Prognostication of Failures Using Signal-to-Noise Ratio to Determine Partial Discharges Activities in Power Transformers

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ABSTRACT The increase in number of power transformer necessitates increased awareness among power system engineers to monitor transformer health in order to avoid complete failures that may results in prolonged outages. The utilities, nowadays, are exploring different ways of detecting these faults in an early stage. This paper aims to present a real-time monitoring technique for a three-phase transformer using data analytics. Accordingly, the use of signal to noise ratio (SNR) for fault detection in power transformers has been described. This technique determines the partial discharge with the help of sensors needed for unique identification of failed transformers in different test systems. The SNR for different transformer coils installed in field conditions has been compared and discussed in detail. The technique is expected to enable power transformer operators for detection of incipient faults and thus can avoid catastrophic failures and the resultant losses.

INDEX TERMS Incipient faults, partial discharges, signal-to-noise ratio, transformer health.

I. INTRODUCTION

Before developing an intelligent health monitoring system, it is essential to have a knowledge of faults in a power transformer that are detrimental to its health [1]. A transformer generally experiences two types of faults namely the internal faults and the incipient faults. Internal faults occur rarely while the incipient faults are negligible at the initial stages but gradually develop into more severe faults [2], [3]. It is generally considered that an incipient fault is the result of weakening of the insulation of the transformer during operation. Throughout its service life, a transformer is under the influence of cyclic chemical, electrical, thermal, mechanical, and electromagnetic stresses during normal and abnormal load conditions [4]. The transformer insulation is subjected to different stresses and degrades gradually during operation, depending on the duration and magnitude of over-voltage which results in the core overheating and overstressing the insulation [5], [6]. Sometimes, poor insulation design and the use of sub-standard materials results in localized overheating due to corona type discharges [7]. Other causes are attributed to the microstructure of the insulating material used and the process through which the insulation is cooled from the molten state, which may result in internal microscopic defects in the form of voids and micro-cracks [8]. Similarly, when the temperature of mineral oil is low and it thickens, a static charge is developed between the metallic parts of transformer and insulating oil. Oil is regarded as non-accumulator, however, when the magnitude of static charges exceeds a certain level to overcome the breakdown strength of insulating oil, sparking will occur that can ultimately lead to flashover, as a result, the transformer can damage if remedial
measures are not exercised. Moreover, the reduction of the thermal integrity results in the loss of physical strength of the insulation, and with passage of time, it will degrade the cellulose paper till it can no longer sustain the electrical and mechanical stresses [9], [10].

The transformer winding insulation is an important component, and a subject to study the incipient behavior inside the transformer. Since the electric field in transformers is far less than the intrinsic strength of the cellulose paper insulation used as winding insulation, the catastrophic breakdown of insulation cannot be ruled out [11]. It has been known that air-filled cavities and voids exist in insulation due to its anisotropic nature [12]. Furthermore, the processes involved in forming and crafting the insulation may result in mechanical defects on a microscopic scale. Some of these defects are harmless and are at-tributed to the nature of chemical bonding and their orientation during processing. How-ever, some defects can be harmful and can sustain partial discharge (PD) activity when the insulation is stressed with fields that are, though far less than the intrinsic strength, yet has a profound effect on the air that exist in these defects in the form of voids and cavities [13]. The PD phenomenon in solid insulation is well understood and occurs in voids, which are material defects and air cavities inside the insulation. PD activity starts in a void when critical field of air breakdown is reached [14].

A. PARTIAL DISCHARGE ACTIVITY

It has been documented that according to ISO 120/121, PD activity of charge amounting to less than 5 pC is an indication of harmless voids and above this threshold the activity in voids leads to their enlargement and ultimately leading to insulation failure [15]. The high localized temperature at potential sites of PD activity produces hotspots. However, the resulting hotspots are difficult to determine and therefore cannot be used as a suitable indicator. The breakdown in void or cavity is intermittent, highly localized and is accompanied with the generation of energy in the acoustic, visible and radio range with a wide frequency band of electromagnetic spectrum between 300 MHz and 3 GHz [16], [17] besides producing hotspots. The void in the winding insulation thus acts as a potential source of electromagnetic radiations. The electromagnetic radiations generated from partial discharge activity appear as noise and are generally referred to as stray frequencies. The stray frequencies due to PD amplitude modulate the information signal which causes noise that manifests itself as radio interference [18], [19]. Traditionally the presence of radio interference in power equipment is detected by using conventional radio receivers tuned to the AM band: 500 kHz to 1.6 MHz [20], [21]. However, this traditional method depends on the sensitivity of the radio receiver and the directivity of the antenna and is less accurate, and does not provide the magnitude of the PD pulse [22]. Besides, with traditional method the exact source and location of PD cannot be identified [23], [24].

Partial discharges, also accompanied by thermal effects inside the insulation are mainly responsible for its gradual degradation and therefore are the key contributor towards insulation deterioration [25]. Since the PD activity is highly localized, it therefore causes localized heating that results in local hot spots at locations of PD activity. The action of PD accompanied by high localized thermal effects causes melting of cavity walls and thereby erosion that result in enlargement of cavity. Cumulative intermittent PD activity gradually enlarges the cavity gradually to an extent that forms a bridge for the complete breakdown of insulation [26]. Thus the onset of PD activity inside the insulation is a positive feedback mechanism of degradation and therefore loss of insulation life [27]. As a consequence of the presence of PD inside insulation, both stray electromagnetic frequencies and localized heating are produced and these can be considered as vital parameters for monitoring the health of transformers [28]. As the transformer life mainly depends on the condition of insulation; the deterioration of insulation can be regarded as a key factor for complete failure of the transformer in practice. PD activity is electrical in nature, but is accompanied by thermal effects that are mainly responsible for insulation degradation ultimately leading to breakdown [29], [30].

B. PARTIAL DISCHARGE MODEL FOR WINDING INSULATION

The thermal effects of PD activity can be modelled in terms of electrical parameters [31]. An instinctual way to view the phenomenon of partial discharge is to consider the transitory change in capacitance across the dielectric with a cavity or void [32]. In the presence of partial discharge, the cavity goes from non-conducting to conducting state. Apparently, the capacitance increases when the void becomes conductive in the presence of partial discharge, which is clear indication of a conduction current that flow down the dielectric material to charge the additional capacitance while maintaining constant voltage across it [33]. This conduction current flows through the impedance of the dielectric and therefore produces a voltage pulse that also propagates down the dielectric [34]. However, the voltage in the void collapses in a few nanoseconds, so that the resulting voltage pulse that travels in both directions away from the void with PD activity has a pulse width in the nano-second range [35]. Since the PD activity inside the insulation can provide vital information related to insulation deterioration, in the present work, a-partial-discharge- (PD) method has therefore been used and for this purpose both the symbolic and reciprocal-models are-proposed.

As the current-density varies directly with temperature rise, the current-density sets parameters for the selection-of the-conductor for-LV and-HV-windings. The-load at which-maximum efficiency occurs depends on the current-density, therefore its selection is-extremely-critical for $I^2R$-losses-in the-transformer windings. Based on-the iterative inversion of paper resistivity presented, the resistance-of the-insulation for-both HV-and-LV windings-has been-calculated by using
the functional relationship [36].

\[ R = f(\rho) \]  

(1)

where:

- \( R \) Resistance of the insulation
- \( \rho \) Resistivity of insulation

After calculating the corresponding values of insulation resistance \( R \) and insulation capacitance \( C \), the symbolic model was re-fabricated into a reciprocal model. The reciprocal model is a pre-requisite model for Simulink modeling, which makes it easier to understand the flow of the model and select required blocks for Simulink implementation.

The Simulink-model for incipient fault because of PD in the winding insulation of transformer

Partial discharges cause degradation of the winding insulation by inflicting thermal damage [37], [38]. Partial discharge, as discussed earlier occurs in voids and defects inside the insulation is accompanied by generation of frequencies in UHF band [39]. Thus, the SNR can be used as a tool for monitoring of PD activity and therefore the health of the transformer winding [40], [41]. To obtain the SNR from noise generated due to partial discharges within the winding insulation of transformer, complete HT coils of 10/13MVA, 132kV/11kV were considered. A total of four coils were considered, three of which were rejected in the quality control tests for partial discharge activity, and one coil among them was tested for no partial discharge activity. These coils were labelled as 1 for the coil with no PD activity observed and 2, 3 and 4 for those coils in which PD activity was observed in the manufacturer quality control test. UHF sensors were used to detect the PD activity within the winding insulation. UHF transformer sensors can be used to detect internal PD on power transformers in a frequency range between 300 MHz and 3 GHz [42], [43]. The UHF frequency range can be chosen under difficult on-site conditions, such as high impact of the measurements due to corona discharges or other disturbances within the typical HF range (100 kHz to 10 MHz). UHF sensors are suitable for retrofitting as well as for pre-installation.

Although there are several other techniques for monitoring the partial discharge phenomenon such as Chemical detection, acoustic detection and optical detection methods. The major drawback of all these techniques is that they cannot be implemented during the operation of transformers, while

hindrance in transformer operation increases the financial losses for the buyer and the consumer. The SNR based technique compared to aforementioned techniques do not require halting transformer operations. Very few researchers have worked on this focused area of the transformer. Also many research papers used frequency analysis approach but this paper used frequency analysis along with the partial discharge monitoring of transformer winding.

II. EXPERIMENTAL SETUP

A photograph of the complete coil is shown in Fig. 2. It is composed of copper wire with inter-leaved turns with oil impregnated Kraft paper as insulation between turns. Each coil under test was rested on a 1-inch wooden block placed at the bottom of the steel tank. For continuous monitoring of PD activity in power transformers, it is essential to place the Ultra High Frequency (UHF) sensors where the attenuation is minimum, and the sensitivity is maximum. Since the frequencies in the UHF range are strongly attenuated within few centimeters, when the magnitude of the PD pulse may be small due to ionization process with charges less than few pico-Coulombs, placing a sensor in a shielded area can therefore reduce its sensitivity to the UHF signals. Owing to the attenuation of the UHF signals and the consideration of the electrical field voltage, certain positions must be considered for the installation of UHF sensors. Locations must be selected where the UHF sensors can measure PD pulses with the highest sensitivity. In a study of PD, a statistical threshold was used to filter the weak signals, and it was found that the weakest signals were always received from the sources in the winding furthest away from a UHF sensor. Only the sources within the middle winding were measured above the threshold of all sensors. The selection of locations was based on the stochastic distribution of hot-spots and where the insulation is mostly stressed. However, since the height of the complete HT coil element of power transformers seldom exceed 1 meter, the best location of sensors was either midway within the coil element or near the top few turns of winding where the probability of hot spots is maximum [44].

FIGURE 1. Simulink model for winding insulation.

FIGURE 2. Transformer HT coil assembly.
With each coil under test two UHF sensors A and B were installed; one in the center (sensor A) of the coil assembly whereas the other (sensor B) was installed on the inner wall of the steel tank near the top portion of the coil under test.

In the present work UHF sensors of type FOS4 manufactured by Power Diagnostix Systems GmbH, Germany together with application software were used. The type FOS4 is the latest family member of Power Diagnostix fiber optic transmission systems, which offers high speed data acquisition through fiber optic cables on multiple channels in parallel. The system consists of FOT4 transmitter units and FOR4 receiver units. Each channel acts as an independent transient recorder with its own storage and settable acquisition speed and storage depth. The sampling rate is 20 mega-sample/sec. and, hence, sufficient to even acquire the pointing vector of the incoming acoustic wave, when using a two-dimensional three-sensor configuration. The sensors sub-type TFS1 and TVS2 of FOS4 type were used as shown in Fig. 3. UHF sensors of type TFS1 and PD signals can be used for PD pattern analysis as well as for triggering acoustic measurement systems.

The scalable system allows the acquisition of acoustic PD signals or other measurement signals under AC, DC, or impulse testing in laboratories as well as on site. The modular system accepts up to twelve optical channels and comes with high-speed controller card to communicate with a computer. Besides this, the FOS4 system has additional signal output on the rear side and can be used as a digital isolated amplifier without the use of any software. For PD location purposes the ICM acoustic software offers complete control of the FOS4 system that includes averaging and trigger logic. The positioning of the sensors must be done in a manner that should reduce the effect of stray capacitance that may result due to the high electric field in the vicinity of the coil. The sensor sub-type TFS1 was installed in the center of the coil under test inside the steel tank while the sensor TVS1 was installed through flange that replaced the explosive vent at the top of the lid near the top turns of the coil. Fiber optic cables with metallic sheath were used to derive the signal from the sensors and conveyed to the measuring circuit. The metal sheath of cable provides interference from external sources. The cable from the UHF sensor TVS1 was taken out of the steel tank enclosure through a small, drilled perforation in the lid.

The coil assembly was then carefully placed in the steel tank. Once the coil assembly was placed, the tank was filled with a fresh sample of transformer oil based on Chloro-fluoro Benzene having dielectric strength of 12kV/mm. Thus, the coil was enclosed in a steel tank filled with fresh sample of transformer oil. The steel tank and the coils were acquired from the sponsor industry (Heavy Electrical Complex). The steel tank was that of a single-phase transformer unit. The tank has an insulation bushing secured to the lid. The lid also incorporated an explosive vent valve. Prior to placing the coil inside the steel tank, a copper clamp was secured to the coil insulation. The clamp was electrically connected to the ground terminal provided at the wall of the steel tank. One of the terminals of the coil was passed through insulation bush mounted on the lid of the metal tank. The end of this coil was secured to the thimble of the insulation bush with an end connector for connecting the coil to the test circuit. The coil enclosed in the steel tank is shown in Fig. 4 with side and top view.

The experimental arrangement consisted of coil assembly under test, measuring circuit and the testing transformer as shown in Fig. 5.

The supply to the coil under test was obtained from a single-phase, 50Hz, 5kVA, 220V/100kV step-up testing transformer in high voltage laboratory, whose primary voltage was controlled through an autotransformer. The test transformer was placed as far as possible from the measuring system to avoid effect of stray capacitance with the couplings of measuring system. To avoid any electromagnetic interference due to corona and for safety purpose, the testing transformer was placed in Faraday cage with solid grounding through a 1-inch diameter, 6 feet length copper rod.

The PD activity was monitored with the following procedure. With the sensors placed at the selected locations and the measuring circuit connected, the transformer HT coil under test was placed in the steel tank. The tank was then filled with clean fresh transformer oil so that the coil assembly was completely immersed. The lid was then placed on the tank with the terminal of the coil taken out through the insulating
bushing. The lid was then secured tightly. The end of the coil was then connected to the output terminal (secondary) of the transformer. The ground terminal of the testing transformer was connected to the steel tank by a bolt located at the base. With all the connections made according to the schematic arrangement as shown in Fig. (5), the main supply was switched ON and the voltage gradually increased through the autotransformer to a point where partial discharge activity was noted, but care was taken not to increase the voltage beyond 78kV (voltage rating of the coil). The PD activity was noted, which was in the form of noise as seen on the screen of computer. The computer software then recorded the noise Fig. and the amplitude of the PD pulse lying within the sensitive bandwidth of the interface circuit. Due to the intermittent and random nature of PD activity, the test voltage was maintained for 5 hours at the value where PD activity was noted. Each coil was tested in the similar way and the PD activity recorded.

III. RESULTS AND DISCUSSION

The results obtained from the output of either sensor A or B were similar, which means that the location of sensor installation inside the transformer would not affect the output pulse magnitude of a discharge. Since sensor A was installed at the center of the transformer coil assembly, which was immersed in oil whereas sensor B installed outside the coil assembly on top, the transformer oil plays no part in the attenuation of the signal. Thus, output from either sensor A or B can be taken as the result of PD activity inside the coil.

The reference voltage set from the MCPHA was 100 volt (taken as 1pu) [41]. Thus, using the value of 5pC charge that result in 0.0625 pu voltage, the threshold SNR for any harmful PD activity is about +24 dB [45]. Thus, SNR above +24dB is indication of absence of PD activity whereas; SNR less than +24dB is the presence of PD activity. However, to allow an additional factor of safety, a discharge of 1pC was considered as a threshold limit for PD activity. As according to the calibrated value from a standard laboratory discharge detector, the voltage associated with 1 pC of PD activity is approximately 1% of the reference voltage or 0.01pu. Corresponding to the PD activity level amounting to 1pC, the SNR is therefore +40dB. Thus, any SNR value between +24dB and +40dB is indication of harmless PD activity, whereas SNR above +40dB is an indication of negligible or almost no PD activity. However, SNR less than +24dB is a matter of concern since the level of PD activity is relatively harmful and may attribute to substantial damage to the insulation that ultimately paves way for breakdown.

A. PD ACTIVITY IN COIL 1

Fig. (6) shows the result obtained from the test on coil 1. As seen in Fig. (6) there is no PD activity at the rated voltage of the coil applied for 5 hours and the entire graph simply consists of spikes that are probably due to small electromagnetic noise present in the environment and noise picked up within the measuring circuit. Moreover, the very small amount of noise detected may perhaps also be due to slight corona that may occur inside the tank as the distance of coil from the walls of the enclosure tank was less than that in actual transformer assembly.

Referring to Fig. 6, the spikes have magnitude within about ±1 volt range with respect to a reference voltage of 1pu selected for calculations. The 1pu voltage is set from the MCPHA as a reference voltage. This amounts to a charge less than about 0.1pC, which is far less than the Fig. of 5pC as expected in the PD activity.

As shown in the graph of Fig. 6 the maximum noise voltage corresponding to the noise picked by the UHF sensors amounts to about 0.01 pu. This gives an SNR of +40dB, which is an indication of absence of any harmful discharges. This small level of noise may also be an indication of small corona type discharges, which may be expected during testing due to ionization activity resulting from the field concentrated at the tip of the antenna of UHF sensor. This small amount of noise may also be attributed to that picked up by signal during propagation through the cables and connecting leads.

As mentioned earlier the threshold charge due to partial discharges that produces harmful effects is about 5pC as a generally accepted value by most testing laboratories. However, in the present work, keeping in view the sensitivity of the detecting system, a PD activity amounting to charge of 1pC was considered to allow greater factor of safety for transformer insulation. Thus, the onset of PD activity was marked by a discharge of 1pC.

B. PD ACTIVITY IN COIL 2

Fig. 7 shows the partial discharge activity for coil 2, removed from a faulty 132kV/11kV sub-station transformer. The transformer was taken out from service after 5 years of its commissioning due to the severe voltage fluctuations in one of the phases. On removal from service and performing routine test on coils, the insulation of the yellow phase coil was found faulty, and the entire transformer was therefore moved to storage.

As seen in Fig. 7 the PD level exceeds the allowed range. The amplitude of the pulses due to PD activity are in the range
of about $+3.8$ pu volts and $-2.3$ pu volts, with the maximum discharge amounting to about 10.6pC.

FIGURE 7. PD activity in coil 2.

The result of PD activity in coil 2 as recorded is given in Table 1.

### TABLE 1. Results of PD activity.

| Max Voltage (kV) | Min Voltage (kV) | Max Frequency (GHz) | Min Frequency (GHz) | Charge (pC) |
|------------------|------------------|---------------------|---------------------|-------------|
| 15.80            | 9.47             | 1.5                 | 0.5                 | 10.6pC      |

**C. PD ACTIVITY IN COIL 3**

Figure 8 shows the partial discharge activity for coil 3. The PD activity started at 9.47kV, which increased to 10.6pC when the voltage was raised to 15.8kV. Beyond this voltage the PD activity increased enormously which lead to tripping of the testing transformer. The voltage was therefore maintained at 15.8kV and the noise due to PD activity was observed and recorded for 5 hours. The SNR calculated based on maximum noise voltage for PD activity in coil 2 is about $-12$dB, which is an indication of excessive noise.

Similarly coil 3 underwent similar procedure of testing as coil 1 and 2. This coil was rejected by the factory due to higher-than-normal PD activity when tested for discharges in the quality control laboratory. The result of noise voltage as received through UHF sensors and displayed on MCPHA is shown in Fig. 8.

Referring to Fig. 8, the PD activity is excessive with amplitude of PD pulses shooting to about $+2.2$ pu volts and $-1.15$ pu volts, which started at 11.7kV and increased to significant value at 16.7kV. The maximum charge associated with PD pulses amounts to about 5.5pC to 6pC, which is indication of harmful PD activity. Table. 2 gives the values of relevant quantities as obtained through the software for coil 3 tested.

The result of PD activity in coil 3 as recorded is given in Table 2.

Referring to Fig. 8, based on 100 volts (1pu) set as reference voltage in the measurement system of MCPHA, the SNR for coil 3 was calculated to be about $-6.8$dB. The value of SNR is negative, an indication of excessive noise that is attributed to the partial discharge activity. This is obvious since this coil was rejected by the factory due to partial discharges.

**D. PD ACTIVITY IN COIL 4**

In a similar manner, coil 4 was tested for PD activity. This coil was removed from a 132/11kV, 50MVA power transformer, which was removed from service due to persistence overheating when the transformer was loaded beyond 50% of its rated load value. Moreover, when the load was increased on the transformer beyond its 50% rating, there was abnormal voltage sag on the yellow phase. This transformer has been in service for 6 years. The result of noise voltage in pu attributed to PD activity within coil 4 is shown in Fig. 9.

It can be seen in Fig. 9 that the noise voltage corresponding to PD pulses have significant magnitude with amplitude of pulses of about $+3.7$ pu volts and $-2.15$ pu volts, indicating
excessive harmful PD activity within the coil insulation. Table 3 gives the essential quantities recorded. Referring to Table 3, the PD activity within the coil started at 11.2kV and increased to a level corresponding to charge of 10pC when the voltage was increased to 17.5kV. Beyond this voltage the testing transformer indicated overloading and therefore the voltage was maintained at 17.5kV for a period of 5 hours. The SNR calculated on the basis of maximum noise voltage of +3.7 pu is —11.36dB. This is also an indication of excessive noise and therefore significant harmful PD activity.

The result of PD activity in coil 4 as recorded is given in Table 3.

| TABLE 3 | Voltage vs frequency. |
|---------|-----------------------|
| Max Voltage | Min Voltage | Max Frequency | Min Frequency | Charge |
| 17.5 kV    | 11.20 kV    | 3.0GHz       | 2.5GHz       | 10pC   |

IV. CONCLUSION

It can be noted from the results that the PD activity follows a random pattern and is intermittent in nature. The intermittent nature is mainly attributed to the successive build-up of pressure and venture during PD. The PD activity becomes less when the gas pressure inside the cavity increases and then re-occur when the gas pressure is reduced through venting of gas from the cavity into the bulk material. It can be observed from the test results that the SNR reduces when there is PD activity and goes to negative value when the level of PD is excessive. It is worth mentioning that the level of PD activity marked by the noise and decreasing SNR corresponds to the extent of damage to the insulation.

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