Indonesian Journal of Electrical Engineering and Computer Science
Vol. 34, No. 3, June 2024, pp. 1434~1443
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v34.i3.pp1434-1443

Analysis of converter transformer pressboard insulation degradation under surge using mathematical morphology

Shrikant S. Mopari[1], Dagadu Shankar More[1], Anjali S. Bhalchandra[2], Pannala Krishna Murthy[3], K. M. Jadhav[4]
[1]Department of Electrical Engineering, Walchand College of Engineering, Sangli, India
[2]Department of Electronics Engineering, Government College of Engineering, Aurangabad, India
[3]Department of Electrical Engineering, Sri Chaitanya Institute of Technology and Research, Khammam, India
[4]Department of Basic and Applied Science, MGM University, Aurangabad, India

Article Info

Article history:

Received Sep 16, 2023
Revised Jan 11, 2024
Accepted Mar 16, 2024

Keywords:

Atomic force microscopy
Converter transformer
Elevated temperature
Fast fourier transform
Frequency domain spectroscopy
Mathematical morphology
Pressboard insulation

ABSTRACT

Nowadays, with the significant expansion of industrial growth, the bulk power requirement can only be satisfied through high-voltage direct current HVDC transmission. The converter transformer is the utmost vital part of the HVDC transmission. Pressboard insulation is most commonly used as inter-disc insulation in converter transformers. During working conditions due to elevated temperature and different operational stresses, insulation material gets deteriorated. It may cause a risk to the life of the converter transformer. The effects of elevated temperatures as well as frequency on pressboard insulation of the converter transformer are examined in this study. The condition evaluation and morphological changes in pressboard insulation at elevated temperatures can evaluate with the help of frequency domain spectroscopy (FDS) and atomic force microscopy (AFM) techniques. The impact of elevated temperatures on insulation material can be analyzed based on surface roughness and dielectric parameters. In MATLAB Simulink environment, a dual winding single-phase converter transformers valve side star winding 60 discs model is constructed for impulse test. Based upon arrival time and velocity of traveling wave, insulation degradation location can be identified by using mathematical morphology. The simulation results demonstrate that the suggested method can notably located degradation across disc winding.

Corresponding Author:

Shrikant S. Mopari
Department of Electrical Engineering, Walchand College of Engineering
Sangli, India
Email: mopari1977@gmail.com

1. INTRODUCTION

Due to the drastic increments in industrial growth and large requirement for electrical energy, high voltage direct current transmission (HVDC) is most constructive solution to transfer huge amounts of power for long distances. In HVDC, among all the devices the converter transformers play a dynamic role in bulk power transmission. Different stresses such as AC, DC, and AC-DC composite as well as reversal of polarity due to faults also add considerable impact on insulation material of converter transformer. Due to the above aspect the converter transformerinsulation structure is different than the conventional power transformer.

Thus, insulation is the key element that determines the life of the converter transformer. Various studies reported that the surges and voltage stresses on the winding insulation are the prime causes of breakdown of converter transformer [1]. The international council on large electric systems (CIGRE) reported that near about 22% of the convertertransformers failures were occurred because of the winding damage. The statistical data of probable causes of converter transformer failure up to 2012 are illustrated as shown in Figure 1 which reported that mechanical failures are mostly related to bushings and load tap changers. Still, dielectric and thermal failures continue to be dominant causes for the outage of the converter transformers [2].

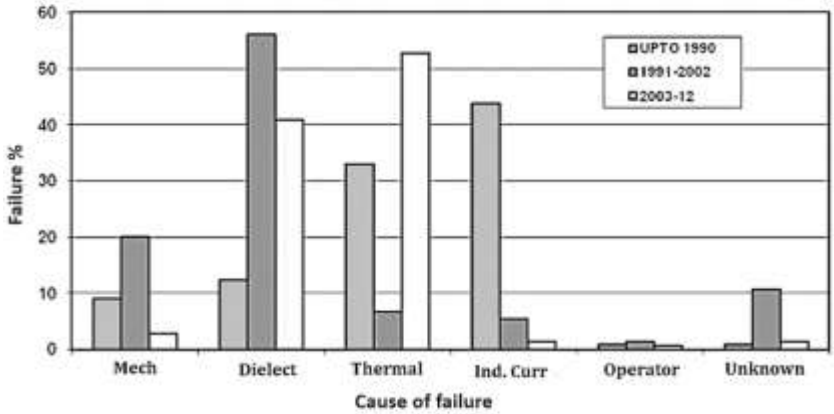

Figure 1. Probable cause of converter transformer failures (as per CIGRE AG B4-04)

Early, in the 1990s, return voltage measurement (RVM) [3] and polarization and depolarization current (PDC) methods [4]. Time domain-based dielectric diagnostic methods were the windiest used for assessment of the transformer insulation [5]. However, the frequency domain spectroscopy (FDS) technique provided more advantages over time domain based, due to its on-site insulation diagnosis, hence became more popular [6].

In this aspect, the researcher [7] utilized atomic force microscopy (AFM) images, based on DP values researcher has investigate the electrical as well as mechanical stresses and physical structure of paper insulation. The thermal aging of pressboard insulation examines by scanning electron microscope (SEM), and X-ray diffraction analysis (XRD) [8]. The dielectric loss tangent (tan δ) curve discriminates effect of moisture as well as aging on OIP insulation. During low-frequency regions, the extraction of tan δ parameters is more persuade by aging effect while moisture acts as the principal cause during high-frequency regions [9]. In addition, the researcher in the paper [10] investigated experimental and simulation analysis of breakdown characteristics of OIP and time variables of given impulse lightning voltage. The dielectric current plays a vital role that contributes to the breakdown characteristics.

Sima *et al*. [11] have utilized atomic force microscope observation in addition to frequency-domain spectroscopy to investigate the impact of surface morphology and dielectric property due to the lightning impulse accumulative effect. Thus, the practical analysis confirms that the accumulative effect can lead to surface roughness and dielectric parameters which can create a considerable impact on polar products, fiber deformation. Morshuis *et al*. [12] presented a review of exact stress conditions for a HVDC systems subjected to specific operating conditions, leading to an accelerating degradation process that is ultimately responsible for early insulation breakdown. Gómez *et al*. [13] analyses stress produced with the help of a lumped parameter model. The transformer winding turn-to-turn capacitance matrix can be determined by electrostatic simulation utilizing the FEM method. The winding stresses are generally larger for the initial and ending portion of the winding part with the largest stress magnitude being three times the dielectric strength of air. Saha and Yao [14], an experimental study of the wave process in the winding of UHVDC converter transformers by the scale-down model is conducted with the help of similarity theory. The proposed model computes potential gradient distribution with a 20% deviation between the tested and simulated value.

With the above, the researcher has investigated surge propagation and potential distribution in UHVDC converter transformers; capacitance parameters play vital role in determining initial potential distribution and production of core loss can slightly decrease maximum potential of each node [15]. Some literature also discusses transient voltage distribution across the converter transformer. The author utilized the an soft FEM software method to find out capacitance parameters. Moreover, gradient voltage for star winding occurs at the initial portion and the magnitude is higher than delta winding [16]. The usage of 12-pulse converters in HVDC transmission systems results in the dominating harmonic orders, the 11th and

13th, which are mostly to blame for scorching the insulation and early transformer breakdowns. Using ETAP modelling software, the researcher [17] demonstrated a novel way to mitigate harmonic distortions in third rail electrical systems. However, in order to reduce reactive volt-Ampere absorption as well as harmonic contents, researcher [18] proposed a modified converter topology.

The researcher analyzed an equivalent circuit model of a single-phase converter transformer with dual winding and used the 2D finite element technique (FEM) to extract the parameters from the electric field simulation [19]. The author suggested a unique technique that uses wavelet transform with 99.3% effectiveness for fault location to distinguish between different fault states and detect line faults in HVDC transmission [20]. To detect motor faults, the multi-resolution wavelet analysis is applied with the signal frequency corresponding to the peak of each power spectrum [21].

A comparison study for more accurate fault location based on factual data for transmission lines was presented by the researcher [22]. After looking at a number of fault detection techniques, the researcher discovered that the wavelet transforms with Biorthogonal 2.2 as the mother wavelet provides a greater level of accuracy for early defect detection. In the MATLAB environment, the researcher used discrete wavelet transform (DWT) and Fast Fourier Transform (FFT) analysis to compare the localization of faults in a double-ended transmission line. For defect identification, the discrete wavelet transform (DWT) produces reliable results with a maximum error of 0.25%, which is 0.6% smaller than the error found with FFT analysis [23]. Using the daubechies (Db4) wavelet as the mother wavelet, it is possible to discriminate between the islanding and non-islanding problems in power systems. A framework for choosing parameters for DG operation is provided by the study [24].

The researcher examined the use of a traveling wave fault localization technique to identify faults in a loop distribution system using single ended fault detection. The suggested technique may be implemented in a 10 KV distribution system with a distance location accuracy of 99.7% and a signal-to-noise ratio of 30 db [25]. Chiradeja and Ngaopitakkul [26] presented a technique for identifying and pinpointing winding to ground problems in power transformers. This approach utilizes wavelet analysis and a backpropagation neural network (BPNN), achieving an impressive overall efficiency of over 95%.

An assessment of surface roughness (Ra) in incrementally manufactured components using various image processing techniques. This approach categorizes photographs into three distinct groups according to the extent of surface roughness, using the Euclidean distance method, the Hamming distance method, and the Wavelet-based method. The findings indicate that the wavelet-based approach has achieved the greatest classification effectiveness of 95.4%. The hamming and euclidean distance approaches provide classification efficiencies of 78.39% and 81.48% respectively, as reported in reference [27].

The suggested technique utilizes phase current and is based on morphological gradient wavelet (MGW) to detect incipient faults. It specifically focuses on identifying fault-induced or operation-induced transients and uses their unique properties to identify the incipient faults. The efficacy of the suggested approach is assessed using data obtained from PSCAD/EMTDC. Furthermore, to validate the suitability of the suggested approach, various disruptions resulting from enduring faults, capacitor bank switching, load variations [28]. Scanning electron microscopy investigation reveals a significant reduction in the diameter of cellulose fibers in the solid insulating material when submerged in mineral oil. Additionally, there is observable evidence of bond breakage [29].

Abdullah *et al.* [30] presented a novel method for utilizing wavelet de-noising phenomena to identify partial discharge measurement data. By using db2 as the mother wavelet, the researcher was able to improve the measurement accuracy of partial discharge. The effectiveness of pre-processing filters for images in real-time noise reduction from transformer oil images taken at different temperatures. This study found that the non-local means filter outperformed other filtering techniques in terms of results [31]. It is possible to precisely detect the converter transformer winding deterioration locations where pressboard insulation is impacted by using digital image processing techniques. This will help shorten power outages' length [32].

In order to reduce the length of power outages, it is therefore extremely difficult to identify the earliest signs of inter-disc insulation breakdown inside the converter transformer winding. This work presents a novel approach to identify and localize insulation breakdown in disc windings using mathematical morphology. The neutral current waveform may be assessed by computer simulations, and travelling wave techniques can be employed to show the exact location of insulation degradation brought on by applied impulse.

2. EXPERIMENTAL SETUP AND CHARACTERIZATION

The 10 mm circular oil-impregnated pressboard samples are pre-heated to 110 °C for a whole day. The samples are held in a vacuum at pressures between 25 and 50 mbar to eliminate the moisture content. Once more, 110 °C is applied and maintained for 8 hours, and as per standard, the vacuum is also maintained for 6 hours. The sample is progressively chilled to 60 °C before the oil impregnation procedure is initiated.

Lastly, samples are stored in glassware that is sealed and dry. Oil-impregnated pressboard was prepared using an experimental setup at Vivid Grid Solutions Ltd., E-106, Waluj MIDC, Aurangabad.

Using the PSM 1735, Newtons4th Ltd., impedance analyzer, studies of the various dielectric properties, including AC conductivity, real and imaginary portions of permittivity, and tanδ, were conducted as a function of higher temperatures at 50, 70, 90, 110, and 130°C and frequency. The output frequency range of the system is 10μHz to 35 MHz. The applied voltage was a sinusoidal AC waveform of 2.5 volts. The dielectric parameters—the dielectric loss and relative permittivity—are determined using the phase difference, applied voltage, and applied current. In this case, an investigation of the dielectric response is carried out for frequencies in the range of 1 Hz to 10 MHz. The method used to prepare the sample using the experimental setup is depicted in Figure 2.

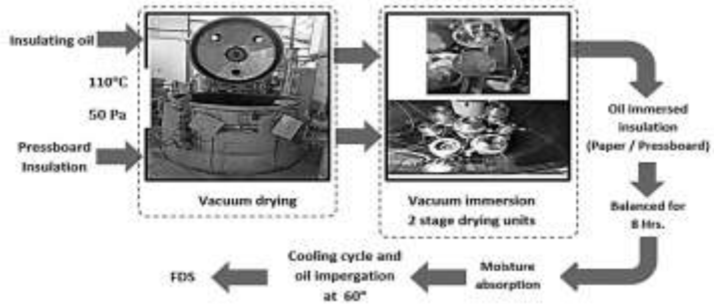

Figure 2. Experimental setup and flowchart for sample preparation

3. RESULTS AND DISCUSSION

3.1. Atomic force microscopy image-based study

The performance of inter-disc pressboard insulation is significantly impacted by variations in high temperatures and frequency. Atomic force microscope (AFM) observations are used to study the micro damages on the insulating surface induced by extreme temperature changes. In order to analyze surface degradation on pressboard insulation, AFM pictures are gathered at different temperatures. The samples are subjected to temperature changes every 20 °C in the range of 50 °C to 130 °C, with frequency variations ranging from 1 Hz to 10 MHz assuming homogeneous deterioration, two locally relevant locations around the sample centre are randomly selected and subjected to AFM testing.

The AFM image of the pressboard insulating sample at different temperatures is displayed in Figure 3. Regarding the virgin sample, there isn't a noticeable protrusion on its surface. The temperature rises, some surface fissures form, and greater swellings with appreciable increases in protuberances than in virgin samples appear on the surface. Using AFM pictures, the topography of temperature-aging samples was examined. Following the completion of the FDS procedure, AFM image datasets are gathered from the BARC in Mumbai. Suitable insulation images are obtained using the AFM instrument PARK XE-7, which has a scan window size of 3x3 µm and a scan rate of 0.5Hz.

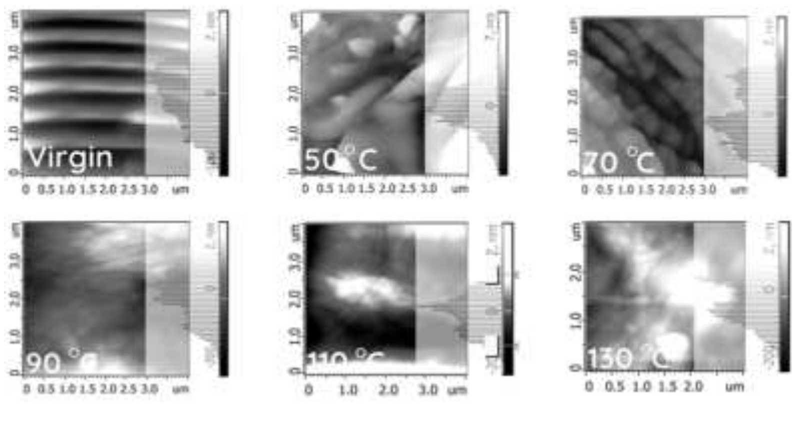

Figure 3. AFM images of the pressboard insulation sample at various temperatures

When compared to a virgin sample, the average roughness rises 19.71%, 46.63%, 46.06%, 51.50%, and 66.73% times at higher temperatures of 50, 70, 90, 110, and 130 °C, respectively. Statistical parameters at different temperatures are displayed in Table 1.

4. ANALYSIS OF CONVERTER TRANSFORMER INSULATION DEGRADATION

The specifications of a single phase, 315 MVA, 230/123/213 kV dual winding converter transformer were evaluated using the ANSYS Maxwell programme. The exact location of inter-disc pressboard insulation degradation is found using the mathematical model of a 123 kV star winding. This is achieved by measuring the neutral current under the 100 kV, 1.2/50µsec impulse, as seen in Figure 4. The insulation degradation of the converter transformer winding is examined using the FDS data at 50 Hz and an elevated temperature of 110 °C. The neutral current of the converter transformer is displayed at different disc regions in Figure 5.

The steep wavefront slope stresses the first section of the winding during the abnormal operation, resulting in a little uneven voltage distribution at the first part of the converter transformer winding. Neutral current waveform is altered when insulation degradation occurs at the transformer winding. Thus, it is very challenging to identify the changes by comparing various waveforms due to their superimposed nature in the time domain.

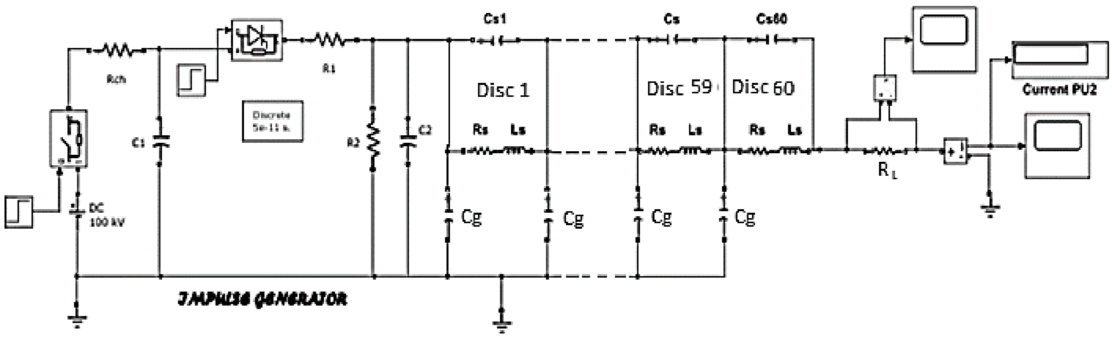

Figure 4. MATLAB Simulink model of 60 disc of 123 kV valve side winding

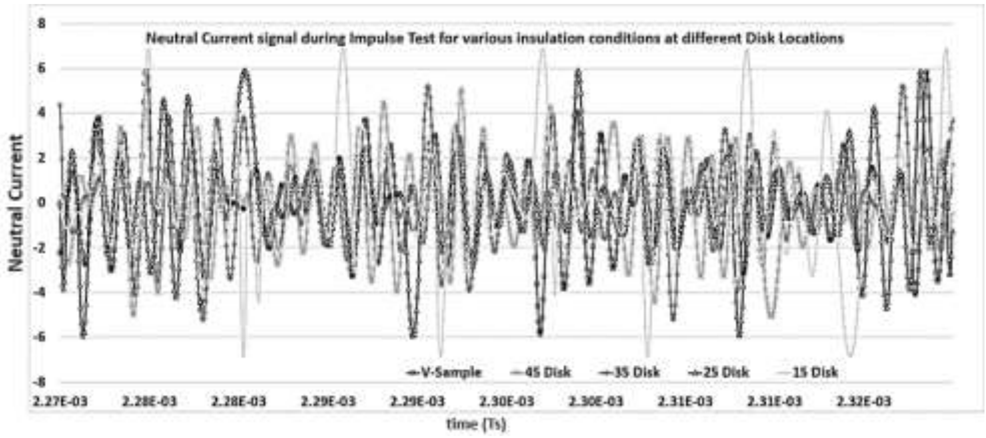

Figure 5. The neutral current of the converter transformer at various disc locations

4.1. FFT analysis

The insulation degradation analysis using FFT is carried out in MATLAB Simulink environment. A doubledtraveling wave-based fault detection technique for determining insulation degradation of the converter transformer is developed. As per the location of the insulation degradation the dominant frequency will vary between 100 KHz to 200 KHz. Fault distance is detected by capturing the neutral current and analyzed using fast fourier transform (FFT). Figure 6 shows FFT analysis of neutral current with degraded insulation at various discs of converter transformer.

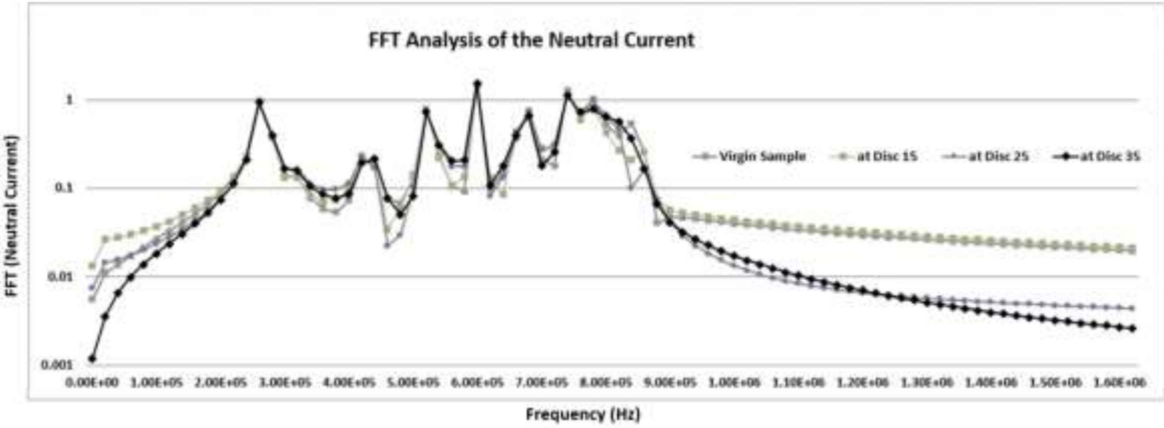

Figure 6. FFT analysis of neutral current with degraded insulation at different discs of converter transformer

4.2. Analysis of pressboard insulation degradation by mathematical morphology

To identify changes in neutral current, MM analysis is carried out and the location can be extracted based on the traveling wave phenomenon. When the impulse is applied across degraded insulation of the converter transformer winding, it can generate numerous frequency components which can carry very sensitive fault information. The neutral current is recorded for varied insulation degradation conditions over the converter transformer winding. After reaching to steady state neutral current is analyzed using MM.

The dilation and erosion operations are performed on the capture of neutral current waveforms. Here, the signal and structuring elements are represented by f and g respectively. The dilation and erosion of a signal f(x) processed by g(s) are defined as (1) and (2):

$$(f \oplus g)(x) = \max s\{f(x + s) + g(s)\} \quad (1)$$

$$(f \ominus g)(x) = \min s\{f(x - s) - g(s)\} \quad (2)$$

Where $(x + s),(x - s) \in D_f$ and $s \in D_s$; D_f and D_s are the definition domains of f(x) and g(s), respectively. The opening off by g, denoted by $f^\circ g$ and Closing is the dual operation of opening and is denoted by $f \bullet g$.

$$f^\circ g = (f\, \Theta\, g) \odot g \quad (3)$$

$$f \bullet g = (f \odot g)\, \Theta\, g \quad (4)$$

Lastly, to clean the artifacts before use for digital analysis the signal is normally subjected to opening and closing operations. Thus, all predominant frequency components are identified by MM to analyze a neutral current waveform due to insulation degradation. The generated traveling wave contains dominant frequency components that travel across both ends of the winding. The transformer winding has frequency dependent parametric nature, each component travels at a different velocity. The traveling velocity and characteristic impedance are calculated using as (5) and (6).

$$Z0 = \sqrt(L/C) \quad (5)$$

$$W0 = 1/\sqrt(LC) \quad (6)$$

Hence, Z_0 is found to be 122.71Ω for healthy conditions and 128.86Ω for insulation degradation. Similarly, travelling velocity W_0 is calculated as 5.45×10^6 red/secand $5.732\text{x}10^6$red/secrespectively.

Refraction and reflection will occur at the degraded insulation point, which can be considered as discontinuity point. Thus, the generated reflected and refracted wave will be propagated along the transformer winding, and the time gap between two consecutive peaks is utilized to determine the approximate location of the converter transformer winding across insulation degradation as shown in Figure 7. The sampling time is considered as 0.5 nano-sec throughout the simulation. From Figure 7, based on the gap between the two consecutive peaks, the dominant frequency components for insulation degradation location are presented. Figure 8 shows that the dominant frequency due to the insulation degradation will consciously be increasing in nature. In the virgin sample, the dominant frequency is around 113 KHz, and for degraded insulation at 15 discs, the frequency is about 120 KHz. Similarly, degraded insulation at 25 and 35 discs is about 130 KHz and 142 KHz respectively. The distance can be calculated using as (7).

$$Distance\ = (1/\sqrt{LC})x\ \Delta t\ x\ (sampling\ time/2) \tag{7}$$

Where: Δt: Time gap between two peaks
Table 1 shows absolute average percentage error of various location of insulation degradation of the converter transformer can be calculated with the help of (7).

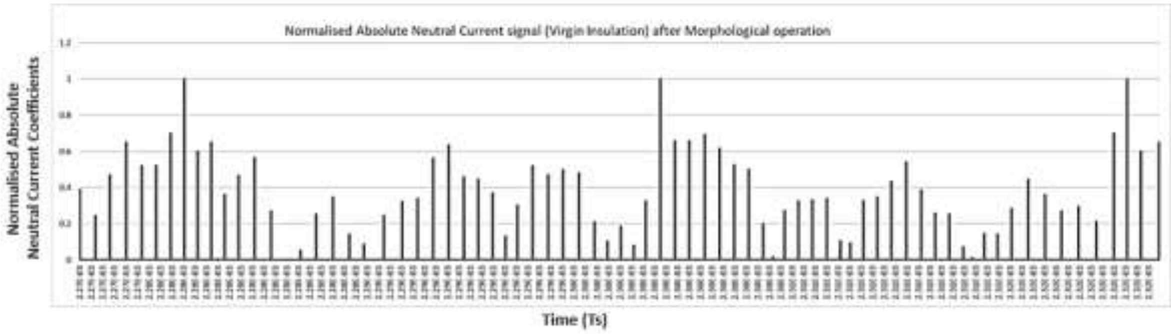

Figure 7. Analysis of neutral current using mathematical morphology

Table 1. Absolute average percentage error of various location of insulation degradation

Time gap between two consecutive peaks	43684	35705	26125	18752	11165
Actual disc number	60	45	35	25	15
Disc no. as per calculation	59.62	48.73	35.66	25.59	15.24
Absolute percentage error	0.6333	8.28	1.88	2.36	1.6

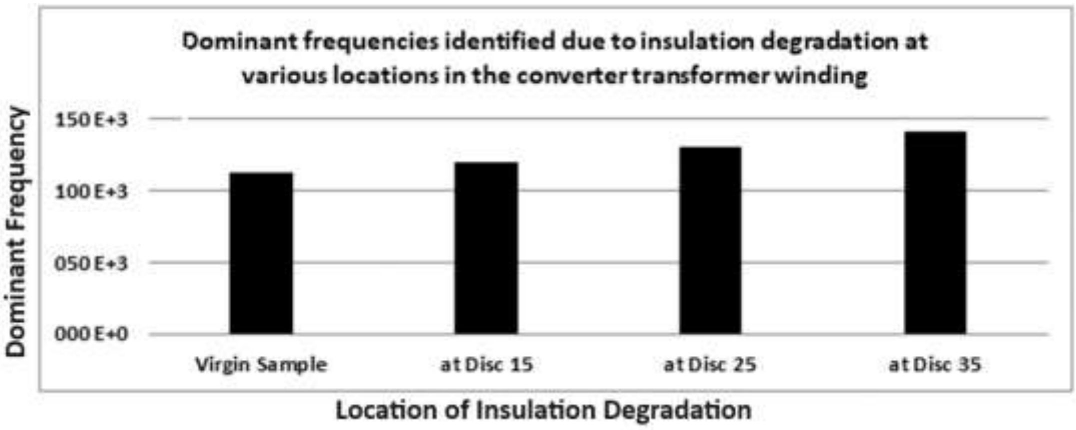

Figure 8. Dominant frequencies identified due to insulation degradation at various locations in the converter transformer winding

Thus, the precise location of insulation degradation across the winding of the converter transformer can find out with the help of MM. The neutral current capture at various locations and the time gap between two consecutive peaks is utilized. The exact insulation degradation can be identified with a maximum percentage error of 8.28% and a minimum percentage error of 1.6% across the converter transformer winding.

5. CONCLUSION

The pressboard insulation performance is considerably governed through the change in frequency and increased temperature. The FDS with elevated temperatures results in micro-morphological irreversible changes within the insulation structure and it is demonstrated by studying AFM images. The average and RMS value of roughness of the insulation surface will progressively increase with the elevated temperatures. The insulation degradation evaluation is completed throughout 60 discs winding model of valve side star winding of converter transformers using FFT in MATLAB Simulink environment.

A frequency domain-based fault detection technique for determining insulation degradation of the converter transformer is developed in this paper. The insulation degradation is detected by capturing the neutral current and the distance of insulation degradation from the neutral point can be identified by frequency domain using fast fourier transform (FFT) by considering the dominant frequencies of the waves. The current is also analyzed by using mathematical morphology to identify the location of the insulation degradation. Simulation results show that good accuracy is achieved in identifying the location of the degraded insulation with a maximum percentage error of 8.28% and a minimum percentage error of 1.6% across the converter transformer winding. Thus, the mathematical morphology can be effective to find the location of the insulation degradation between the discs of the converter transformer winding to reduce outage time.

ACKNOWLEDGEMENTS

The authors express their gratitude to Mr. Pravin Kadhane, a research scholar in the physics department of Savitribai Phule, Pune University, and Dr. R C. Kamble, an Assistant professor, for their recommendations and unwavering support during the experimental work.

REFERENCES

[1] CIGRE AG B4 -04, "HVDC LCC Converter Transformers Converter Transformer Failure Survey Results," From 2003 to 2012. Brochure No 617, pp. 54, 2015.

[2] Jwg a2/B4.28, "HVDC Converter Transformers. Design Review, Test Procedures, Ageing Evaluation and Reliability in Service," *CIGRE brochure* no. 406, pp. 338, 2010.

[3] G. M. Urbani and R. S. Brooks, "Using the recovery voltage method to evaluate aging in oil-paper insulation," in *IEEE International Conference on Conduction & Breakdown in Solid Dielectrics*, pp. 93–97, 1998, doi: 10.1109/icsd.1998.709234.

[4] T. K. Saha and Z. T. Yao, "Experience with return voltage measurements for assessing insulation conditions in service-aged transformers," *IEEE Transactions on Power Delivery*, vol. 18, no. 1, pp. 128–135, Jan. 2003, doi: 10.1109/TPWRD.2002.803722.

[5] T. K. Saha, "Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 10, no. 5, pp. 903–917, Oct. 2003, doi: 10.1109/TDEI.2003.1237337.

[6] T. K. Saha and P. Purkait, "Investigation of Polarization and Depolarization Current Measurements for the Assessment of Oil-paper Insulation of Aged Transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 11, no. 1, pp. 144–154, Feb. 2004, doi: 10.1109/TDEI.2004.1266329.

[7] R. J. Liao, C. Tang, and L. J. Yang, "Study on the microscopic figures of power transformer insulation paper under electrical and thermal stresses," *International Journal of Modern Physics B*, vol. 22, no. 20, pp. 3397–3403, Aug. 2008, doi: 10.1142/S0217979208048516.

[8] R. Liao, Chao Tang, Li-jun Yang, and S. Grzybowski, "Thermal aging micro-scale analysis of power transformer pressboard," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 5, pp. 1281–1287, Oct. 2008, doi: 10.1109/TDEI.2008.4656235.

[9] R. Liao, J. Hao, G. Chen, and L. Yang, "Quantitative analysis of ageing condition of oil-paper insulation by frequency domain spectroscopy," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 3, pp. 821–830, Jun. 2012, doi: 10.1109/TDEI.2012.6215085.

[10] W. Sima, P. Sun, M. Yang, J. Wu, and J. Hua, "Impact of time parameters of lightning impulse on the breakdown characteristics of oil paper insulation," *High Voltage*, vol. 1, no. 1, pp. 18–24, Apr. 2016, doi: 10.1049/hve.2016.0009.

[11] W. Sima, P. Sun, Q. Yang, T. Yuan, C. Lu, and M. Yang, "Study on the accumulative effect of repeated lightning impulses on insulation characteristics of transformer oil impregnated paper," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 21, no. 4, pp. 1933–1941, Aug. 2014, doi: 10.1109/TDEI.2014.004298.

[12] P. Morshuis, A. Cavallini, D. Fabiani, G. Montanari, and C. Azcarraga, "Stress conditions in HVDC equipment and routes to in service failure," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 1, pp. 81–91, Feb. 2015, doi: 10.1109/TDEI.2014.004815.

[13] P. Gómez, F. P. Espino-Cortés, and F. De León, "Computation of the dielectric stresses produced by PWM type waveforms on medium voltage transformer windings," in *Annual Report - Conference on Electrical Insulation and Dielectric Phenomena, CEIDP*, pp. 199–202, Oct. 2011, doi: 10.1109/CEIDP.2011.6232631.

[14] Z. H. Pu, J. J. Ruan, Y. D. Zhang, Z. Y. Du, and Q. J. Xie, "Wave Process in Scale-Down Model of UHVDC Converter Transformer under the Lightning Impulse Voltage," *IEEE Transactions on Magnetics*, vol. 51, no. 11, 2015, doi: 10.1109/TMAG.2015.2438155.

[15] S. He *et al.*, "New equivalent circuit model of UHVDC converter transformer winding for surge propagation investigation," *The Journal of Engineering*, vol. 2019, no. 16, pp. 2921–2925, Mar. 2019, doi: 10.1049/joe.2018.8448.

[16] H. Jia, X. Liu, S. Tian, L. Wang, and F. Gao, "Numerical calculation of the lightning transient voltage distribution on converter transformer winding based a dual winding model," *The Journal of Engineering*, vol. 2019, no. 16, pp. 3012–3016, Mar. 2019.

[17] D. S. Hoo, K. H. Chua, Y. S. Lim, B. H. Lim, M. B. Bonab, and L. Wang, "Mitigation of harmonic distortions in third rail electrical systems," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1, pp. 348–357, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp348-357.

[18] R. G. Shahin and H. D. Al-Majali, "Performance analysis of multi-level high voltage direct current converter," *International Journal of Electrical and Computer Engineering*, vol. 12, no. 2, pp. 1368–1376, Apr. 2022, doi: 10.11591/ijece.v12i2.pp1368-1376.

[19] S. S. Mopari, D. S. More, P. K. Murthy, and M. P. S. Chawla, "Estimation of Inductance and Capacitance Parameters of Single Phase Dual Winding Converter Transformer with FEM," in *Proceedings - 2022 IEEE 11th International Conference on Communication Systems and Network Technologies, CSNT 2022*, pp. 83–88, Apr. 2022, doi: 10.1109/CSNT54456.2022.9787659.

[20] P. K. Murthy, J. Amarnath, S. Kamakshiah, and B. P. Singh, "Wavelet transform approach for detection and location of faults in HVDC system," in *IEEE Region 10 Colloquium and 3rd International Conference on Industrial and Information Systems, ICIIS 2008*, pp. 1–6, Dec. 2008, doi: 10.1109/ICIINFS.2008.4798483.

[21] L. Wang, H. Guo, and S. Zhang, "Motor Fault Diagnosis Based on Wavelet Transform," *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 11, no. 9, Sep. 2013, doi: 10.11591/telkomnika.v11i9.3288.

[22] M. Parsi, P. Crossley, P. L. Dragotti, and D. Cole, "Wavelet based fault location on power transmission lines using real-world travelling wave data," *Electric Power Systems Research*, vol. 186, p. 106261, Sep. 2020, doi: 10.1016/j.epsr.2020.106261.

[23] A. H. Bin Mustapha *et al.*, "Fault location identification of double circuit transmission line using discrete wavelet transform," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 15, no. 3, pp. 1356–1365, Sep. 2019, doi: 10.11591/ijeecs.v15.i3.pp1356-1365.

[24] S. Raza, Amjad, M. Umer, and A. Khalid, "Analysis of power system parameters for islanding detection using wavelet transform," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 17, no. 3, pp. 1184–1193, Mar. 2019, doi: 10.11591/ijeecs.v17.i3.pp1184-1193.

[25] S. Myint and W. Wichakool, "A simple faulted phase-based fault distance estimation algorithm for a loop distribution system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 25, no. 1, pp. 14–24, Jan. 2022, doi: 10.11591/ijeecs.v25.i1.pp14-24.

[26] P. Chiradeja and A. Ngaopitakkul, "Winding-to-ground fault location in power transformer windings using combination of discrete wavelet transform and back-propagation neural network," *Scientific Reports*, vol. 12, no. 1, p. 20157, Nov. 2022, doi: 10.1038/s41598-022-24434-9.

[27] P. K. Gandla, V. Inturi, S. Kurra, and S. Radhika, "Evaluation of surface roughness in incremental forming using image processing based methods," *Measurement: Journal of the International Measurement Confederation*, vol. 164, p. 108055, Nov. 2020, doi: 10.1016/j.measurement.2020.108055.

[28] M. Huang, Q. Wu, X. Han, C. Mo, and L. Zhang, "Detection of Incipient Faults in Distribution Cables Based on Mathematical Morphology," in *2019 9th International Conference on Power and Energy Systems, ICPES 2019*, pp. 1–6, Dec. 2019, doi: 10.1109/ICPES47639.2019.9105453.

[29] T. Mariprasath, V. Kirubakaran, S. Madichetty, and K. Amaresh, "An experimental study on spectroscopic analysis of alternating liquid dielectrics for transformer," *Electrical Engineering*, vol. 103, no. 2, pp. 921–929, Apr. 2021, doi: 10.1007/s00202-020-01136-x.

[30] A. Z. Bin Abdullah *et al.*, "Wavelet based de-noising for on-site partial discharge measurement signal," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 16, no. 1, pp. 259–266, Oct. 2019, doi: 10.11591/ijeecs.v16.i1.pp259-266.

[31] C. M. Maheshan and H. Prasanna Kumar, "Performance of image pre-processing filters for noise removal in transformer oil images at different temperatures," *SN Applied Sciences*, vol. 2, no. 1, p. 67, Jan. 2020, doi: 10.1007/s42452-019-1800-x.

[32] S. S. Mopari, D. S. More, A. S. Bhalchandra, P. K. Murthy, K. M. Jadhav, and R. C. Kamble, "Health assessment of converter transformer pressboard insulation based on FDS and digital image processing," *Measurement: Sensors*, vol. 29, p. 100873, Oct. 2023, doi: 10.1016/j.measen.2023.100873.

BIOGRAPHIES OF AUTHORS

Shrikant S. Mopari received a B.E. degree from Sant Gajanan Maharaj College of Engineering, Shegaon, and M.E. degree in electrical engineering from Walchand College of Engineering, Sangli. He is currently working toward a Ph.D. degree in the Department of Electrical Engineering, Walchand College of Engineering, Sangli. India. He was a teaching experience of 20 years. In 2010, he joined the Government College of Engineering, Chhatrapati Sambhajinagar (Aurangabad). An Assistant Professor. His research interests include Power electronic, high voltage direct current transmissions (HVDC) and FACT. He can be contacted at email: mopari1977@gmail.com.

Dagadu Shankar More received the B.E. and M.E. degrees in electrical engineering from Walchand College of Engineering, Sangli. The Ph.D. degree in the Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India. He was in Industry for four years, where he was involved in the design and development of custom built low-voltage, high-current rectifiers. In 1990, he joined the Walchand College of Engineering, as a Lecturer, where he is currently an Associate Professor. His research interests include permanent-magnet axial and radial-flux machines and switched reluctance machines. He can be contacted at email: dagadu.more@walchandsangli.ac.in.

Anjali S. Bhalchandra received her Ph.D. in electronics engineering from S.R.T.M. University, Nanded, India, in 2004. She has scientific and technical background covering the areas of electronics and communication. Currently, she is professor of Electronics Department, and Principal Government College of Engineering, Aurangabad. Her research interest includes image processing, signal processing and communication. She has contributed in 100 plus papers in reputed journals and conference proceedings. Dr. Bhalchandra is a fellow of the Institution of Engineers, India and life member of Indian Society for Technical Education. She can be contacted at email: asbhalchandra@gmail.com.

Pannala Krishna Murthy has a Doctorate Degree in Electrical Engineering from JNTU, Hyderabad. Over 50 International Publications to his credit. The research areas include, Electrical power Systems, Power Electronics, Power Quality, Data mining, Optimization algorithms, Electrical Engineering material Characterization, Bio-Medical testing and analysis. Presently working as Principal, Sri Chaitanya Institute of Technology and Research w.e.f. 01.07.2019. He is also active in the R&D activity - serving as in association with CANORX® Software Services Pvt. Ltd., as Advisor Governing Counsel since 25th March, 2020. He can be contacted at email: krishnamurthy.pannala@gmail.com.

K. M. Jadhav presently working as Emeritus Professor (Physics) & Head of the Department at University Department of Basic and Applied Science, MGM University, Chhatrapati Sambhajinagar (M.S.) India and Formerly Senior Professor (Higher Grade) at Department of Physics Dr. Babasaheb Ambedkar Marathwada University, Chhatrapati Sambhajinagar (Aurangabad). Sir's specialization is in Solid State Physics, Nuclear Physics, Nano-Ferrites and Material Science. He has guided 52 Ph.D. Students, four granted patents and completed four research projects. Sir has citations 9148, h-index 57 and i-10 index 160. He can be contacted at email: drjadhavkm@gmail.com.