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Partial discharge ultra high frequency measurement system for suspended movable bubble defect in transformer

***Abstract**. Suspended movable bubble defect is often ignored during power transformer partial discharge (PD) detections. The key problem is the lack of PD simulation test platform for this kind of insulation defect. The current study designed a test platform to generate PD from suspended movable bubble defect. PD signals were detected using ultra high frequency (UHF) methods. The experimental data indicated that the device can simulate suspended movable bubble defect in oil that causes PD, and the PD signals show different characters with still bubble defect .*

***Streszczenie.** W artykule przedstawiono wyniki badań dotyczących budowy układu generacji wyładowań niezupełnych z uwięzionych bąbli powietrza w izolacji transformatora. Sygnały generowane przez wyładowania, wykrywane są za pomocą metod ultra-wysokich częstotliwości. Wykonane badania potwierdzają skuteczność detekcji wyładowań niezupełnych, wynikających z obecności bąbli powietrza w izolacji. (**Wykrywanie i pomiar ultra-wysokich częstotliwości wyładowań niezupełnych, wynikających z uwięzionych, przemieszczających się bąbli powietrznych w izolacji transformatora**).*

Keywords: partial discharge, transformer, suspended movable bubble defect, ultra high frequency.
Słowa kluczowe: wyładowanie niezupełne, transformator, uwięzione, ruchome defekty bąbli powietrznych, ultra-wysokie częstotliwości.

Introduction

Large power transformer failure due to insulation breakdown has serious consequences, which includes high maintenance costs and economic losses. Partial discharge (PD) online monitoring can detect the existence of transformer insulation latent defects. Determining the extent of insulation degradation can prevent the occurrence of unexpected transformer insulation failures, which significantly affect the safe operation of power transformers. Based on various actual transformer defects, the following discharge models can simulate real transformer internal defects: oiled-paper clapboard structure discharge model, discharge model along the surface, air-gap discharge model, oil corona discharge model, metal particle discharge model, and so on. The suspended movable bubble in transformer oil is a typical defect; this defect, caused by the action of the oil pump, presents suspended and mobile conditions. The existing air gap defect model cannot identify this kind of PD.

A certain amount of air bubbles enters the power transformer during installation, oiling, and maintenance; it is a typical bubble insulation defect that causes PD inside the device [1–4]. Pure transformer oil has good insulating property, but this property is significantly reduced if the oil is mixed with gas. Suspended bubbles in the transformer oil leads to PD in oil that leads to further oil–paper insulation deterioration, resulting in more gas, the oil and bubbles are prone to discharge, reducing the device oil insulation property [5–8].

Little domestic and international studies have been carried out on suspended bubbles in transformer oil. Some studies were conducted on the relationship between the electric field and bubble behavior [9–13]. Pompili created bubbles in transformer oil, which induced PD more easily; the initial discharge voltage amplitude, discharge repetition rate, and other parameters were affected [11,12], but no further investigation was conducted. In [13], Shiota designed the first experimental device that simulates bubbles in oil by injecting gas using a micro-syringe. In forced oil circulation transformers, when the flow velocity changes, the shape of the bubble changes. These changes affect the electric field distribution and alter the discharge characteristics. Analysis of the effects helps attain normal transformer operations and reduces the probability of failure. No studies on the discharge characteristics of suspended bubble affected by oil flow velocity have been conducted.

To investigate the discharge characteristics of suspended movable bubble PD defect in transformer oil, the author has designed a set of PD test platform that can simulate suspended movable bubble defect. This device can conveniently vary the oil flow rate, temperature, defect severity, and other test conditions, performing experiments under different conditions. Test results show that this kind defect is quite different from the existed still bubble defect, and the designed measurement system was proven capable of accurately detecting PD signals based on UHF method.

Oil flow cycling system

A test system design must be able to simulate suspended movable bubbles, generate PD signals, and vary the influencing factors to obtain the PD signals and different factors that affect the suspended movable bubble defect. The test system designed by the authors is constructed using the oil duct model, pump, flow control valves, temperature controller, and flow meter. Discharge is generated in the oil duct model, and the pump is operated at rated power, resulting in an impetus that starts the oil flow cycle. The flow control valve is adjusted within the oil flow rate of the oil duct. A flow meter is used to measure the oil flow rate, and a temperature controller is used to control and measure the temperature of the oil. The flow meter and the temperature controller are installed inside a stainless steel tube, and the oil duct model, pump, flow control valves, and stainless steel tube are sealed in a plastic tube. The circulation line is shown in Fig.1.

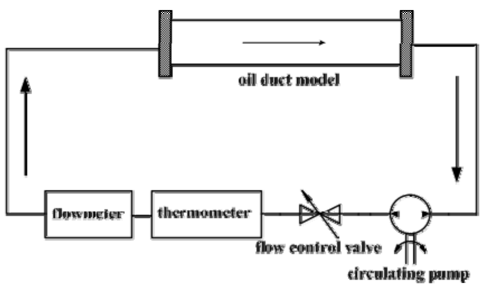


Fig.1. Oil flow diagram of the circulation line

When the transformer oil flows through the flow meter, the liquid initiates impeller rotation with a rotation speed proportional to the flow; thus, the flow meter size reflects the size of oil flow in the oil duct. The flow velocity in the oil duct is obtained by the speed of instantaneous flow, i.e.,

(1) $$Q_v = W \bullet H \bullet v$$

where Q_v is the oil flow capacity in the oil duct, W is the oil duct width, H is the height of the oil duct, and v is the flow velocity in the oil duct. The flow meter used is LWGY-40, which has a measurement range of 1–20 m^3/h, and the oil flow velocity can be manually increased gradually from 0.81 m/s to 4.35 m/s.

To study the temperature effect on PD from the suspended movable bubble defect, the oil temperature inside the circulation line needs to be accurately measured, and the oil temperature can be adjusted within a certain range. Excluding radiation effect, the needed time $\Delta t'$ for the oil temperature to rise to Δt=1 °C is

(2) $$\Delta t' = cm\Delta t / p$$

where c is the specific heat of the transformer oil, m is the oil mass, and p is the power of the heating pipes. The total amount of oil of the designed device is 8 L, the density of the oil is approximately 0.85 kg/m^3, c is equal to 2.0 kJ/(kg·°C), and the power of the heating pipes is 250 W. Therefore, oil temperature rise of 1 □ requires 54.4 s.

Oil duct model

Each sector of the actual transformer winding is composed of a series or parallel rectangular cross-sectional oil ducts, and insulating oil radially flows in the oil ducts. A strong electric field is present in the oil duct because of the voltage difference among the pie windings. In the current paper, an organic insulating material was used to design the oil duct model. The oil duct model was placed on flat-plate electrodes with applied voltage after being filled with transformer oil to simulate the oil duct of the actual transformer windings, as shown in Fig. 2 and Fig.3. Fig.2 shows the structure of the oil duct model. A spherical-shaped shielded cap is used to prevent corona, and 50 Hz AC voltage is applied between two electrode plates by the conducting rod. The two electrode plates and the conducting rod are made of copper, and the oil duct is made of plexiglass with sufficient dielectric strength. Both ends of the oil duct have two pipe interfaces for connecting the circulation line. Fig.3 shows a cross-sectional view of the oil duct model. the width of the oil duct is W, W is equal to 85 mm. The height of oil duct is H, H is equal to 15 mm, and the cross-sectional area of the oil duct and the connecting pipes are equal.

To produce the PD signal of the defect model, AC voltage is applied between the upper and lower plate electrodes of the oil duct model. The field strength of the actual transformer oil duct is generally 1.5 kV/mm (RMS), and the analog AC field strength in the designed oil duct is at least 1 kV/mm to generate PD. According to the design, the height of the oil duct is 20 mm, including an oil gap of 15 mm and an organic glass of 5 mm. The relative dielectric constant of the oil and organic glass are 2.2 and 4, respectively. The AC field strength in the oil reaches 1 kV /mm (RMS), as calculated by the plate capacitor model, The required applied voltage can be calculated as

(3) $$U = dE\,.$$

where U is the applied voltage, d is the height of oil duct model, E is the electrical field strength

In a uniform electric field or under a weak vertical component of an uneven electric field, the surface flashover voltage and the flashover distance are approximated by linear relationship. The flashover voltage under power frequency is 12.5 kV/cm, the height of oil duct model is 20 mm, and its flashover voltage is 25 kV, which is higher than the applied test voltage and ensures that no surface flashover and corona occur.

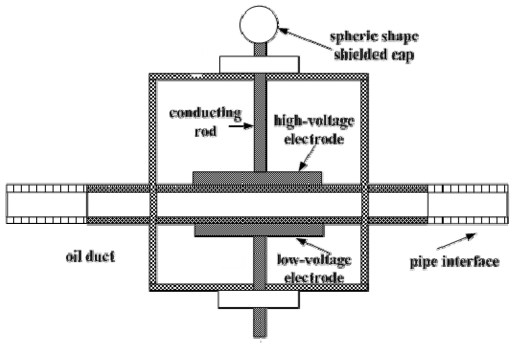


Fig.2. Structure of the oil duct model

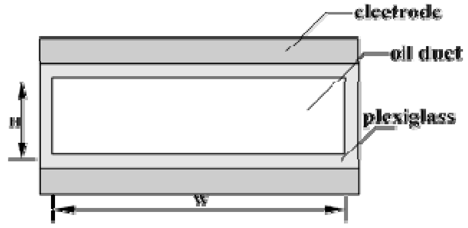


Fig.3. Cross-sectional view of the oil duct model

Transformer oil is regarded as incompressible viscous fluid, meaning that the insulating oil flow is an incompressible viscous flow. When actual fluid flows in the pipeline, two flow states are present: laminar and turbulent flows. The Reynolds number R_e is commonly used to determine the flow regime and can be calculated by the following:

(4) $$R_e = 0.354 \frac{Q_v}{D_d v_l}$$

where D_d is the equivalent diameter of the duct, and v_l is the kinematic viscosity of fluid under the operating mode.

For the oil duct shown in Fig. 3, the rectangular tube has a length W and height H. The equivalent diameter D_d can be calculated as

(5) $$D_d = \frac{2WH}{W + H}\,.$$

According to equations (4) and (5), the calculation result shows that in the design flow rate range, the Reynolds number is large enough to initiate a fully developed turbulent flow state easily. Therefore, this model can reflect the suspended movable bubble defect generated PD under a turbulent flow state.

PD measurement system

To simulate the oil suspended movable bubbles realistically, the whole oil cycle passages are filled with transformer oil first. A certain amount of oil is then pumped out from the oil cycle with an injector so that the corresponding amount of gas enters into the circulating-oil pipeline. The entire cycle pipeline is sealed and the submersible oil pump is started at a certain speed for the whole cycle. The oil pump impeller centrifugal force breaks the gas into tiny gas bubbles, evenly distributing them throughout the oil pipeline at a certain speed through the electric field area. The still bubble defect is compared with the suspended movable bubble, produced based on the suspended bubble. When the pump is stopped for more than 2 min, the oil flow in the duct reverts to its static condition. At this point, the volume size of the still bubbles does not change very much but gradually moves up to the electrode side. The still bubbles remain attached to the wall.

Sensor performance directly affects the credibility and accuracy of data in the signal detection and collection system. The author used a sleeve monopole antenna [14] to detect PD signal. The ratio of standing waves was less than two in the range of 350–525 MHz. The experiment was conducted using suspended movable bubble simulation device. Fig.4 shows the experimental circuit schematic for PD detection of suspended movable bubble defect in oil duct. T1 is a 0–380 V induction voltage regulator, T2 is a 50 kV/0.5A, n=1000:1 testing transformer without corona, C1 and C2 constitute a capacitive voltage divider with values of 2,000pF/2uF, R is a 20 kΩ protective resistance. The applied 50 Hz AC voltage was manually increased from 0 kV peak to 50 kV peak gradually. PD was generated by simultaneously applying AC high voltage above the discharge inception level in the suspended air bubble defects. The PD signals were measured with a WavePro 7100 oscilloscope, which has a 1 GHz bandwidth and maximal 20 GS/s sampling rate. The true PD pulse shape was recorded, and the shape of the individual PD pulse was observed using ultra wideband detection techniques coupled to a fast oscilloscope acquisition.

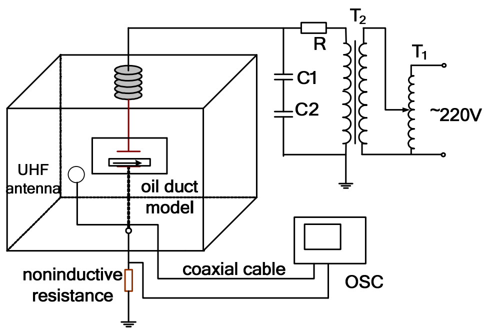


Fig.4. PD measurement system for suspended movable bubble defect

In the experiment, certain amounts of air were injected into the oil, driven by the circulating pump. The flow control valve was turned on, and the numeroscope of the flow meter was observed. The circulating oil flow velocity was from 1 m/s to 3.5 m/s, stepped-up by 0.5 m/s increment. The injected air was separated into 1–1.5 mm-diameter bubbles. The applied AC voltage was gradually increased and observed in the oscilloscope. When discharge pulse signals began to appear, the experimental conditions and the initial discharge voltage were recorded and the waveforms of the discharge signals were recorded.

PD test results

Fig.5 and Fig.6 show the two state bubble defect discharges of the UHF signal and the corresponding spectral distribution. The experiment was carried under applied voltage of 15 kV, the gas content in the oil duct was 10 mL /L, the oil flow rate was 2 m/s, and the oscilloscope's sample rate was 10 GHz/s. The experimental process revealed that still bubbles discharge easily compared with suspended movable ones. The starting discharge voltage of still bubbles is 13.5 kV, whereas that of the movable bubble is 14.8 kV.

Contrasting the UHF single waveform and the spectrum in Fig. 5 and Fig.6, the discharge pulse signal duration is about 400 ns. Two kinds of bubble defect PD signal states arise, namely, multi-peak oscillator discharge pulses with an amplitude of approximately 20 mV. The still bubble defect PD signal amplitude, which is higher than the movable bubble defect and has a longer attenuation time. The energy of suspended movable defect PD signal is concentrated at 300 MHz, while the still bubble defect PD signal has a wide range distribution, concentrated at 100-200MHz and 500-700MHz, indicated that still bubble defect is more easily to generate PD. During the initial discharge stage of still bubble defect, the discharge happens more easily, but the amplitude is not high. When the discharge time is extended, high-amplitude PD signal appears.

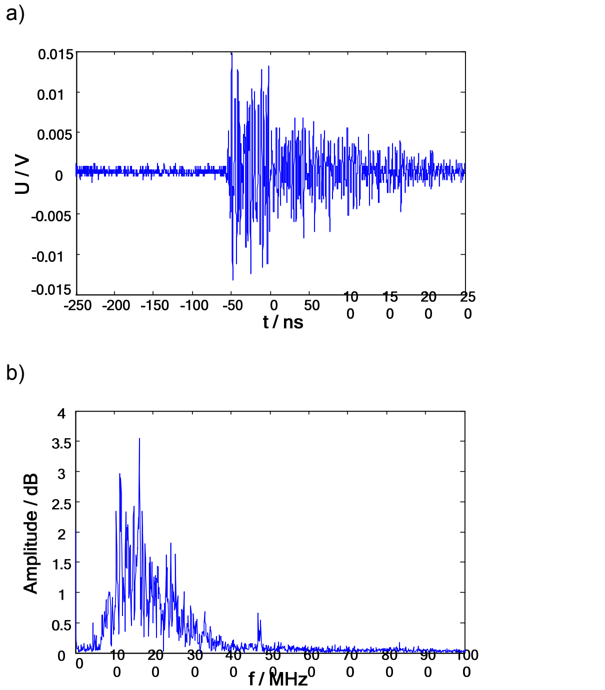


Fig.5. Suspended movable bubble defect: a) UHF signal, b) Frequency-domain distribution

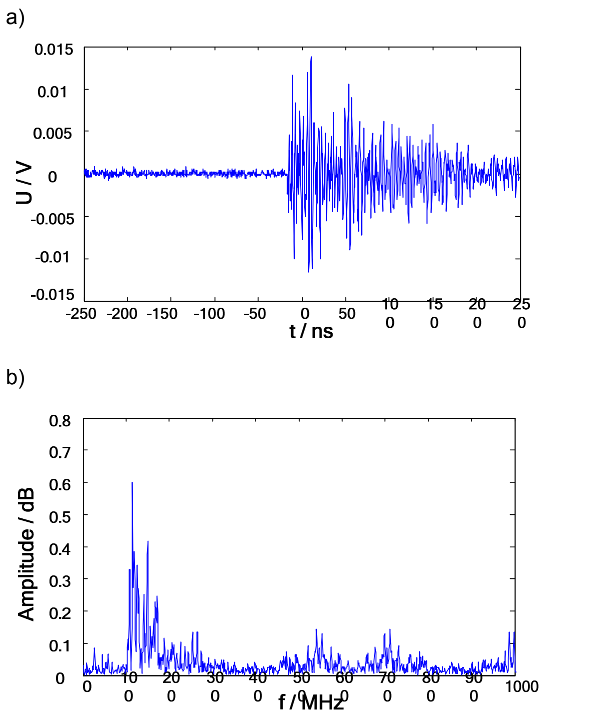
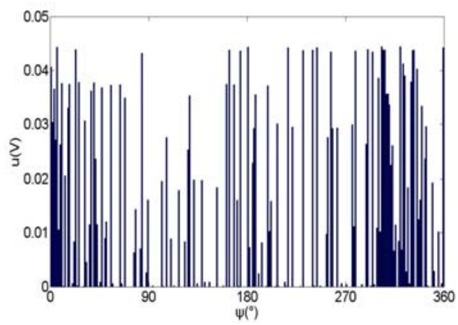


Fig.6. Still bubble defect: a) UHF signal, b) Frequency-domain distribution

Fig.7 shows the φ-u distribution of the two states of bubble defect discharge, where φ is the power frequency phase position, u is the discharge signal amplitude. They are quite different in the distribution, and the φ-u distribution of the suspended movable bubble defect discharge is uniform in phase, whereas the still bubble defect PD φ-u distribution concentrated at the 0–220° phase.

a)



b)

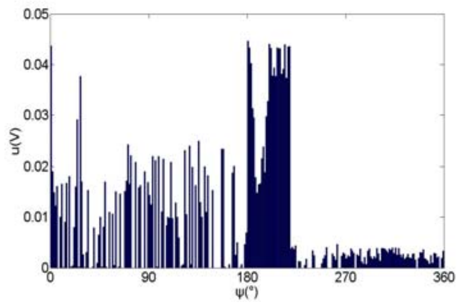


Fig.7. Amplitude–phase distribution of discharge: a) Suspended movable bubble defect, b) Still bubble defect

Conclusions

Based on the analysis of an actual power transformer operating environment, a PD test system was developed to simulate suspended movable bubble defect in transformer oil. Through the calculation of the flow and temperature controls, suitable control and measuring instruments were chosen, and a PD test platform was built based on UHF method. PD experiments on still and movable bubbles were carried out to test the platform, and many PD samples were obtained using a high-speed sampling system, revealing the difference between the two kinds of bubble defects. The spectrum of still bubble defect PD signal has a wide range distribution, while the spectrum of suspended movable bubble defect PD UHF signal is concentrated at 300MHz. The φ-u distribution of the suspended movable bubble defect discharge is uniform in phase, whereas the still bubble defect PD φ-u distribution concentrated at the 0–220° phase. The experimental results show that, the design of PD measurement system can accurately detect PD signals based on UHF method, and reveal the PD characterics of suspended movable bubble defect.

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