer behaved like a capacitive network, but further studies [8] indicated that this is only valid over a limited frequency range and is inadequate for studying PD propagation [9].

When the dominant partial discharge frequencies are up to a few hundred kHz, each section, including one disc or one layer of the transformer winding can be modeled as a lumped circuit that takes into account capacitance, inductance, resistance and also dielectric losses [10, 11]. This model is not adequate for a MHz region.

If each turn of a transformer winding can be modeled with a lumped parameter network, this model can be employed for studies from a few hundred kHz up to a few tens of MHz. This model may be employed for PD propagation studies, too.

4. WAVELETS AND NOISE SUPPRESSION

The main objective of de-noising is to suppress the interfering part of the signal. However, the ability to separate the true signal from noise improves with increased knowledge about the main signal source, as well as the noise attributes.

With reference to noise characteristics, which are normally involved, two main kinds can be distinguished. Firstly, continuous type noises which include sinusoidal and white noise. Secondly, pulse shaped noises, which are periodically appearing noise pulses and stochastically occurring pulse shaped noises.

Sinusoidal noises are usually generated by radio or communication services and can be suppressed by a frequency rejection filter. White noise is especially due to wave transmission and the suppression of white noise can be usefully performed with the wavelet transform [2, 12]. Cross correlation methods are employed to eliminate periodically appearing noise pulses. Localization methods in various investigations have shown their remarkable ability to suppress stochastic pulse shaped noises like corona discharges.

The wavelet transform normally uses both the analysis and synthesis wavelet pair. Synthesis is used for waveform reconstruction. The signal obtained from the measurement is decomposed into its constituent wavelet levels. Each of these levels represents that part of the noisy signal occurring at that particular time in that specific frequency band. In this sense, the key idea underlying the WT strategy is that a given signal can be disassembled into a series of scaled and time-shifted forms of a mother wavelet producing a time-scale view of a signal from which the original can be recovered. As it can be seen, the decomposed signals possess a powerful time-frequency localization property, which is one of the major benefits provided by the wavelet transform. On the other hand, wavelet de-noising methods are based on either hard or soft threshold approaches. A de-noised signal can be retrieved by inversing wavelet transform, which genuinely is the inverse of the threshold wavelet coefficients.

The mentioned algorithm is a rough description of a de-noising algorithm based on wavelet transform and implies another advantage of this kind of de-noising. In fact, a peculiarity of this filtering technique is that no reference signal is needed.

The complexity of noise suppression when measurements are on a power transformer is obvious. When a signal propagates from its site of origin to the measuring terminals in the line and neutral ends of the transformer, it is strongly modified. Depending on the original location of the PD and transfer characteristics of the windings between the PD source and terminals, pulses will be significantly distorted and attenuated in magnitude. Therefore selecting the most suitable wavelet for noise suppression, especially when the measurements are on a power transformer, is vitally important and this has been investigated on PD pulses measured in the laboratory for PD location purposes.

5. WAVELET OPTIMIZATION

The selection of a suitable wavelet and its associated analysis algorithm depends on the desired application. Furthermore, improving the optimal method needs to have an exact understanding as to the detection circuit and PD pulse shape.

In practical measurements, discharge voltage signals are captured by feeding the discharge current into a detection circuit. Therefore, depending on the configuration of the detection circuit, voltage signals will likely have different shapes.

Measuring voltage signals causes some problems in practice. In fact, for the normal transformer connection, the neutral end of the winding is grounded, which makes calibration at this end impossible. Including an inductance with low impedance at power frequency in the neutral end will alleviate the problem.

Detection circuits have been a concern in many investigations [13, 14] and are usually realized as either RC or an RLC impedance circuit. Simulated pulse in this paper is supposed to be obtained from an RLC circuit.

Obviously, based on what measurement circuit has been chosen, the mother wavelet, which provides the optimal results with the obtained data, would be different from another circuit with another data.

By the word "Optimal", it is meant that the characteristics of the synthesized signal are closer to the main signal as much as is possible by the software tools available.

For better understanding, a simulated PD pulse, which is supposed to be obtained utilizing a detection circuit with an RLC impedance circuit, is considered. The transfer function of RLC impedance circuits can be expressed as

$$G_{RLC}(s) = \frac{1}{C} \cdot \frac{s}{s^2 + s/\tau + \omega_0^2} \tag{3}$$

Where $\tau = RC$ and $\omega_0 = 1/\sqrt{LC}$. Figure 2 shows the detection circuit of an RLC impedance circuit.

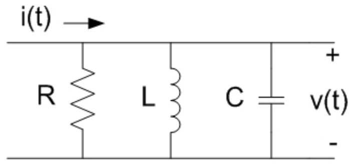


Fig. 2. RLC detection circuit

For the input of a Dirac current pulse *i(t)*, the output voltage pulse *v(t)* is represented as a damped oscillatory pulse, as shown in Fig. 3.

Wavelet detail coefficient distribution and the wavelet pattern, throughout the entire time-scale, is used to determine the most suitable wavelet for a given pulse.

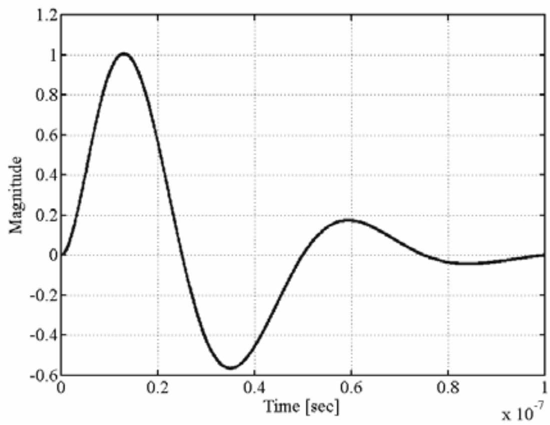
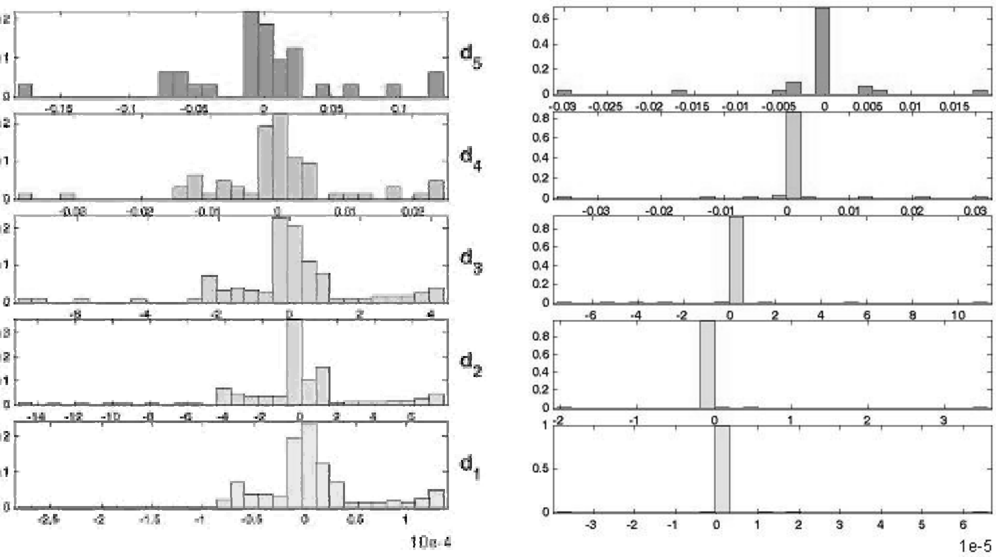


Fig. 3. Simulated PD pulse

Figure 3 demonstrates the magnitude of the simulated PD pulse versus time in seconds. Pulse magnitude has been normalized to provide a better view on the wavelet pattern histogram, which is used to recognize the optimal wavelet suited to the simulated pulse.

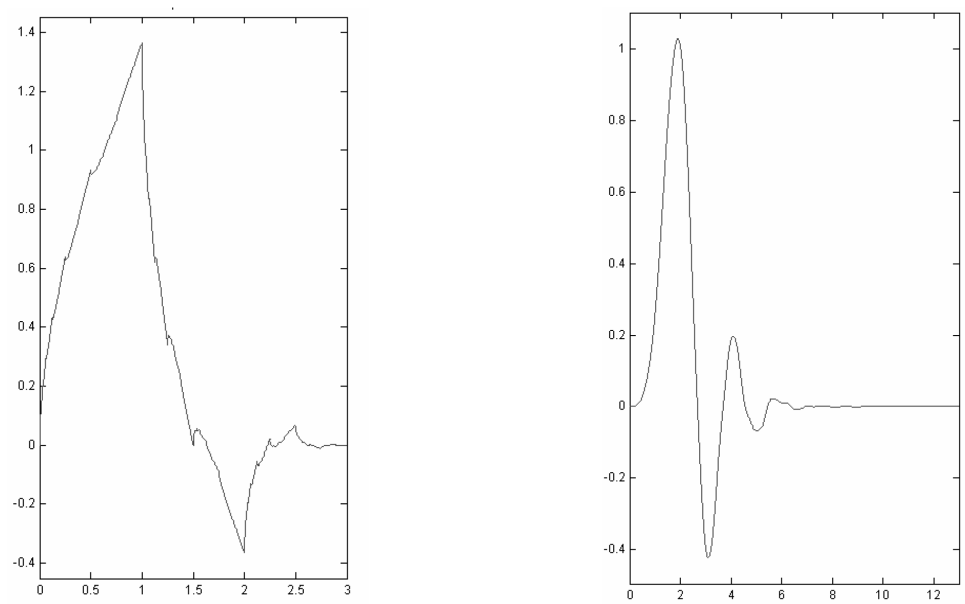
Figures 4a and 4b show the wavelet pattern histogram of the simulated PD pulse in Fig. 3. Wavelet patterns have been gained after applying DWT with 5 levels using Daubechies wavelets, db2 and db7, respectively.

The values of the coefficients, as Fig. 4 illustrates, are significantly different and those gained using db7 are greater than the db2. Detail coefficient distributions for other simulated pulses showed that similarity between the mother wavelet and a simulated pulse or a correlation between them can be used as a criterion for choosing the optimal wavelet. More similarity gives better correlation. Fig.5a and 5b show the mother wavelet for db2 and db7, respectively.



(a) (b)

Fig. 4. Detail coefficient histograms of the simulated PD pulse, sampling frequency 10 GHz; 1001 points; (a) with the db2; (b) with the db7



(a) (b)

Fig. 5. Mother wavelets, a) db2, b) db7

In statistical analysis, the correlation coefficient, γ, is used to detect one particular relationship between the mother wavelet and the signal under examination. The greater the value of γ, the more approximate the wave shape between two variables [3].

6. APPLICATIONS IN PD PROPAGATION AND LOCATION STUDIES

A 66 kV / 25 MVA interleaved winding with 19 fully interleaved discs plays the role of a single-α winding. When this main winding is connected to the tap winding with a different structure and magnitude response, a multiple-α winding is constructed. Tap winding has 10 ordinary discs. The upper disc is connected to a bushing, and the lowest disc is connected to the upper disc of the main winding. The transformer core was removed and a ground aluminum cylinder was placed instead. Obviously, in practice, producing a multiple-α transformer winding is a result of meeting a few requirements such as uniform initial voltage distribution on the winding, and these requirements prevent having a winding, which is a combination of interleaved and ordinary sections next to each other throughout the winding. In this investigation tap winding has ordinary discs where main winding has fully interleaved discs and this combination has been done on purpose to study whether different kinds of combinations would provide a better insulation system or not. Figure 6 shows the experimental set up.

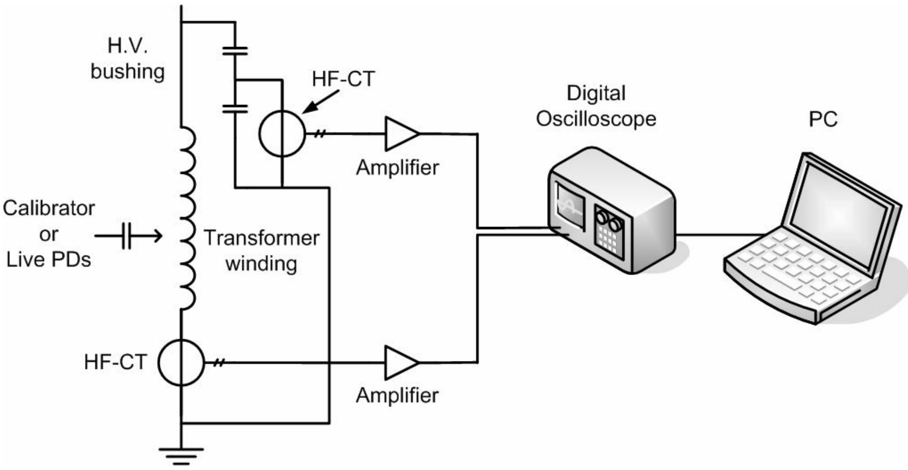


Fig. 6. Experimental set up for PD location

The injected partial discharge signal is generated by an electric calibrator. The resulting current signals at line and neutral ends are detected by home-made high frequency current transformers (HF-CT) and recorded with a 500 MHz digital storage oscilloscope. The home-made sensors are designed to provide maximum sensitivity in the frequency range where the test object behaves as a capacitive ladder network.

The terminal disturbances resulting from a partial discharge inside the winding consist of a wide range of frequencies. Only those components which are within the capacitive frequency range can be transmitted from the partial discharge site to each terminal without significantly changing their phase and attenuation factor with frequency.

On the other hand, the terminal transient voltages measured by some investigators using wide or narrow band detectors may not correctly reflect the capacitively transferred components and thus, sometimes leads to a big location and propagation errors. The reason might be that the frequency ranges were chosen more or less arbitrarily and were not suitable for the individual winding under test.

A fundamental problem in this measurement method lies in the difficulty of accurately assessing the initial, capacitively transferred, voltage magnitude. This problem is normally solved by using digital filtering techniques.

a) Magnitude response of the test objects

In [14] it was shown that there exists a range of frequency in which the signal components do not change phase when traveling through the winding.

The magnitude response of the test objects were found by injecting a variable frequency sine wave (up to 10 MHz) into one terminal and measuring output from the other open-circuit terminal. The results for single-α winding and multiple-α winding have been shown in Figs. 7 and 8, respectively. As it can be seen, single-α winding in the frequency range between ~50kHz to ~500kHz, behaves as a capacitive network, whereas this frequency range for multiple-α winding is between ~150kHz to ~300kHz. The open-circuit transfer function between two ends of the winding in the frequency range in which the winding behaves as a capacitive network is as shown below [8, 15]:

$$H(\omega) = \frac{1}{\cosh(\alpha)} \tag{4}$$

With the multiple-α winding, in the frequency range between ~150 kHz to ~300 kHz, the phase of $H(\omega)$ is about zero and $|H(\omega)|$ is nearly constant with the value of 0.17. From this value, the equivalent capacitive distribution coefficient α_e may be determined from the equation below:

$$\alpha_e = \operatorname{arccos}h\left[\frac{1}{H(\omega)}\right] = 2.46 \tag{5}$$

In other words, the multiple-α winding might be considered with an equivalent capacitive distribution coefficient with the calculated value, whereas this parameter for single-α winding is:

$$\alpha = \operatorname{arccos}h\left[\frac{1}{0.61}\right] = 1.1 \tag{6}$$

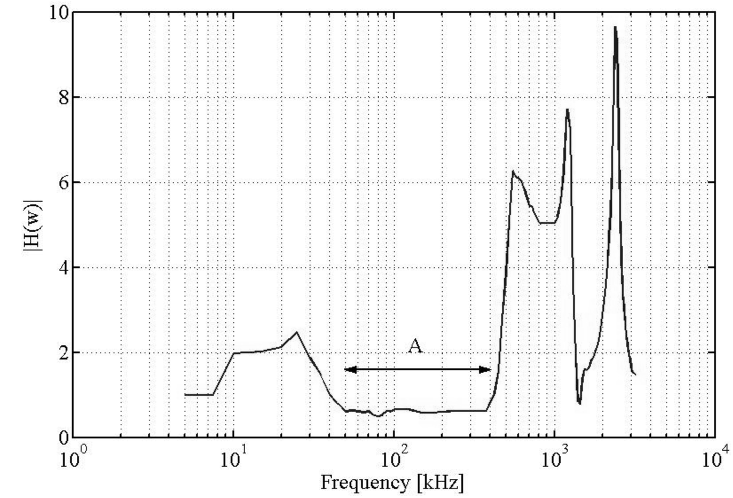


Fig. 7. Magnitude response of the single-α winding

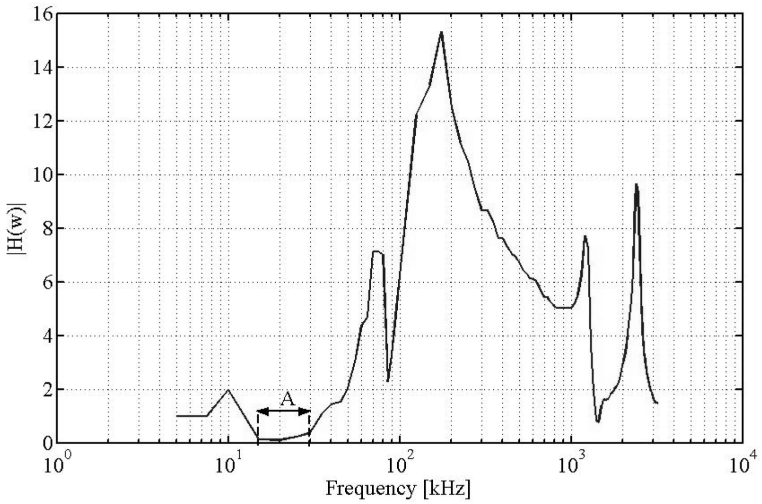


Fig. 8. Magnitude response of the multiple-α winding

Compared to the magnitude response obtained for single-α winding in Fig. 7, the frequency range in which the multiple-α winding has capacitive behavior is smaller. This will decrease the sensitivity of the PD location for multiple-α winding obtained through the terminal current measurement method.

b) PD propagation and location

As the transformer main winding structure is homogeneous and no differences can be considered throughout the winding, the whole winding is taken into account as 1 tail and the tests are supposed to provide an almost even curve when the voltage ratio is plotted versus partial discharge location. The reason is that the magnitude response of the winding is dependent upon the structural data, which is one of the differences between single-α and multiple-α windings. To investigate the proposed idea, the ratio of the peaks of the two terminal signals as a function of the PD location has been depicted, while a PD pulse is generated by an electric calibrator. Figure 9 is the result when the test object is the main interleaved winding only, and Fig. 10 for multiple-α structure.

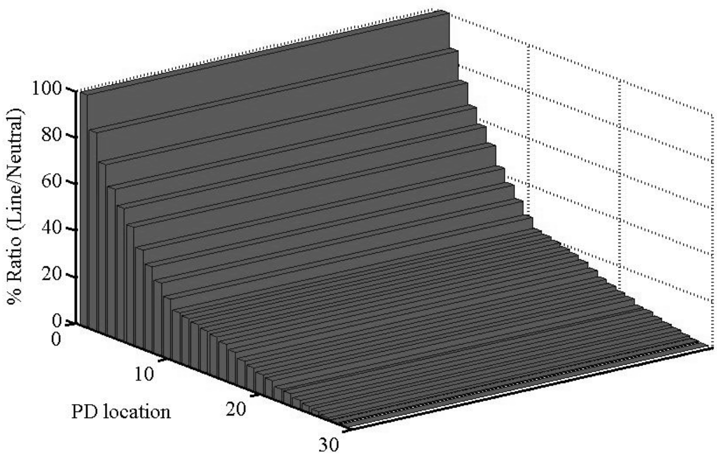


Fig. 9. Pulse distribution curve for single-α winding

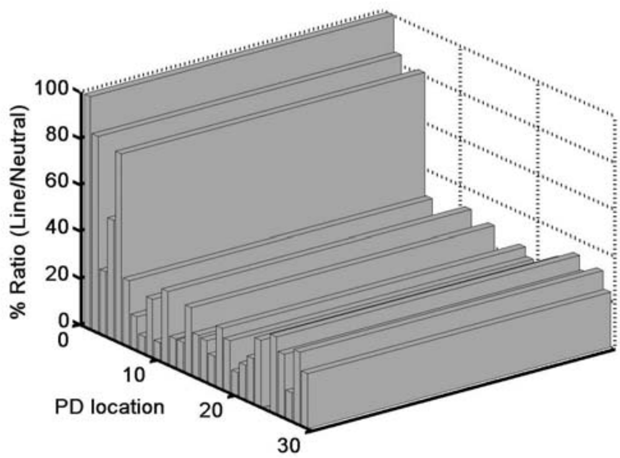


Fig. 10. Pulse distribution curve for multiple-α winding

Comparing the two figures implies that the combination of the aforementioned windings to make a multiple-α winding results in an unreliable reference curve for the PD location. This comparison might be a criterion to have a better understanding as to produce multiple-α windings in order to be used within especially large power transformers.

Figure 11 shows a recorded signal from the neutral end when the PD is injected from the line end. The need for de-noising was discussed in [14].

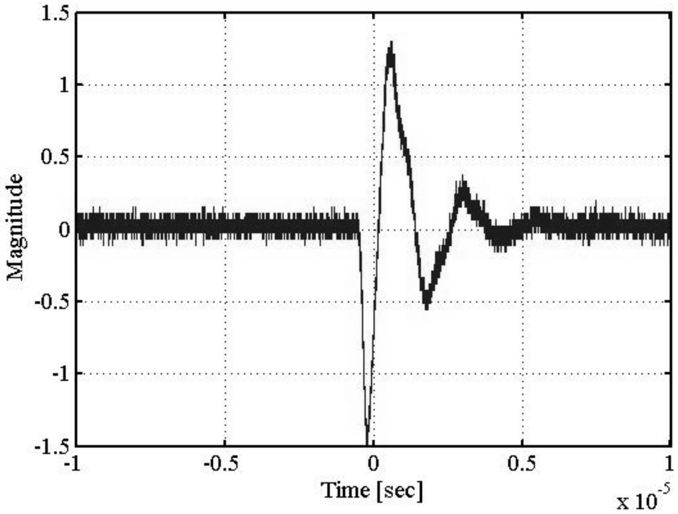


Fig. 11. Sample recorded signal from neutral end

After applying the wavelet, the ratio of the peaks of the two terminal signals as a function of the PD location for single-α winding is depicted in Fig. 12. With multiple-α winding many experiments were conducted, in which every time resulted in no comparable curves between the electric calibrator and the live discharge source.

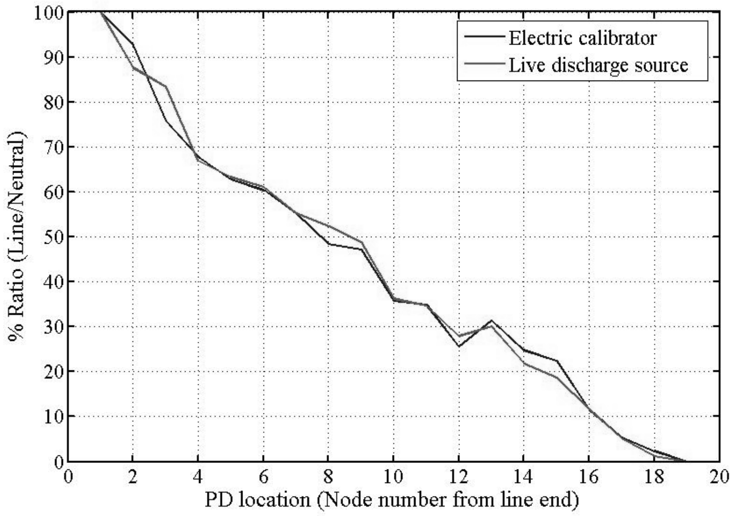


Fig. 12. Ratio curves after de-noising with db7 for single-α winding

The maximum difference between the electric calibrator and live discharge source curves is about 4%, which for the single-α winding provides an accuracy to determine the PD location of the two discs deviation.

7. CONCLUSION

Reaching the optimum inner insulation design is one of the challenges a transformer designer is faced with. This challenge has made designers to switch from ordinary layer and disc windings to multiple-α windings. Multiple-α windings have more complicated structures and comprise various parts with different physical structures and electrical characteristics. On the other hand, the transformer winding behavior varies with the frequency, which in turn is influenced by the winding design. By measuring the electrical signals from the two terminals and using the appropriate method (Capacitive ratio), the propagation and location of the single-α and multiple-α windings were investigated. With single-α winding, selecting an optimal wavelet gives promising results concerning the location of PD sources using the capacitive network method, whereas multiple-α winding measurement results were unreliable.

However, the selection of a suitable wavelet and its associated analysis algorithm depends on the desired application and improving the optimal method needs to have an exact understanding as to the detection circuit and PD pulse shape.

This investigation has also proved that every combination of different winding structures might not result in an optimum inner insulation design. However, an optimum design and manufacturing process through the application of the multiple-α windings can lead to a uniform transient voltage distribution along the transformer winding due to its structural characteristics.

Acknowledgment- The first author would like to especially thank TAVANIR Management Co. in providing him the opportunity to do a part of his PhD at UNSW, Sydney, Australia.

REFERENCES

1. Leibfried, T. (1998). Online monitors keep transformers in service. *Computer Applications in Power, IEEE, 11*(3), 36–42.
2. Shim, I., Soraghan, J. J. & Siew, W. H. (2000). Digital signal processing applied to the detection of partial discharge: An overview. *IEEE Electrical Insulation Magazine, 16*(3), 6-12.
3. Ma, X., Zhou, C. & Kemp, I. J. (2002). Interpretation of wavelet analysis and its application in partial discharge detection. *IEEE Transactions on Dielectrics and Electrical Insulation,[see also Electrical Insulation, IEEE Transactions on], 9*(3), 446-457.
4. Louis, A. K., Maab, P. & Krivda, A. (1993). Classification of partial discharge. *IEEE Trans. EI, 28*, 917-931.
5. Daubechies, I. (1990). The wavelet transform, time-frequency localization and signal analysis. *IEEE Trans. Information Theory, 36*, 961-1005,
6. Mallat, S. G. (1989). A theory for multi-resolution signal decomposition: The wavelet representation. *IEEE Trans. Pattern Analysis and Machine Intelligence, 11*, 674-693.
7. Mohammad, S., Naderi, M., Vakilian, T. R., Blackburn, B. T., Phung, H. N., Mehdi, O. & Naderi, S. (2005). An optimal wavelet filtering method for noise suppression of PD measured signal and its location in power transformer winding. *IEEE International Conference on* Dielectric Liquids (ICDL 2005)*, Coimbra, Portugal, 26*, 269-272.
8. James, R. E., Phung, B. T. & Su, Q. (1989). Application of digital filtering techniques to the determination of partial discharge location in transformers. *IEEE Transactions on Electrical Insulation, [see also Dielectrics and Electrical Insulation, IEEE Transactions on], 24*(4), 657–668.
9. Hettiwatte, S. N., Crossley, P. A., Wang, Z. D., Darwin, A. & Edwards, G. (2002). Simulation of a Transformer Winding for Partial Discharge Propagation Studies. *Power Engineering Society Winter Meeting, New York, USA, 27-31 January, 2002. IEEE, 2*, 1394-1399.
10. Wang, Z. D., Crossley, P. A., Cornick, K. J. & Zhu, D. H. (2000). An algorithm for partial discharge location in distribution Power transformers. *IEEE/PES Winter Meeting, Singapore, 23-27 January 2000, Vol.3,* 2217-2222.
11. Mohammad, S., Naderi, M., Vakilian, T. R., Blackburn, B., Phung, T., Zhang, H. & Naderi, M. S. (2005). A method for studying partial discharges location and propagation within power transformer winding based on the structural data. *Proceedings of 2005 International Symposium on Electrical Insulating Materials (ISEIM 2005), Kitakyushu, Japan, 5-9 June 2005, 2*, 490-493.

12. Werle, P., Akbari, A., Borsi, H. & Gockenbach, E. (2002). Enhanced online PD evaluation on power transformers using wavelet techniques and frequency rejection filter for noise suppression. Electrical Insulation, 2002. *Conference Record of the 2002 IEEE International Symposium*, 195-198.
13. Zingales, G. (2000). The requirements of a PD measuring system analyzed in the time domain. *IEEE Trans. DEL, 7*, 2-5.
14. Phung, B. T., Blackburn, T. R. & Lay, W. W. (2003). Partial discharge location in transformer windings. Paper O.14.01, *13th Int. Symp. on High-Voltage Engineering (ISH), Delft, The Netherlands*, *Aug.25-29, 2003. ISBN*, 90-77017-798.
15. Su, Q. (1989). Detection and location of partial discharges in transformer and generator windings using electrical methods. Ph.D. Thesis, University of NSW, Australia.