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A Signal Processing Technique for PD Detection and Localization in Power Transformer Winding

Mohammed Abd Ali Aziz[1], Zulkurnain Abdul-Malek[2]
[1]Ministry of Electricity, Republic of Iraq
[2]Institute of High Voltage and High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

Abstract: Precise detection and localization of faults in power transformer windings for ultimate protection is the key issue. The insulation quality in windings majorly determines the enduring transformers function. Achieving as accurate and efficient detection method of partial discharge (PD) in transformer windings is challenging. The occurrence of PD being primarily responsible for the transformers failure its detection is considered as preventive measure to avoid large-scale economic losses. This paper briefly overviews the salient features of the conventional acoustic and travelling wave methods those electrically determine the dominant capacitive region in the frequency domain. We propose a technique which is based on the PD signal detection and the measurement of the characteristics transfer functions in the frequency domain. A distributed circuit transformer model with eight sections is developed and simulated via Matlab code. PD signals analogous to sources in various locations are injected at different points within the transformer windings. The PD source positions are determined in terms of the number of turns from the line-end. The determination of PD locations on the basis of zero frequency differences is demonstrated. Our method significantly improved the accuracy to identify the PD location. The limitations associated with the appearance of noise and the frequency range for detection is overcome. The occurrence of crests and troughs in the frequency spectra are used to locate the source of PD activity in transformer windings.

Keywords: Transformer windings, Partial discharge, Localization, Travelling wave, Frequency spectra.

Introduction

Definitely, transformers being one of the integrated and expensive parts of a power system the quality of insulation significantly decide their durability. Finding the faults and evaluating the insulation quality of transformers windings is prerequisite in shielding them from sudden operational failures and avoid high economic loss. Moreover, the decay of this insulation over long time that originates from the collective consequences such as electrical and other stresses, temperature fluctuations, moisture, and oxygen attacks is unavoidable. Tiny electrical sparks called PD that occurs inside the transformers due to the electrical breakdown of interior media or the emergence of highly non-uniform electric field requires constant monitoring. Early detection of PD insulation fault is taken as preventive measure for irreparable transformer damage.

The generation of PD is accompanied by the propagation of acoustic and electromagnetic waves along different directions of the transformer windings. Consequently, PD detection and localization can be achieved by measuring the electrical or acoustic signals at the transformer terminals. However, the suffering of PD signal from attenuation and reflection during propagation through the winding limits their accurate measurements. The quest for achieving suitable and reliable methods for detecting and localizing the PD in transformer winding insulation is ever-growing [1-5].

Generally, acoustic wave method relying on the electrical determination of the dominant capacitive region in frequency domain and the travelling wave method is employed for PD detection and analyses. The accuracy and sensitivity of each method depends on the location of the discharge within the winding insulation. Signal attenuation and reflection being the main limitations of the acoustic and travelling wave methods often provide inaccurate results. However, in the high frequency range technique of capacitive ladder based distributed equivalent circuit can overcome such shortcomings.

This paper proposes a method based on the frequency spectrum analyses where the measured signals at the transformer terminals reveal unique signatures depending on the location of the PD activity. A distributed circuit transformer model containing eight sections is developed and analyzed using Simulink/Matlab.The transfer functions at the line-end terminals are computed. The position of the PD source is determined in terms of the number of turns from the line-end. This method may be applied to determine any type of discharge signal.

PD Detection and Localization Methods

Acoustic method

Acoustic method is widely used for the PD detection. This method detects and locates the position of PD by determining the attenuation in amplitude or phase delay of the propagated acoustic waves originates from PD. These acoustic waves are detected by Piezoelectric Transducers (PZT) also called acoustic sensor. Its application becomes limited due to the capture of interferences from noisy environment in case mounted outside the transformer. By placing a number of acoustic sensors on the tank surface of the transformer the detection and localization of PD can effectively be performed. Fig. 1 illustrates the locations of acoustic sensors on the transformer tank surface.

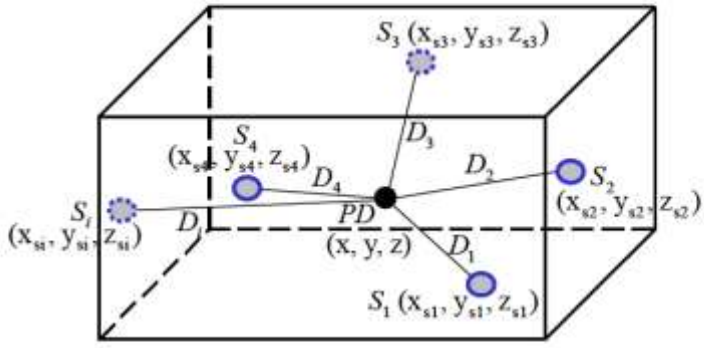


Figure 1: External acoustic sensors (S_i) on the surface of the transformer tank with located PD inside. The distances are represented as D_i in Cartesian coordinates.

Generally, the signals emanating from PD travels on direct path and spends a time called the arrival time. Finally, this signal is captured by acoustic sensors. In fact, the signal arrival time to each sensor as shown in Fig. 2 is entirely different due to the positional variation of sensors. This data on time lag between the sensors are used as input in the PD localization algorithms.

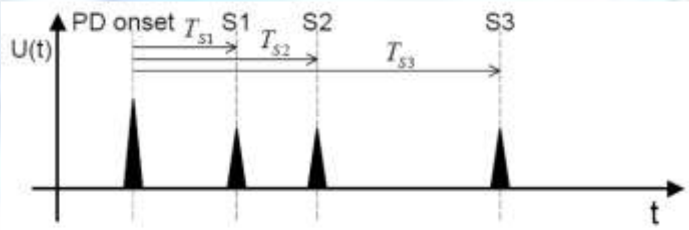


Figure 2:Time arrival of acoustic signals with PD as reference.

The spatial co-ordinate (x, y, z) of PD is determined following the well known sphere formula with the assumed velocity [2] is given by,

$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_s . T_{s1})^2$$
$$(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2 = (v_s . T_{s2})^2$$
$$(x - x_{s3})^2 + (y - y_{s3})^2 + (z - z_{s3})^2 = (v_s . T_{s3})^2$$

where T_{si} is the arrival time of arrival and v_s is the assumed velocity.
The radius of the sphere yields,

$$D_i^2 = (v_s . T_{si})^2$$

The complex nature of the acoustic signal often makes the accuracy of location measurement poor. Furthermore, the presence of signal attenuations, multiple reflections and refractions, and the mechanical noise due to core and transformer solid barriers also severely affect the precision [2].

Electrical Method

Figure 3 represents the frequency dependent equivalent circuit of transformer winding. This is a distributed circuit with RLC elements. The phase of the transfer function becomes zero at the critical frequency. Consequently, the winding surge impedance reaches infinity signifying an open-circuited transformer winding behavior. The regions around this criticality are classified into low and high frequency regime. In the low frequency (below critical frequency) region, the signal propagation along the winding follows travelling wave pattern and the transformer winding behaves as a transmission line. Thus, the technique of travelling wave can be implemented to localize the PD in this region.

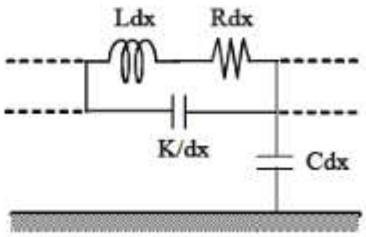


Figure 3: Simplified transformer winding model as equivalent circuit with resistance (R), inductance (L), shunt capacitance (C) and series capacitance (K).

However, in the high frequency region (above critical frequency), the winding behaves as capacitive ladder network and the technique of capacitive ratio can be used to identify the PD location. This technique can be implemented by analyzing the variation of the magnitudes of the two terminal signals ratio along the winding length. Transformer windings are categorized into ordinary and interleaved types. The frequency characteristics of each type of winding are determined by injecting a low voltage impulse with variable frequency (up to 10 MHz) at one end of the winding and its response is measured at the other end. The influences of the winding physical design is represented by the distribution factor, $\alpha = \sqrt{C/K}$.

The transformer windings in the frequency range of 1 to 10 MHz are tested using the above mentioned equivalent circuit [5]. Figure 4(a) displays the characteristic response of interleaved winding type in the high frequency limit (above 20 kHz). The observed response of constant magnitude clearly exhibits the capacitive ladder network type behavior of the winding in the frequency range of 20 kHz – 1MHz. Furthermore, below 20 kHz the windings reveal transmission line type performance. In interleaved winding arrangement, individual coils stacking and separation from insulating barriers results an increase in the series capacitance [3].

Figure 4(b) illustrates the characteristic response of the ordinary winding. It displays frequent variation in the magnitude above the critical frequency (1 MHz) and does not behave as capacitive ladder. However, in the low frequency limit it behaves as transmission line network with $\gamma = iw\sqrt{CL}$ and $Z = \sqrt{CL}$with γ as the phaseand Z the surge impedance. Travelling wave method is regarded as the best for localizing the PD source due to its high α value.

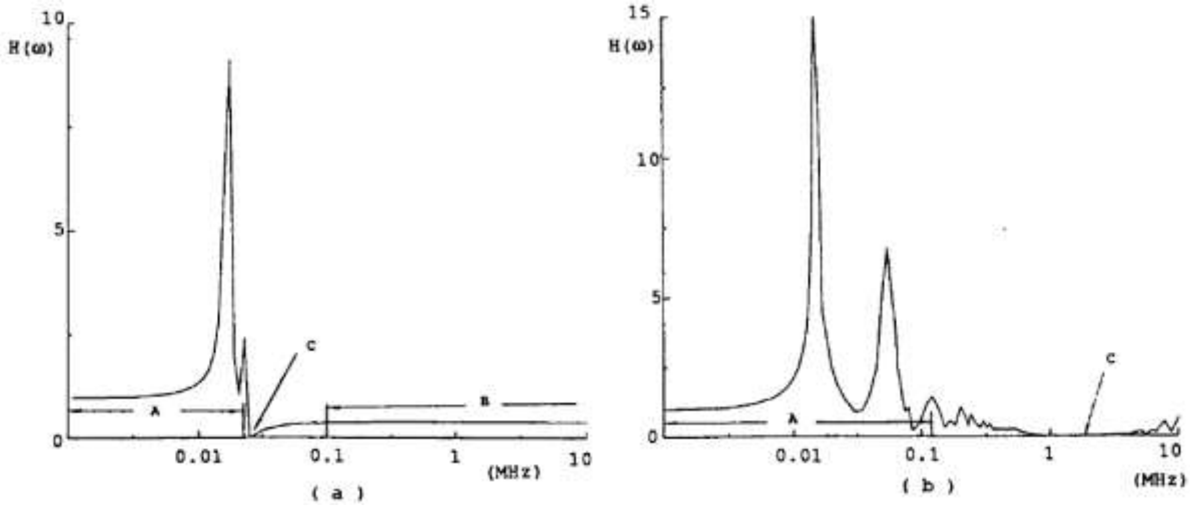


Figure 4: Frequency response of transformer windings in the three main regions such as travelling wave (A), capacitive ladder network (B) and critical frequency (C) for (a) interleaved winding and (b) ordinary winding.

The capacitive ratio method for the PD localization is limited its specific frequency range. Furthermore, the capacitive distribution method achieves very low PD location accuracy when the neutral terminal is directly grounded.

Travelling Wave Method

The travelling wave technique achieves superior performance especially for higher values of α in the range of 12-18. In this method, the transformer coil is divided into a number of sections and a PD source is injected in a given segment. The travelling wave is generated from the discharge source and gets propagated through all sections before reaching towards the winding ends. The peaks of the travelling wavesare then be monitored at the bushing and neutral terminals. The travelling time is considered as the time difference between the injection time and the arrival time at the winding terminal. Figure 5 shows the measured signals at both bushing and neutral ends of the transformer winding, where the PD is simulated as needle-plane electrode.

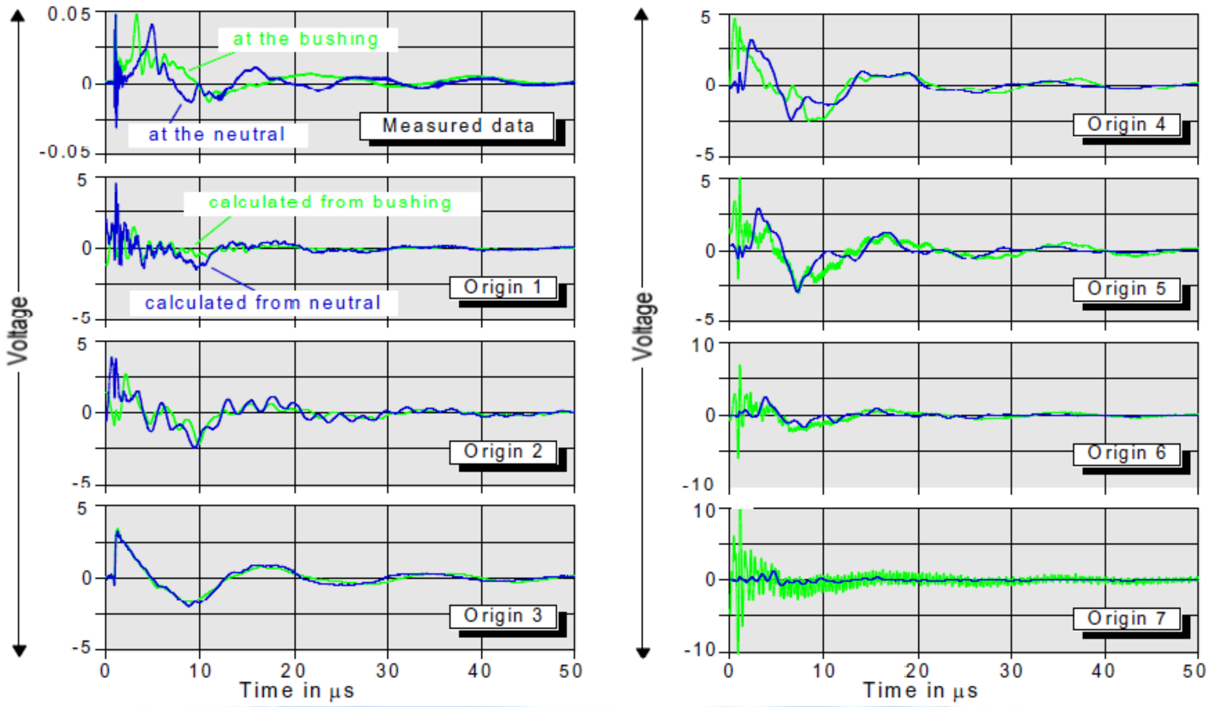


Figure 5: PD signal at the bushing and neutral terminal from the 1st origin to the 7th origin.

The location of a PD source in any section is determined by profiling the sources in all sections and their respective arrival times [4].Nevertheless, for low values of α in between 4-8, the accuracy for PD location measurement is very low. Besides, a precise time measurement is very complicated for very fast travelling wave involving various noises.

The Proposed Method

Frequency Spectrum Analyses

The spectral analysis in the frequency domain deals with the captured high frequency signal at the transformer terminals. The signal is processed via Fast Fourier Transform (FFT) for better understanding and acquiring useful information. FFT renders a more sensitive demonstration of the effect on the measured current signals compared to other PD localization methods. It is very effective for determining the PD signal in the predominant capacitive coupling zone of the transformer's winding frequency response [5].We used different frequency components in the transformer winding transfer function spectra to locate the PD source.

Methodology

Transformer Winding Model

Figure 6 depicts the model for transformer winding using distributed equivalent circuit consisting of frequency dependent RLC parameters in the form of capacitive and inductive branches. The capacitive branch (K) includes the effect of inter-turn and inter-disc capacitance. The inductive branch (L) contains the inductance for each turn of the conductor. The capacitance to the ground (C) encloses the capacitances of the core and the tank. The total length of the winding is l and C_B is the bushing capacitance.

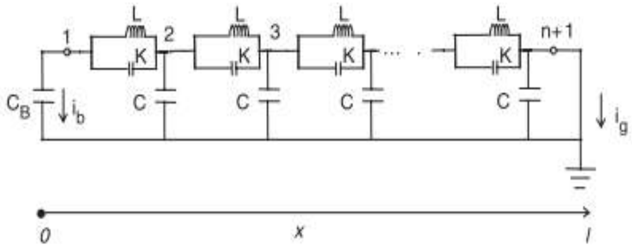


Figure 6: Equivalent circuit of a uniform transformer winding.

Transfer Function Characteristics

A simplified LC ladder network model is used to illustrate the transient behavior of the winding by assuming relatively smaller effects of conductor and dielectric losses. ReferringFig. 6, a current $i_b$at the bushing tap and i_g at the neutral end appears due to the occurrence of PD at position x_0 ($x = 0$). The expressions for the currents are written as,

$$i_b(jw) = \frac{c_B * r.\sinh(r(1-x_0))}{-c.\cosh(rl)+c_B .r.\sinh(rl)} . i_{pd}(jw)(1)$$

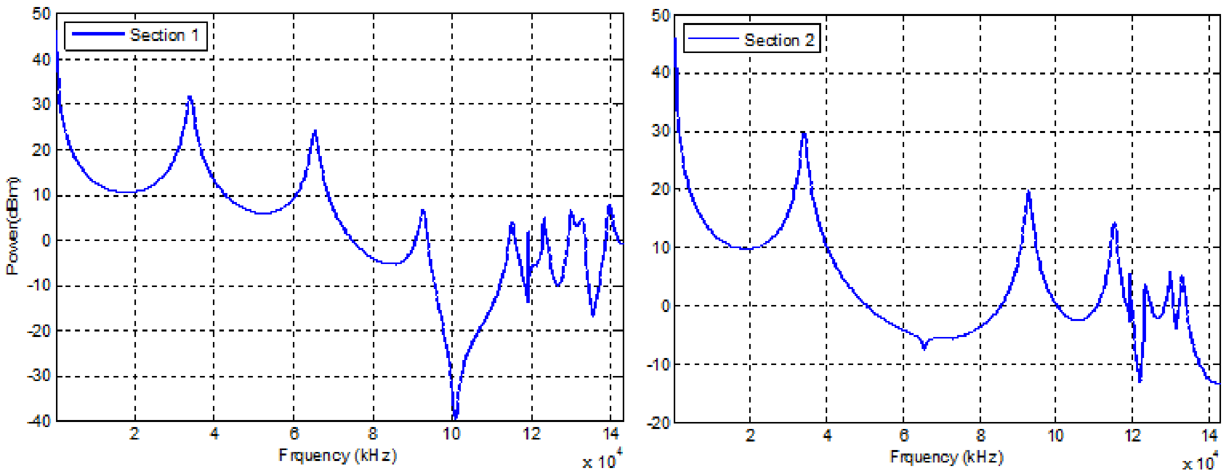
$$i_g(jw) = \frac{-c.\cosh(rx_0)+c_B .r.\sinh(rx_0)}{-c.\cosh(rl)+c_B /r.\sinh(rl)} . i_{pd}(jw)(2)$$

$$\text{where } r^2 = \frac{-lCw^2}{1-LKw^2}$$

The denominators in both equations are dependent on the physical parameters of the windingand the numerators are connected to the location of the discharge source (x_0) havingconstant pole frequencyand variable zero frequencies. It is worth noting that the frequency positions of poles are determined by the overall winding construction and those of zerosare directly associated with the physical location of the discharge source [6].

Frequency Spectra of Transfer Function

The simulation aims to realize the transfer functions at one-end (line or neutral end) of the winding terminals generated due to the injectionof PD source at different locations within the transformer winding. The position of the PD source is determined in terms of the number of turns from the line-end. A model of 22kV prototype interleaved winding [6] containing eight sections is developed using Simulink/Matlab. The line-end terminal is connected to the first winding turn and the neutral-end terminal to the eighth section. A current pulse mimicking the PD was consecutively injected into each section starting from the first one. The generated output currents are transferred to the Matlab code for further analyses using FFT signal processing. The frequency spectrum (response) as shown in Fig. 7(a)-(h) resulting from FFT exhibits various characteristic poles and zeros. It is clear from the figures that the zeros (negative peaks) are shifted to the right side as the PD source changed the location (sections number) along the coil.



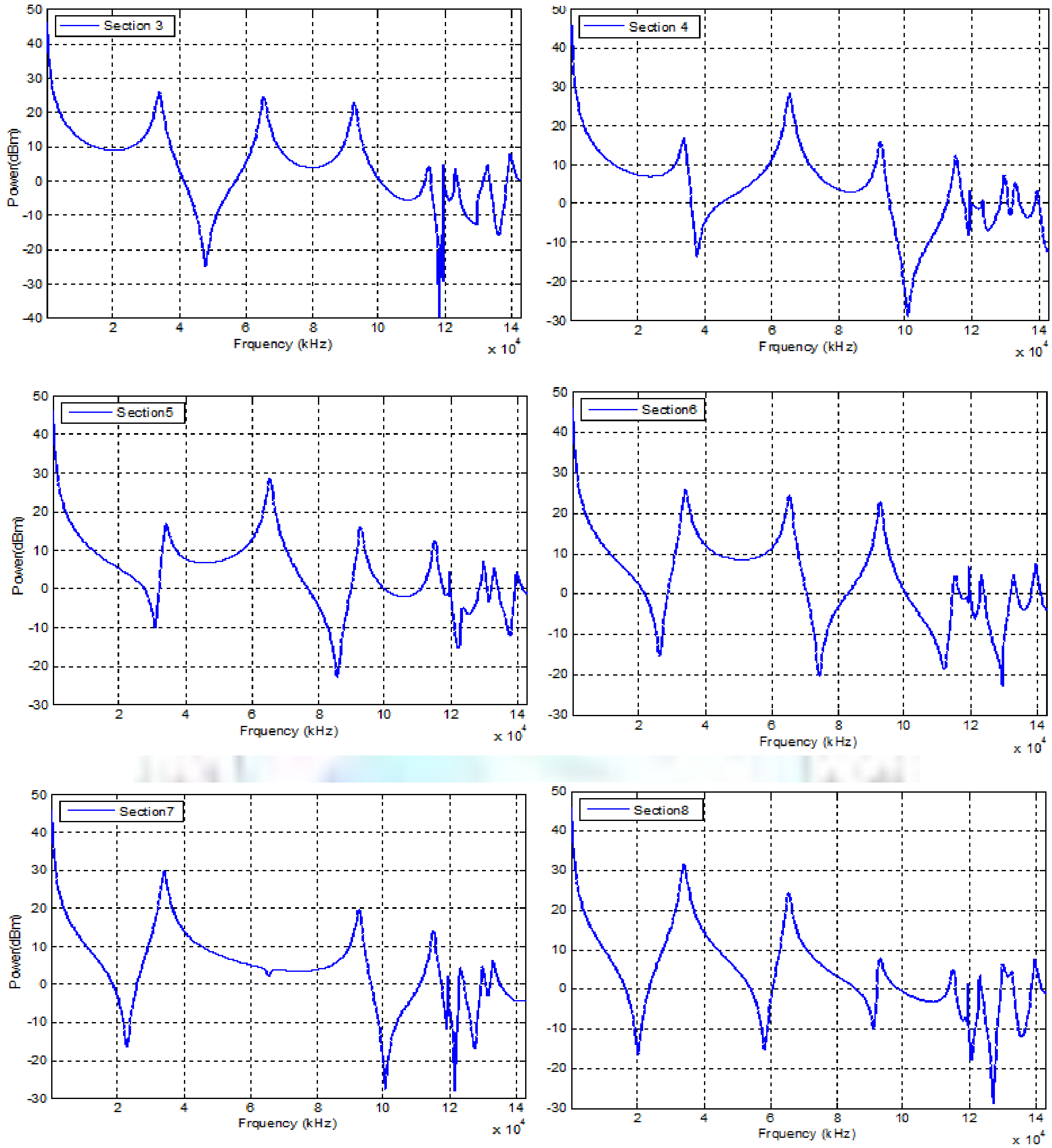


Figure 7: Frequency dependent transfer functions (dB) between line-end current and PD source for alleight winding sections

Results and Discussion

The transfer functions for different PD source locations as shown in Fig. 7 clearly displays occurrence of the crests (or poles). They occur at fixed frequencies and remain unaffected by the location of the PD source as summarized Table 4.1. Conversely, the troughs (or zeros) in the line-end transfer functions reveal an increase in the frequency as the PD source moves away from the line-end. The measured signal is found to be more oscillatory due to the propagation path of the winding for those PD which are located further away from the line-end. The measured PD signal at the terminal (transformer bushing) can be described based on the obtained frequency spectra. The frequencies corresponding to the first zero for second, fourth and sixth section appears at 20, 24, 31 and 47 kHz, respectively as listed in Table 4.2. This observation exhibit a direct correlation between the PD source location and the zeros of frequency. Indeed, the PD locations are determined on the basis of zero frequency differences. Furthermore, the accuracy in identifying the PD location can further be improved using analyses of second zero of frequency. Our observations on the locations of pole and zeros are in good agreement with previous report [8], which clearly shown in figure 8. The frequency dependent winding response for all poles corresponding to i = 1, 6, 8.

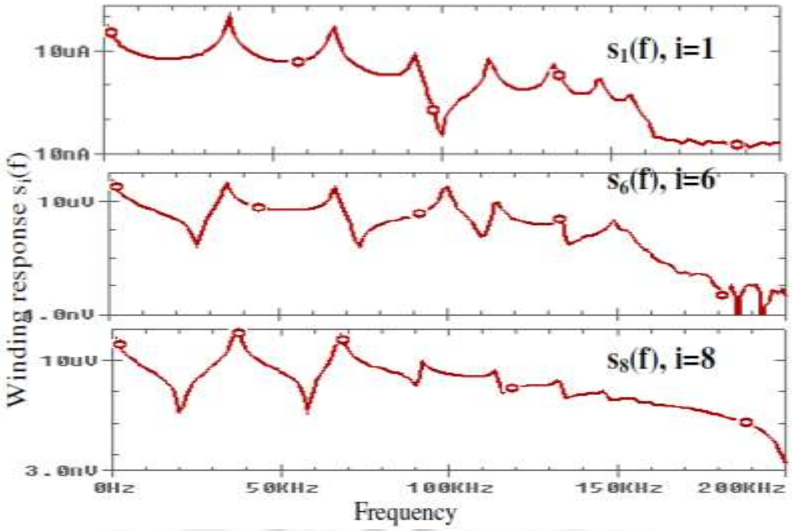


Figure 8: Frequency dependent winding response.

Table 4.1: The simulated results for the position of poles (P, kHz) in the transfer function frequency spectrum.

PD Sections	P1	P2	P3	P4	P5
1	33	65	93	113	119
2	33	-	93	114	119
3	33	65	93	113	119
4	33	65	93	113	119
5	33	65	93	113	119
6	33	65	93	113	119
7	33	-	93	113	119
8	33	65	93	113	119

Table 4.2: The simulated results for the position of zeros (Z, kHz) in the transfer function frequency spectrum.

PD Sections	Z1	Z2	Z3	Z4	Z5
1	20	58	91	-	120
2	24	-	-	102	122
3	27	-	74	112	122
4	31	-	86	-	123
5	38	-	102	119	-
6	47	-	-	119	123
7	65	-	-	-	123
8	-	-	101	119	-

Conclusions

Various PD localization methods based on the equivalent RLC circuit models are reviewed and their shortcomings are highlighted. A frequency spectrum method is proposed to overcome such weaknesses. The transfer functions at one-end (line or neutral end) of the winding terminals resulted from the injection of PD source at different locations within the transformer winding are computed. Simulink/Matlab is used on a model of 22 kV prototype interleaved winding having eight sections. A current pulse mimicking the PD is injected into every section and the response is analyzed via FFT signal processing. The characteristics of the transfer function between the line-end or neutral-end measuring terminals and the source of discharge is conveniently used to locate PD. The acquired crests and troughs in the frequency spectra are exploited to locate the occurrence of PD within transformer windings. The frequencies of the troughs (zeros) in the simulated spectra are found to increase with the movement of discharge away from the line end measuring terminal. The frequency location of the first zero is demonstrated to render an indication of the PD location within the transformer winding. It is further suggested that the second zero can also be utilized to enhance the location accuracy. The admirable features of the simulated results on frequency response suggest that our proposed method may constitute a basis for precise fault diagnosis using the localization of PD.

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References

[1]. J. Fuhr, M. Haessig, P. Boss, D. Tschudi, and R. A. King, “Detection and location of internal defects in the insulation of power transformers,” IEEE Transaction on Electrical Insulation,vol. 28, 1993,pp. 1057-1067.
[2]. S. Markalous, S. Tenbohlen and K. Feser, “Detection and location of partial discharge in power transformer using acoustic and electromagnetic signals,” Dielectric ad Electrical Insulation, IEEE Transactions on,vol.15,2008, pp. 1576 –1583.
[3]. R.E. James, B.T. Phung and Q. Su, “Application of digital filtering techniques to the determination of partial discharge location in transformers,” IEEE Trans. Electrical Insulation,vol.24, 1989.
[4]. E. Gockenbach and H. Borsi, “Transfer function as tool for noise suppression and localization of partial discharges in transformers during on-site measurements,” International Conference, 2008, pp. 1111-1114.
[5]. Z. D. Wang, P. A. Crossley and K. J. Cornick, “Partial Discharge location in power transformer the spectra of terminal current signals,” High Voltage Engineering, Eleventh International Symposiom, vol.5, 1999, pp. 58 – 69.
[6]. S. N. Hettiwatte, Z. D. Wang, and P. A. Crossley, “Investigation of propagation of partial discharges in power transformers and techniques for locating the discharge,”IEE Proceedings Science, Measurement andTechnology, vol.152, 2005, pp. 25-30.
[7]. M. A. Eldery, T. K. Abdel-Galil, E. F. El-Saadany and M. M. A. Salama, “Identification of partial discharge locations in transformer winding using PSD estimation,” Power Delivery, IEEE Transactions,vol. 21, 2006, pp. 1022-1023.
[8]. V. Jeyabalan,“Interpreting the frequency responses of PD signals for PD location in transformer windings Gram schmidt orthonormalized method,”IEEE 10th International, Conference, 2012,pp. 1-4.