This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Health Analysis of Transformer Winding Insulation through Thermal Monitoring and Fast Fourier Transform (FFT) Power Spectrum

Muhammad Aslam[1], Inzamam Ul Haq[1], Muhammad Saad Rehan[1], Faheem Ali[2], Abdul Basit[1], Muhammad Iftikhar Khan[2] and Muhammad Naeem Arbab[2]

[1] US Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology, Peshawar, 25000, Pakistan
[2] Department of Electrical Engineering, University of Engineering and Technology, Peshawar 25000, Pakistan

Corresponding author: Muhammad Aslam (muhammad.aslam@uetpeshawar.edu.pk)

This work was supported by USPCAS-E, funded by the United States Agency for International Development (USAID), within the Applied Research Program.

ABSTRACT This paper presents a health analysis technique for transformer winding insulation through thermal monitoring and Fast Fourier Transform (FFT) power spectrum. A novel thermal model for the Kraft paper insulation of transformer is proposed by using the transformer's top-oil and winding hot-spot temperature models. The relationship between the temperature rise of oil inside the transformer tank and the winding insulation degradation are considered by utilizing the data-sets and daily load cycles of a 10/13 MVA, 132/11 kV, 50 Hz, ONAF grid power transformer. The model based on IEEE Guide for loading mineral-oil-immersed transformers is developed in Simulink. The hotspot temperature rise from the thermal model is used as a reference to analyze the winding insulation degradation in the form of high frequency partial discharges (PDs) upon the output parameters of the transformer. Using data analysis techniques, a correlation is presented between the load cycles and the hot-spot temperature through which the health status of the transformer winding insulation is estimated. Moreover, the high frequency transients were detected using the Fast Fourier Transform (FFT) spectrum analyzer tool in MATLAB. The preliminary study shows that high frequency PDs are detected for the overheated and deteriorated state of the winding insulation. The results show that the proposed technique is feasible for the health analysis of power transformers and successfully predicted the deterioration of the transformer winding insulation.

INDEX TERMS Fast Fourier Transform (FFT), Health Assessment, MATLAB Simulink, Power Transformer, Power Spectrum estimate, Partial Discharge, Thermal Monitoring, Winding insulation model.

I. INTRODUCTION

A. GENERAL BACKGROUND

Power transformer's health is an important aspect in defining the reliable operation of the power system. Any failure in power transformer will not only affect the reliable operation of the power system but also result in huge financial damage [1]. For the substation transformers (>100 kV), the most prone location to the failure are the power transformer windings [2], shown in Figure 1. The root cause of these failures is the winding insulation, therefore its real-time condition monitoring and health assessment is very crucial for power system operation.

Transformer insulation is the key element in defining the life expectancy of transformer i.e. the assessment of insulation is the assessment of transformer [3, 4]. The transformer insulation is mostly made up of oil and cellulose i.e. kraft paper [5, 6]. The kraft paper provides the electrical insulation to the transformer windings whereas the oil provides the thermal stability by acting as an insulation medium [7-9]. The quality of the kraft paper deteriorates both physically and chemically with nonlinear loads, transient voltage surges, switching and internal heating of the transformer caused by the heavy overloading [10-13], thus reducing the transformer life time. In the same way, the quality of the transformer oil deteriorates with moisture and oxidation[14, 15]. Hence the analysis of the failure percentage of large oil-immersed power transformer and their winding insulation is an important factor to assess the health of power transformers.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

B. LITERATURE SURVEY

Different variety of exquisite techniques have been proposed to monitor accurately and assess the health and life expectancy of the power transformers. Such as synthetic analysis method which is based on weight coefficients and association rule [16], Evidential Reasoning Technique [17, 18], Fuzzy logic [19], Sweep Frequency Response Analysis (SFRA)[20, 21], Genetic Neural Network (GNN) [22], and modern machine learning techniques [23, 24]. The predictive maintenance and transformer condition assessment offer a flexible and low cost solution [25]. But still there are some shortcoming in aforementioned methods; one them is the comprehensiveness and complexity they provide to the diagnosis process and therefore arises concerns regarding their accuracy and the completeness of their sampling data[26]. In [27], N'cho et al. reviewed the modern physiochemical techniques available for the condition assessment of the power transformer insulation. Fofana et al. [28] reviewed a number of some basic and advanced electrical-based test techniques for the problems related to winding turn to turn insulation. Moreover, Tenbohlen et al. [29] presented the applicability of different online and offline diagnostic and condition assessment techniques for power transformers in the recent years.

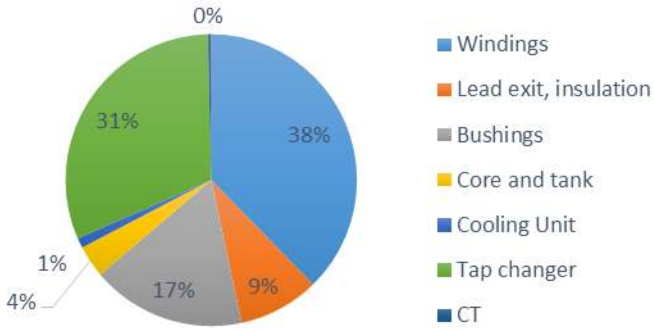

FIGURE 1. **Failure location of substation transformer [2].**

1) PARTIAL DISCHARGE APPROACH

In the recent years, the PD detection method is getting the attention of the researchers and several techniques have been adopted for the detection and measurement of PD discharges in the insulation system of electrical equipment. Those are the methods defined by the IEC 60279 [30], acoustic and electromagnetic signals [31], and optical [32] detection methods. Among these detection techniques, Ultra High Frequency (UHF) sensors are getting more attention to detect, locate and characterize the PD activity [33-38]. Due to its better immunity against external noise and potential of localizing faults, monitoring through UHF sensors was first deployed for the prognosis of power transformers in 1997 [39]. Since then, a lot of development has been done in this field and still more and more is needed to be done to further improve its accuracy and sensitivity. Electromagnetic waves (EM) radiated from the PD pulse are detected by UHF sensors, tends to undergo austere attenuation within the transformer and hence results in low sensitivity of the PD signals[40].The main contributing parameter in PD generation and the deterioration of winding insulation is the hot spot temperature (HST) of the windings. An accurate estimation of the winding HST is required to assess the better health of power transformer. It is believed as a critical limiting factor for transformer loading. Hence increasing the importance of knowing the HST at every moment of transformer operation with real load condition and ambient temperature. In order to better understand the phenomenon of PD inside the transformer winding insulation, the most cost effective, safe and a diverse approach is the computer based modelling and simulation approach.

2) SIMULATION MODELING APPROACH

Simulation models can portray an accurate estimation of the real-time behavior of any equipment and this approach is now getting quite popular and widely adopted by the industries for the condition assessment and estimation of the equipment [41]. A significant amount of work has been done on predicting the winding HST. The most commonly used hot spot thermal model is presented in clause 7 of IEEE loading guide manual [42]. Moreover, Swift *et al.* [43] suggested a methodology to use the IEEE clause 7 model based on the fundamentals of heat transfer theory. Susa *et al.* [44, 45] presented a more accurate thermal model of transformer by considering the dynamic load conditions. An analogous approach to [43, 46] has been used by Elmoudi *et al.* [47-49] to develop a simplified thermal-electrical equivalent mathematical models to calculate the real time top oil and hot spot temperatures of a substation transformer. The hot spot temperature has a direct effect on the mechanical and electrical strengths of transformer winding insulation. Utilizing the accuracy of the dynamic thermal models, the hot spot temperature can be used accurately to model the winding insulation for the transformer.

C. AIMS OF THE PROPOSED RESEARCH

This article aims to assess the power transformer's health status by tracking the hot-spot temperature and the transient incipient activities like partial discharges (PD) inside the winding insulation. PD in the transformer insulation is incipient in nature which rises gradually with the passage of time. If the necessary actions are not taken to control, can cause catastrophic failure and even a full damage to the unit. Transformer overloading and the increase in the top-oil and hotspot temperature have a direct relation to the development of PD in the transformer winding insulation. PD is an

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

alarming indication in the transformer winding insulation about the growth of some precarious activity inside the transformer tank. PD is the root cause in the deterioration of electrical and mechanical strength of transformer winding insulation. Therefore, it must be recognized in its initial stages, and the most common method used for this purpose is PD detection method. The estimation of the transformer winding insulation health status through thermal monitoring and the detection of high frequency PD will be the subject of this article. The main aims of this article are as follow:

1) To develop a novel winding insulation model for oil-immersed 10/13 MVA, 132/11 kV, 50 Hz substation transformer in MATLAB Simulink that employs the hot spot temperature from the dynamic thermal model of the transformer.
2) To develop a thermal algorithm to define three states of the insulation i.e. healthy state, deterioration state and complete breakdown (short-circuit) state based on the HST of the windings.
3) To present a correlation between the load cycles of the said transformer and HST, upon which the health status of the transformer winding insulation will be estimated.
4) To validate the deterioration state of the transformer winding insulation by detecting the high frequency spikes i.e. PDs in the transformer output through FFT spectral analysis.

The paper is organized as follow: the literature regarding the methods of transformer health assessment are briefly summarized in Section I. Section II, discuss the comparative analysis of the proposed methodology with other techniques. The methodology thermal monitoring and the winding insulation modeling is presented in Section III. The simulation results of the methodology are presented in Section IV. Finally, Section V concludes the research work.

II. COMPARITIVE ANALYSIS TO OTHER TECHNIQUES

The health assessment of power transformers is vast and significant topic and a lot of contribution and research has been done in this area. This paper mainly focuses on the thermal monitoring technique for the health analysis of transformer winding insulation. As most of the power transformer failures are reported due the windings, and the root cause of these failures is the winding insulation breakdown due to transformer overloading and unexpected voltage surges. Therefore, the scope of this study is restricted only up-to the condition assessment of the winding insulation of the transformer and the most recent and relevant literature is reported.

The basic approach for this purpose is to analyze the incipient activities like partial discharges inside the insulation. The valid and relevant approaches reported for the subject matter are; Partial discharge (PD)(IEC-60270), UHF PD measurement, Frequency Response Analysis (FRA), Frequency Domain Spectroscopy (FDS) and Thermal monitoring. The comparison to these state of the art approaches is made on the functionalities presented in Table 1. The main advantages of the methodology presented in this study are the robustness, simplicity and accuracy. Also it provides thermal and frequency analysis both at the same time. Since the data is taken from one transformer and after the development of the simulation model the validation has been done on the same transformer which might give rise to concerns of over-fitting. To address this concern, the model has also been applied to a prototype distribution transformer as well which can be seen in [57].

TABLE 1. Comparative analysis of the presented methodology to other applicable methods

METHODS	OFFLINE	ONLINE	THERMAL MONITORING	OFFSITE	SIMULATION MODEL	FREQUENCY ANALYSIS	COMPLEX
PD (IEC 60270)	✓	✓	×	✓	×	✓	✓
UHF PD	✓	✓	×	✓	×	✓	✓
FRA	✓	×	×	✓	×	✓	✓
(FDS)	✓	×	×	✓	×	✓	✓
Thermal monitoring	×	×	✓	×	✓	×	×
FFT based Thermal monitoring*	✓	✓	✓	✓	✓	✓	×

*: the methodology presented in this study, ✓: applicable, ×: not applicable

III. PROPOSED METHODOLOGY

A. THERMAL MONITORING

Thermal monitoring of power transformer is based on a thermal model of an electrical-thermal equivalent circuit, which works on the heat transfer theory of fundamentals [43]. To estimate the hot-spot temperature and its effects upon the winding insulation, a mathematical model is developed in Simulink. These models use the load current (pu) and ambient temperature (^{o}C) as a variable to analyze

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

the hot-spot and top-oil temperature rise. The hot-spot temperature rise is then used as a function to estimate the health status of the winding insulation. The block diagram of the overall thermal model of power transformer is shown in Figure 2.

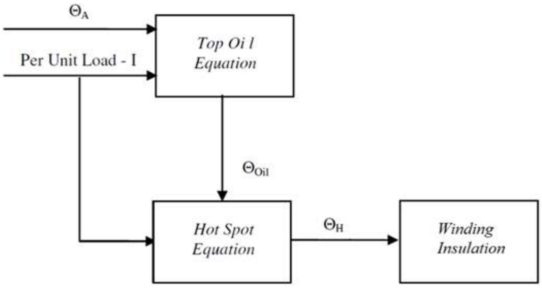

FIGURE 2. Overall thermal model of power transformer

The ambient temperature Θ_A and the per unit load cycles are the inputs to the system. By solving the top oil equation presented in [43], top oil temperature Θ_{oil} is taken whereas the hot spot temperature is evaluated by solving the hot spot equation of the transformer adapted from [43] and finally its effects are studied upon the insulation of the transformer windings.

Typically, oil is being used as coolant in power transformers. The oil takes up the heat generated due to losses inside the transformer and takes it into the heat exchangers i.e. oil-to-air cooler. The oil-to-air cooler then dissipates this heat to the surrounding through natural or forced flow. There is a great analogy between the thermal and electrical circuits as shown in Table 2. It is because of this similarities, the heat transfer problems can be solved through an electrical equivalent circuit.

TABLE 2. Thermal and Electrical quantities analogy adapted form [43]

THERMAL	ELECTRICAL
Heat transfer rate q, watt	Current, i A
Temperature Θ, ºC	Voltage, v, Volt
Thermal resistance R_{th}, ºC /watt	Resistance, R Ω
Thermal capacitance, joules/ºC	Capacitance, F

Thermal conductivity and heat capacity are the two important general properties of the transformer oil. These properties can be made specific to a particular volume of oil, and hence can be used as thermal resistance and thermal capacitance. According to the electrical laws for defining a resistance and capacitance, we have

$$v = i.R \quad \& \quad i = C.\frac{dv}{dt} \tag{1}$$

The corresponding thermal laws are;

$$\Theta = R_{th}.q \quad \& \quad q = C_{th}.\frac{d\Theta}{dt} \tag{2}$$

Where the symbols of equation (1) and (2) are defined in Table 1. The thermal resistance R_{th} for heat transfer case is non-linear, defined in [45]. Hence

$$\Theta = R_{thR}.q^n \tag{3}$$

Where R_{thR} is the rated value of thermal resistance R_{th} and n is the non-linearity exponent depends upon the transformer cooling method as shown in Table 3. Mostly the cooling modes used in power transformers are:

- ONAN (Oil Natural Air Natural)
- ONAF (Oil Natural Air Forced)
- OFAF (Oil Forced Air Forced)
- ODAF (Oil Directed Air Forced)

It should be noted that the non-linearity exponent is n if the moving fluid is air and m if it is oil.

TABLE 3. Exponent values for different cooling modes adapted from [9, 37]

TYPE OF COOLING	IEC		IEEE	
	n	m	n	m
ONAN	0.9	0.8	0.8	0.8
ONAF [1]	0.9	0.8	0.9	0.8
OFAF	1.0	0.8	0.9	0.8
ODAF	1.0	1.0	1.0	1.0

[1] The values adapted for this study.

B. NOVEL WINDING INSULATION MODEL

Windings are the most prone location of failure in power transformer. Almost, 38% of failures belongs to the windings of the transformer [2]. The main reason behind these failure is deterioration of transformer winding insulation. In fact, the health status of insulation is the health status of the transformer. Hence, it is an important aspect for the health analysis of power transformer. Mostly, Kraft paper is used as an insulation between the turns of transformer winding. For modelling partial discharge activity in the windings the most basic RC model has been used as shown in Figure 3.

Due to thermal degradation inside the insulation with the increase of internal temperature, a PD current i_{PD} has been considered. The equations for RC equivalent insulation model are;

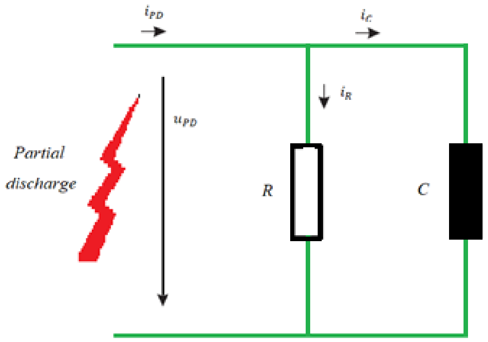

FIGURE 3. RC circuit for winding insulation modeling

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

$$i_{PD} = i_R + i_C \tag{4}$$

$$i_{PD} = \frac{u_R}{R} + C\frac{du_c}{dt} \tag{5}$$

$$C\frac{du_c}{dt} = i_{PD} - i_R \tag{6}$$

Where 'i_{PD}' is the PD current, 'R' is the resistance and 'C' is the capacitance of the insulation. The capacitance can be calculated for the insulation (Kraft paper) of both HV and LV windings by [50]

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{7}$$

Where ε_r = 4.4, is the relative permittivity of the insulating layer i.e. immersed oil Kraft, ε_o = 8.252 x 10^{-12} F/m is the relative permittivity of the free space [51], d is the thickness of the insulating layer and A is the area of the conductor of the windings. From current density of the windings the area of the conductor can be find out by the formula:

$$\delta_{wc} = \frac{I_{wc}}{A_{wc}} \quad or \quad A_{wc} = \frac{I_{wc}}{\delta_{wc}} \tag{8}$$

Where A_{wc} is the area of the winding conductor, I_{wc} represents RMS value of the current in the winding conductor, and the current density of the winding conductor is represented by δ_{wc}. In HV and LV windings the conductor selection is based upon the current density as it has a direct relationship with the temperature rise. The current density determines the I^2R losses of the transformer as that depends on the transformer load. Different transformers have different level of I^2R losses, thus the current density will be different for different transformers [52].

- Self-cooled transformers: 1.1 A/mm^2 to 2.3 A/mm^2
- Forced oil cooled transformers: 2.2 A/mm^2 to 3.2A/mm^2
- Forced air cooled transformers: 5.4 A/mm^2 to 6.2 A/mm^2

The iterative inversion of paper selectivity described in [53] is used for the calculation of insulation resistance for both LV and HV windings. For a constant resistivity of the transformer, the relationship between the resistance of the insulation and resistivity of the transformer oil is a fixed function as given by

$$R = f(\rho) \tag{9}$$

Where R is the resistance of the insulation, ρ represents resistivity of insulation and f represents functional relationship between them. The mathematical model for the winding insulation is shown in Figure 4.

C. THERMAL MONITORING ALGORITHM

The hot-spot temperature calculated from the hot-spot model is used for the analyzing the health status of the transformer winding insulation. An algorithm is developed to analyze the health status of the transformer as shown Figure 5. The mentioned three conditions regarding the transformer winding insulation are analyzed through the winding hot-spot temperature. The HST temperature of the transformer windings under 60 ºC, depicts the healthy state of the transformer winding insulation. Whereas, the deterioration state is depicted for the HST, ranging from 60ºC to 110ºC and the HST above 110ºC is depicted as complete breakdown state of the transformer winding insulation. It must be noted that the temperature may be different for different sets of transformer.

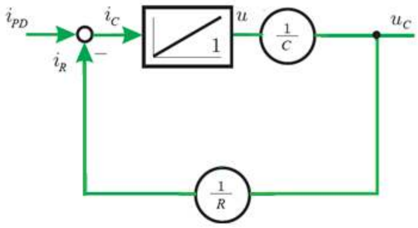

FIGURE 4. **Mathematical model for the transformer winding insulation**

D. INSTALLATION OF MONITORING UNIT AT 500 kV GRID STATION

This research work is carried out on a power transformer at 500 kV Sheikh Muhammadi grid station, Peshawar. The most aged three-phase, 10/13 MVA, 132/11 kV, 50 Hz power transformer is selected for the analysis. The thermal monitoring model presented in this study is based on the health estimation of the transformer winding insulation, therefore, the real-time data has been taken from the incoming line of the grid power transformer.

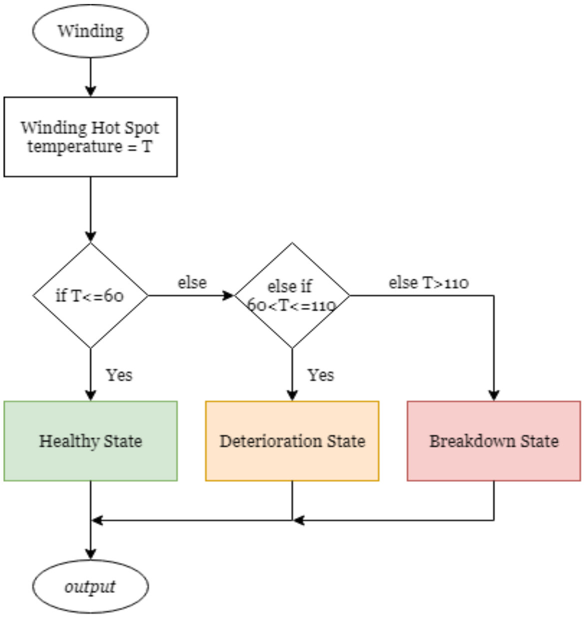

FIGURE 5. **HST based Thermal algorithm for transformer heath assessment**

The daily load cycles and ambient temperature data are measured by installing Schweitzer Engineering

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

Laboratories (SEL)-2414 Transformer Monitor unit shown in Figure 6.

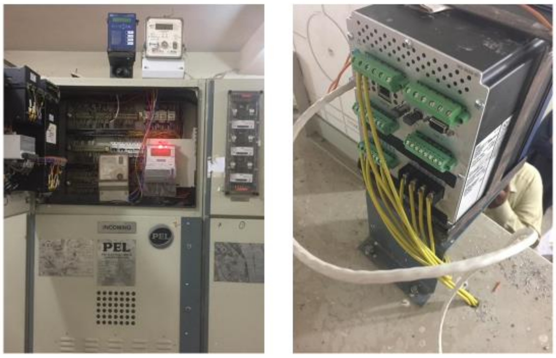

FIGURE 6. **SEL-2414 Transformer Monitoring Unit [54]**

SEL-2414 is installed through the current transformer (CT) and potential transformer (PT) connections from the incoming panel of the power transformer. The connection diagram of SEL-2414 installation is shown in Figure 7.

IV. SIMULATION RESULTS AND DISCUSSION

The simulation results have been taken from the Simulink based dynamic thermal model of a three-phase 10/13 MVA, 132/11 kV, 50 Hz substation power transformer. To train the model for the above mentioned transformer, the required parameters for the hot spot and top oil models are taken from the technical specification of the transformer as shown in Table 4. Whereas the winding insulation parameters calculated by the methodology presented in Section II are shown in Table 5 respectively.

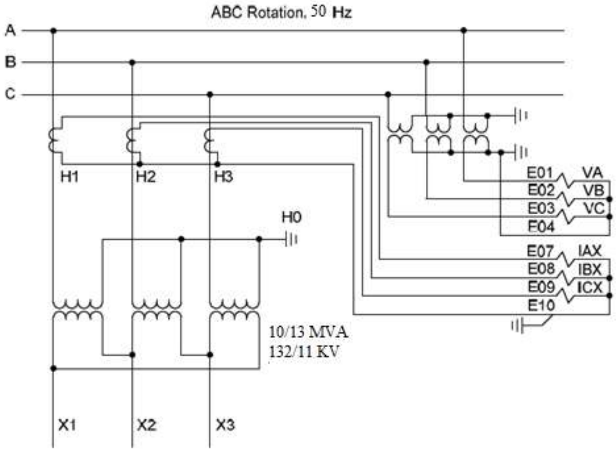

FIGURE 7. **Connection diagram of SEL-2414 to the transformer**

TABLE 4. **Required parameters for thermal model**

PARAMETERS	VALUES
Rated top oil rise over ambient, $\Delta\Theta_{oil\text{-}R}$	50 °C
Rated hot spot rise over top oil, $\Delta\Theta_{hs\text{-}R}$	15 °C
Ratio of load losses to no-load losses, β	4.85
Rated Eddy current losses (pu), $P_{EC\text{-}R(pu)}$	0.43
Top oil temperature time constant, τ_{oil}	170 min
Hot spot temperature time constant, τ_{hs}	6 min
Exponent[1], n	0.9
Exponent[1], m	0.8

TABLE 5. **Calculated parameters for winding insulation**

PARAMETERS	VALUES
Winding voltage, V	11 kV
Insulation resistance, R	8.25 GΩ
Insulation capacitance, C	250 nF

A. DAILY LOAD CYCLE AND AMBIENT TEMPERATURE

To analyze the health status of transformer winding insulation, the daily load cycles (pu) for each phase the ambient temperature (°C) data are measured on July 7th, 2019, as shown in Figure 8 and Figure 9 respectively. The daily load cycles and the ambient temperature are measured for the time span of 24 hours through SEL-2414 device.

B. THERMAL MONITORING

The real-time hot-spot temperature is measured for each phase of the transformer through the dynamic thermal model as shown in Figure 10. The top oil temperature is measured by using load cycles and ambient temperature whereas the hot spot temperature is measured through the top oil temperature and the load cycles.

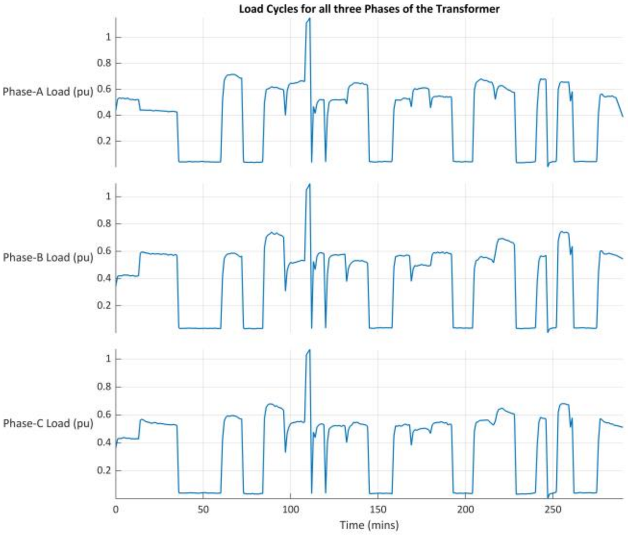

FIGURE 8. **Daily load cycles (pu)**

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

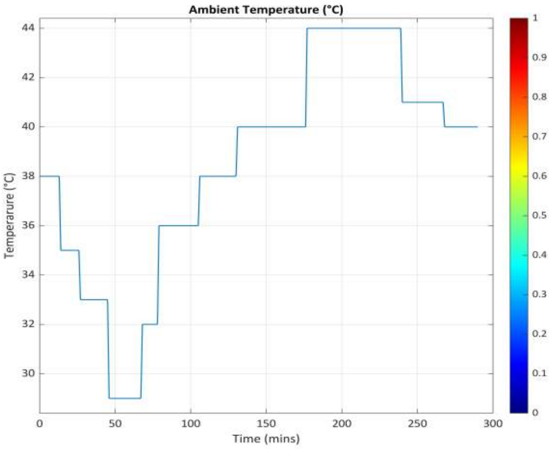

FIGURE 9. Ambient Temperature

C. CORRELATION BETWEEN LOAD AND HST

Correlation is a technique of data processing which is used to know the linear relationship between two variables and quantifies the dependencies between them. In this research work the correlation between the load cycles and hot-spot temperature is evaluated to estimate the health status of the transformer winding insulation. It can be clearly observed from the graphs of the load cycles (pu) and the hot spot temperature that whenever the load (pu) increases, the hot-spot temperature increases whereas it decreases with the decrease in the load (pu) correspondingly. This shows a direct linear relationship between hot-spot temperature and load cycle of transformer as shown in Figure 11.

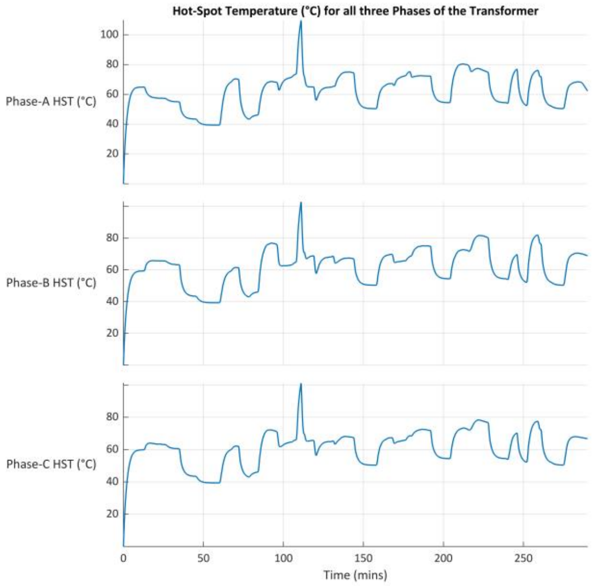

FIGURE 10. Hot Spot temperature for all three phases of transformer

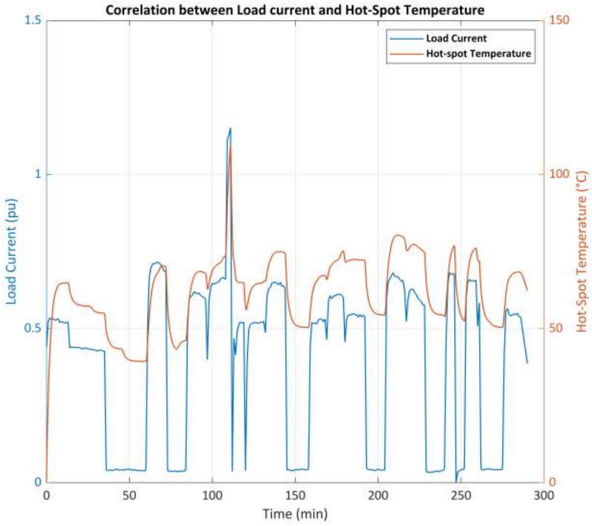

FIGURE 11. Relationship between the load and HST

Moreover, this strong correlation between the load cycles and hotspot temperature is quantified through Pearson correlation function in MATLAB as shown in Table 6. This function returns a correlation coefficient ranging between 1 and -1. More the coefficient closer to 1 or -1, more the stronger will be the correlation. The results from the correlation coefficients ensures the strong relationship between the load and the hot-spot temperature.

D. HEALTH STATUS OF WINDING INSULATION

After quantifying the linear relationship between the load and hot-spot temperature, the hot-spot temperature variable is used estimate the health status of transformer winding insulation. A categorical health status variable is calculated using data analysis techniques based on the thermal monitoring algorithm as shown in Figure 12. Furthermore, the remaining health of the winding insulation is calculated for all three phases by plotting the hot-spot temperature with respect to the health status for each winding. Almost, more than 55% of the winding insulation is deteriorated as shown in Figure 13.

TABLE 6. CALCULATED CORRELATION COEFFICIENTS

Load vs HST	Correlation Coefficient
Phase-A	0.79
Phase-B	0.80
Phase-C	0.76

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

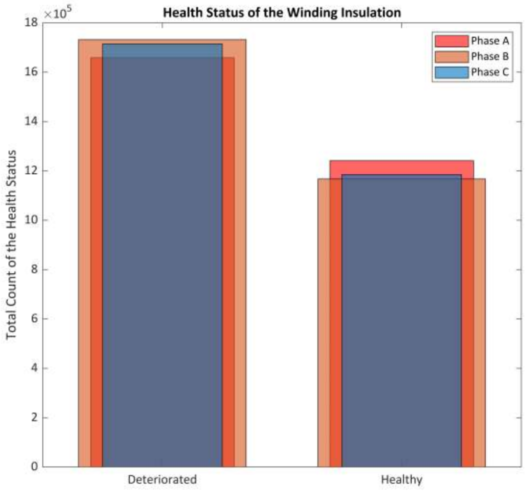

FIGURE 12. Health Status of winding insulation

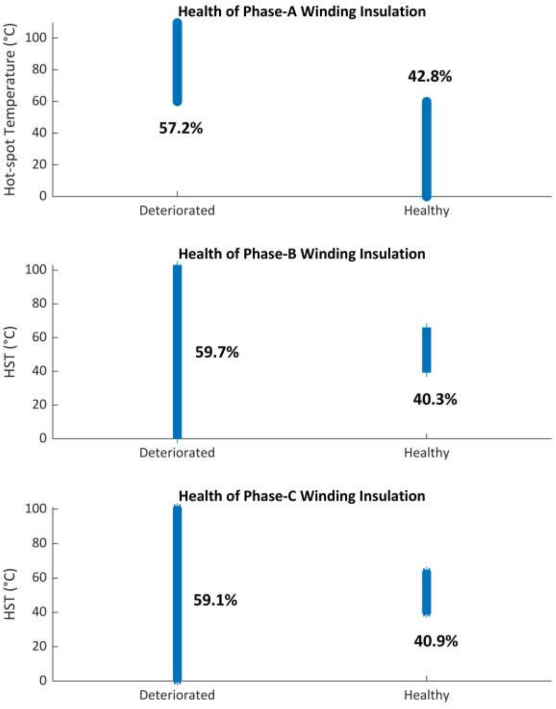

FIGURE 13. Estimated health and deteriorated status

D. FFT BASED POWER SPECTRAL ANALYSIS

The overloading of power transformer drastically increases the winding hot-spot temperature as shown in the above section. This increase in the winding hot spot temperature, initiates certain localized incipient transients in the shape of PD, which are very difficult to detect through normal state of the art monitoring techniques. These PD causes the partial breakdown of winding insulation, which if not detected and mitigated in its initial stages, can grow bigger and may lead to the full breakdown and permanent damage to winding insulation of the power transformers.

To detect and localize the PD inside the winding insulation, the most basic parameter to analyze is the frequency of the radiated electro-magnetic (EM) waves by PD. With increase in the magnitude of PD, its frequency changes i.e. medium frequency (MF), high frequency (HF) and ultra-high frequency (UHF) PDs. A lot of techniques have been proposed for detection of UHF partial discharges [33, 34, 36-38, 55, 56] but no methodology has been reported for the MF and HF partial discharges.

A family of spectral analysis functions are provided by Signal processing toolbox in MATLAB that let you determine the frequency content of a noisy time domain signal. In this research work, FFT based power spectral estimation has been used upon the output signal from the insulation model. The power spectrum as a function of normalized frequency samples is plotted for each phase of the transformer shown in Figure 14, Figure 15 and Figure 16 respectively.

The plots of the power spectrum for each phase shows the expected peaks at 50 Hz. Moreover, the plots are showing an extra spurious peaks of different frequencies that must be due to some noise in the signal. These spurious peaks are definitely not related to the signal of interest. The results obtained are shown in Table 7, and the higher frequency peaks in the FFT spectrum confirms the possibility of PD activity inside the transformer winding insulation. This shows that the winding insulation of transformer is in the deterioration state. Therefore, immediate maintenance and precautionary measures are suggested for the mentioned grid transformer under observation for this study, to halt the PD growth in its initial stages and protect the transformer windings from failure and permanent damage. This shows the incipient activity in the winding of a transformer that is the PD activity inside the winding insulation of transformer.

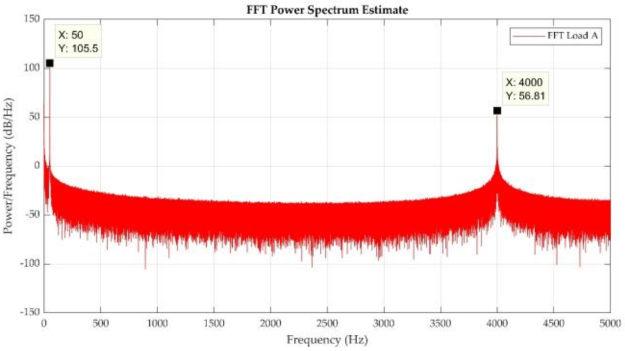

FIGURE 14. FFT Power spectrum for phases-A of transformer

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

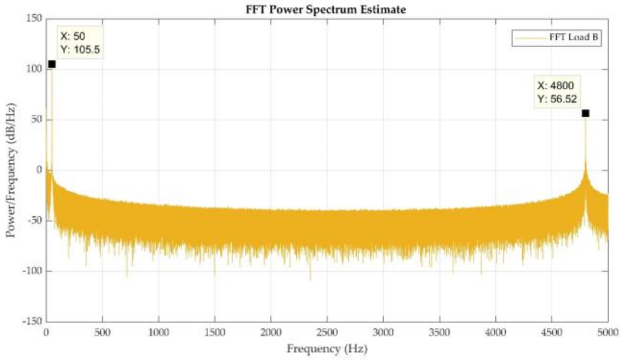

FIGURE 15. **FFT Power spectrum for phase-B of transformer**

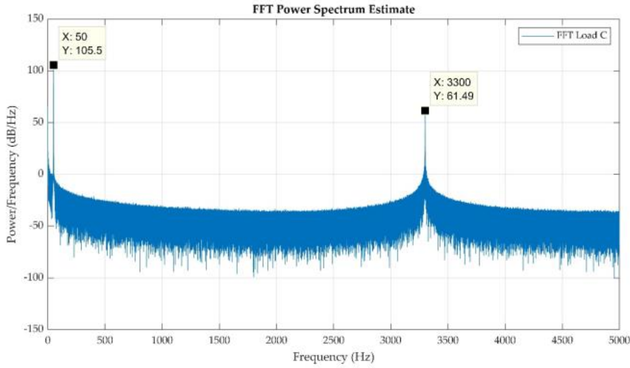

FIGURE 16. **FFT Power spectrum for phase-C of transformer**

TABLE 7. Results for the health assessment of winding insulation

PHASE	LOAD (PU)	HST (^{O}C)	FFT (KHZ)		INSULATION HEALTH	
	max	*max*	f_1[1]	f_2[2]	Healthy	Deterioration
A	1.2	110	0.05	4.0	42.8%	57.2%
B	1.1	103	0.05	4.8	40.3%	59.7%
C	1.1	101	0.05	3.3	40.9%	59.1%

[1] frequencies of the AC signal; [2] frequencies of the PD signal

V. CONCLUSION

A novel thermal monitoring technique for the health analysis of the power transformer winding insulation is presented in this paper. Thermal model for the Kraft paper insulation of transformer windings is developed using the transformer hot spot and top oil winding equations in Matlab Simulink. The thermal model is trained with the ambient temperature and load cycles of a 10/13 MVA, 132/11 kV, 50 Hz, ONAF grid power transformer. The model parameters are taken from the name plate technical specification of the transformer. The under-load operation of the transformer followed by the short-term overloading, causes the drastic increase of hot spot and top oil temperature in transformer. A strong linear correlation between the load and the winding hot-spot temperature is calculated and the health status of the winding insulation has been successfully estimated using data analysis, data processing and data visualization functions in Matlab. Moreover, the FFT spectrum indicates the presence of HF transients in the output signals for each phase of the transformer. These HF transients depicts the development of PD inside the winding insulation, ensuring the deterioration of the transformer winding insulation. Hence, the short-term overloading is the root cause in deteriorating the health condition of the windings insulation and in turn reducing the life time of transformers. As compared to the other health assessment techniques, the analysis methodology presented in this study is based on the physical condition of the transformer and a real-time thermal monitoring results are visualized by utilizing the real-time data of a substation power transformer. The idea presented in this model is numerically validated and is applicable for the health assessment of all types transformers in the future.

ACKNOWLEDGMENT

The authors want to convey their gratitude to the editors of *IEEE Access for* their kind invitation to present this feature article. This research work is carried out at US-Pakistan Center for Advance Studies in Energy (USPCAS-E), UET Peshawar in collaboration with Arizona State University (ASU), United States of America. The administrative and technical staff of Sheikh Muhammadi 500 kV Grid station, provided substantial support in installing the SEL-2414 transformer monitor device and data collection for the load cycles and providing technical specifications of the transformer. Moreover, the authors would like to thank the customer and technical support team of Schweitzer Engineering Laboratories (SEL) for their support.

REFERENCES

[1] M. Guo, X. Kang, Y. Xu, C. Zhao, and Y. J. T. J. o. E. Zhang, "Preliminary reliability evaluation for power system considering geomagnetic data," vol. 2019, pp. 1429-1433, 22 April 2019 2019.

[2] S. Tenbohlen, J. Jagers, G. Bastos, B. Desai, B. Diggin, J. Fuhr, *et al.*, "Development and results of a worldwide transformer reliability survey," in *CIGRE SC A2 COLLOQUIUM 2015:" Challenges of the future for transformers & other substation equipment", Shanghai, China, September 20th–25th, 2015*, 2015.

[3] A. Christina, M. Salam, Q. Rahman, F. Wen, S. Ang, W. J. R. Voon, *et al.*, "Causes of transformer failures and diagnostic methods–A review," vol. 82, pp. 1442-1456, 2018.

[4] C. Q. J. I. E. I. M. Su, "Case study: lessons learned from the failure of a new 230-kV transformer-cable termination," vol. 26, pp. 15-19, 2010.

[5] S. J. T. N. Ohta, ThreeBond, Issued December, "Temperature classes of electrical insulators," vol. 1, 1985.

[6] A. M. Alshehawy, D.-E. A. Mansour, M. Ghali, M. Lehtonen, and M. M. Darwish, "Photoluminescence Spectroscopy Measurements for Effective Condition Assessment of Transformer Insulating Oil," *Processes,* vol. 9, p. 732, 2021.

[7] N. Azis, Q. Liu, Z. J. I. T. o. D. Wang, and E. Insulation, "Ageing assessment of transformer paper insulation through post mortem analysis," vol. 21, pp. 845-853, 2014.

[8] S. Han, Q. Li, C. Li, J. J. I. T. o. D. Yan, and E. Insulation, "Electrical and mechanical properties of the oil-paper insulation

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

under stress of the hot spot temperature," vol. 21, pp. 179-185, 2014.

[9] L. Ruijin, T. Chao, Y. Lijun, and C. Huanchao, "Thermal aging studies on cellulose insulation paper of power transformer using AFM," in *2006 IEEE 8th International Conference on Properties & applications of Dielectric Materials*, 2006, pp. 722-725.

[10] I. E. Commission, "Loading guide for oil-immersed power transformers," ed: IEC Publications, 2005.

[11] N. Schmidt, S. Tenbohlen, R. Skrzypek, and B. Dolata, "Assessment of overload capabilities of power transformers by thermal modelling," 2011.

[12] S. Tenbohlen, T. Stirl, and M. Stach, "Assessment of overload capacity of power transformers by on-line monitoring systems," in *2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 01CH37194)*, 2001, pp. 329-334.

[13] C. Wang, J. Wu, J. Wang, and W. J. E. Zhao, "Reliability analysis and overload capability assessment of oil-immersed power transformers," vol. 9, p. 43, 2016.

[14] S. T. Jan, R. Afzal, and A. Z. Khan, "Transformer failures, causes & impact."

[15] M. Mandlik and T. Ramu, "Moisture aided degradation of oil impregnated paper insulation in power transformers," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 21, pp. 186-193, 2014.

[16] L. Li, X. Longjun, Z. Deng, Y. Bin, G. Yafeng, L. J. I. T. o. D. Fuchang*, et al.*, "Condition assessment of power transformers using a synthetic analysis method based on association rule and variable weight coefficients," vol. 20, pp. 2052-2060, 2013.

[17] R. Liao, H. Zheng, S. Grzybowski, L. Yang, Y. Zhang, and Y. J. I. T. o. p. d. Liao, "An integrated decision-making model for condition assessment of power transformers using fuzzy approach and evidential reasoning," vol. 26, pp. 1111-1118, 2011.

[18] W. Tang, K. Spurgeon, Q. Wu, and Z. J. I. T. o. P. D. Richardson, "An evidential reasoning approach to transformer condition assessments," vol. 19, pp. 1696-1703, 2004.

[19] M. Arshad, S. M. Islam, A. J. I. T. o. D. Khaliq, and E. Insulation, "Fuzzy logic approach in power transformers management and decision making," vol. 21, pp. 2343-2354, 2014.

[20] J. Secue and E. J. E. P. S. R. Mombello, "Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers," vol. 78, pp. 1119-1128, 2008.

[21] A. R. Abbasi and M. R. Mahmoudi, "Application of statistical control charts to discriminate transformer winding defects," *Electric Power Systems Research,* vol. 191, p. 106890, 2021.

[22] Y.-C. J. I. P.-S. Huang, Measurement and Technology, "Condition assessment of power transformers using genetic-based neural networks," vol. 150, pp. 19-24, 2003.

[23] M. Žarković and Z. J. E. P. S. R. Stojković, "Analysis of artificial intelligence expert systems for power transformer condition monitoring and diagnostics," vol. 149, pp. 125-136, 2017.

[24] M. Tahir and S. Tenbohlen, "Transformer Winding Condition Assessment Using Feedforward Artificial Neural Network and Frequency Response Measurements," *Energies,* vol. 14, p. 3227, 2021.

[25] A. R. Abbasi, M. R. Mahmoudi, and M. M. Arefi, "Transformer Winding Faults Detection Based on Time Series Analysis," *IEEE Transactions on Instrumentation and Measurement,* vol. 70, pp. 1-10, 2021.

[26] A. R. Abbasi, M. R. Mahmoudi, and Z. Avazzadeh, "Diagnosis and clustering of power transformer winding fault types by cross-correlation and clustering analysis of FRA results," *IET Generation, Transmission & Distribution,* vol. 12, pp. 4301-4309, 2018.

[27] J. N'cho, I. Fofana, Y. Hadjadj, and A. J. E. Beroual, "Review of physicochemical-based diagnostic techniques for assessing insulation condition in aged transformers," vol. 9, p. 367, 2016.

[28] I. Fofana and Y. J. E. Hadjadj, "Electrical-based diagnostic techniques for assessing insulation condition in aged transformers," *Energies,* vol. 9, p. 679, 2016.

[29] S. Tenbohlen, S. Coenen, M. Djamali, A. Müller, M. H. Samimi, and M. Siegel, "Diagnostic Measurements for Power Transformers," vol. 9, p. 347, 2016.

[30] G. International Electrotechnical Commission %J Edition, Switzerland, "IEC 60270 High-voltage test techniques-Partial discharge measurements, 3," 2000.

[31] S. M. Markalous, S. Tenbohlen, K. J. I. T. o. D. Feser, and E. Insulation, "Detection and location of partial discharges in power transformers using acoustic and electromagnetic signals," vol. 15, pp. 1576-1583, 2008.

[32] R. Schwarz and M. Muhr, "Modern technologies in optical partial discharge detection," in *2007 Annual Report-Conference on Electrical Insulation and Dielectric Phenomena*, 2007, pp. 163-166.

[33] S. Coenen, S. Tenbohlen, and S. Markalous, "Detection of Partial Discharges in Power Transformers using UHF PD Measurements and Acoustic Measurements," ed: University of Stuttgart.

[34] J. Li, X. Li, L. Du, M. Cao, and G. Qian, "An Intelligent Sensor for the Ultra-High-Frequency Partial Discharge Online Monitoring of Power Transformers," vol. 9, p. 383, 2016.

[35] M. Siegel, M. Beltle, S. Tenbohlen, S. J. I. T. o. d. Coenen, and E. Insulation, "Application of UHF sensors for PD measurement at power transformers," vol. 24, pp. 331-339, 2017.

[36] S. Tenbohlen, D. Denissov, S. M. Hoek, S. J. I. T. o. D. Markalous, and E. Insulation, "Partial discharge measurement in the ultra high frequency (UHF) range," vol. 15, pp. 1544-1552, 2008.

[37] T. Umemoto and S. Tenbohlen, "Novel Simulation Technique of Electromagnetic Wave Propagation in the Ultra High Frequency Range within Power Transformers," vol. 18, p. 4236, 2018.

[38] L. A. M. M. Nobrega, G. V. R. Xavier, M. V. D. Aquino, A. J. R. Serres, C. C. R. Albuquerque, and E. G. Costa, "Design and Development of a Bio-Inspired UHF Sensor for Partial Discharge Detection in Power Transformers," vol. 19, p. 653, 2019.

[39] W. Rutgers and Y. Fu, "UHF PD-detection in a power transformer," in *10th International Symposium on High Voltage Engineering*, 1997, pp. 219-222.

[40] P. Wang, J. Li, L. Zhao, T. Jiang, and Z. He, "Investigation on the propagation characteristic of electromagnetic waves in converter transformers," in *2012 International Conference on High Voltage Engineering and Application*, 2012, pp. 353-357.

[41] M. S. Noah and A. A. Shaltout, "Fault discrimination and protection of power transformers using voltage and current signals," in *2014 IEEE International Energy Conference (ENERGYCON)*, 2014, pp. 254-261.

[42] I. J. I. S. C. Board, "Ieee guide for loading mineral-oilimmersed transformers," vol. 57, pp. 1-112, 1995.

[43] G. Swift, T. S. Molinski, and W. J. I. t. o. P. D. Lehn, "A fundamental approach to transformer thermal modeling. I. Theory and equivalent circuit," vol. 16, pp. 171-175, 2001.

[44] D. Susa, M. Lehtonen, and H. J. I. t. o. P. D. Nordman, "Dynamic thermal modelling of power transformers," vol. 20, pp. 197-204, 2005.

[45] D. Susa and M. J. I. t. o. p. d. Lehtonen, "Dynamic thermal modeling of power transformers: further Development-part II," vol. 21, pp. 1971-1980, 2006.

[46] S. S. Ghoneim, K. Mahmoud, M. Lehtonen, and M. M. Darwish, "Enhancing Diagnostic Accuracy of Transformer Faults Using Teaching-Learning-Based Optimization," *Ieee Access,* vol. 9, pp. 30817-30832, 2021.

[47] A. Elmoudi, M. Lehtonen, and H. Nordman, "Thermal model for power transformers dynamic loading," in *Conference Record of the 2006 IEEE International Symposium on Electrical Insulation*, 2006, pp. 214-217.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3104033, IEEE Access

[48] A. Elmoudi, M. Lehtonen, and H. J. p. o. C. Nordman, "Transformer thermal model based on thermal-electrical equivalent circuit," pp. 2-4, 2006.

[49] A. Elmoudi, J. Palola, and M. Lehtonen, "A Transformer Thermal Model for use in an on-line Monitoring and Diagnostic System," in *2006 IEEE PES Power Systems Conference and Exposition*, 2006, pp. 1092-1096.

[50] A. Christina, M. Salam, Q. Rahman, M. S. Arifin, F. Wen, S. Ang*, et al.*, "Partial discharge modeling with increasing applied voltages across different void sizes," in *2017 4th International Conference on Advances in Electrical Engineering (ICAEE)*, 2017, pp. 22-25.

[51] R. Liao, F. Zhang, Y. Yuan, L. Yang, T. Liu, and C. J. E. Tang, "Preparation and electrical properties of insulation paper composed of SiO2 hollow spheres," vol. 5, pp. 2943-2951, 2012.

[52] S. Patel, "*Design of three phase transformer*," in *Design of DC Machines and Transformer*, D. U. o. E. a. Technology, Ed., 1st ed Darshan University of Engineering and Technology, 2000, pp. 1-31.

[53] J. Ruan, S. Jin, Z. Du, Y. Xie, L. Zhu, Y. Tian*, et al.*, "Condition assessment of paper insulation in oil-immersed power transformers based on the iterative inversion of resistivity," vol. 10, p. 509, 2017.

[54] S. E. Laboratorites, "SEL-2414 Transformer Monitor," vol. 20180606, pp. 1-390, 2008-2018.

[55] S. Coenen, M. Reuter, S. Tenbohlen, and S. Markalous, "Influence of PD Location in Transformer windings on IEC60270-and UHF-Measurements," in *International Conference on Condition Monitoring and Diagnosis (CMD)*, 2010.

[56] S. Coenen, S. Tenbohlen, F.-R. Werner, and S. Markalous, "Localization of pd sources inside transformers by acoustic sensor array and UHF Measurements," in *The 2010 International Conference on Condition Monitoring and Diagnosis*, 2010.

[57] M. Aslam, I. U. Haq, M. S. Rehan, A. Basit, M. Arif, M. I. Khan*, et al.*, "Dynamic Thermal Model for Power Transformers," *IEEE Access,* 2021.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/