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Relationship between UHF PD Detection and Apparent Charge Quantity of Metal Protrusion in Air

***Abstract**. On the basis of the experiment model of metal protrusion, the relationship between UHF measurement and pulse current method was investigated by theory and experiment results. The results indicate that the optimal regression curve is energy of UHF signal relative to square of apparent discharge quantity. The variation of voltage has no impact on the regression curve. However, while the distance between protrusion and plate is changed, the slope of regression curve changes according to it and the same energy is corresponding to bigger discharge quantity.*

***Streszczenie.** Bazując na eksperymentalnym modelu rozrzutu metalu w powietrzu badano zależność pomiaru UHV i metodą prądu pulsującego. Stwierdzono, że energia sygnału UHV zależy w kwadracie od natężenia wyładowania. Wprawdzie energia wyładowania nie zależy od zmian napięcia ale wraz ze zmianą odległości między elektrodami wyładowania zmienia się kształt krzywej regresji w zależności od napięcia. (**Zależność między detekcją UHV wyładowania niezupełnego a wielkością ładunku metalu rozpylanego w powietrzu**)*

Keywords: Ultra high frequency; partial discharge;discharge quantity.
Słowa kluczowe: wyładowanie niezupełne, detekcja wyładowania.

1 Introduction

As failures that occur in electrical equipment often result from electrical breakdown in the insulation material, this may occur because of insulation damage caused by the cumulative adverse effects of partial discharge (PD) events. PD measurements have been recognized as an important tool to detect insulation faults for a long time [1-4].

Two effective PD measurement methods are conventional measurement as defined in IEC Standard 60270 and ultra high frequency (UHF) technique [5,6]. IEC60270 standard could give the apparent charge quantity of PD, which is widely used in preventive test of many high voltage equipments. However, the major bottleneck encountered with such measurement used in on-line monitoring is the ingress of external interferences that directly affects the sensitivity and reliability of the acquired PD data. Another disadvantage is that it only provides a slowly damped response to fast PD activity [7]. UHF technique uses a coupling sensor to measure the electromagnetic wave that is induced by PD current pulse. With high speed digital acquirement system, the accurate shape of the UHF signal could be recorded. UHF measurement is a non-contact technique and has the ability to spatially locate PD sources within electrical plant items. It is also insensitive to corona interference by choosing an appropriate measurement frequency band, thereby filtering out any unwanted corona signals. The main disadvantage of UHF technique is that it cannot give the charge quantity of PD.

Several studies have investigated an estimation of charge quantity of PD by UHF method based on the relationship between PD-induced electromagnetic wave and charge quantity of PD according to IEC60270 [8-12]. Japanese specialist Shinya Ohtsuka investigated the relationship between charge quantity of PD in GIS and PD-induced electromagnetic wave measured with UHF method. The results indicate that value of double integral of PD-induced electromagnetic wave's TEM mode component, is basically proportional to the charge quantity of PD current pulse independently of the sensor distance from PD source and the PD current pulse's shape [13].

G.P. Cleary and M.D. Judd investigated the UHF and current pulse of partial discharge activity in mineral oil. The conclusion is that the relationship between the energy of UHF signal and square of charge quantity is linear [12]. Other researches, such as References 7, combining UHF and IEC60270 techniques to diagnose the insulation defect of HV plant or discriminate discharge type.

In this paper, firstly, based on antenna theory, the authors deduced the relationship between UHF signal and its charge quantity. Secondly, on the basis of the experiment of metal protrusion in air, the relationship between UHF measurement and method of IEC60270 was investigated to verify the results deduced by antenna theory. The relationship curves of energy, peak voltage, peak-peak voltage of the UHF signal vs. apparent discharge quantity or the square of apparent discharge quantity were plotted at the same time. The impacts of voltage and the distance between protrusion and plate were investigated as well.

2 Relationship between UHF signal and its discharge quantity

UHF signals are caused by the acceleration of electrons within the PD current. As shown in figure 1, discharge quantity of metal protrusion is q, the current I is PD current. In antenna theory, it is called hertz dipole.

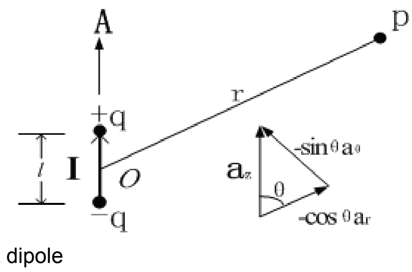


Fig.1 Hertz dipole

Because $I = jwq$, at point *p*,

$$dA = a_z \frac{\mu I e^{-j\beta r}}{4\pi r} dz \tag{1}$$

where: β – wavenumber, $\beta = \omega\sqrt{\mu\varepsilon}$, μ – permeability of medium, ε – permittivity of medium, r – the distance between centre of hertz dipole and point *p*.

According to figure 1, scalar form of *dA* is as follows:

$$d\,A_r = d\,A_z \cos\theta \tag{2}$$

$$d\,A_\theta = -d\,A_z \sin\theta \tag{3}$$

Therefore the magnetic field of hertz dipole H is:

(4) $$dH = \frac{dB}{\mu} = \frac{\nabla\times(dA)}{\mu} = \frac{1}{\mu}\begin{pmatrix} \frac{a_r}{r^2\sin\theta} & \frac{a_\theta}{r\sin\theta} & \frac{a_\phi}{r} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial\theta} & 0 \\ dA_r & rdA_\theta & 0 \end{pmatrix}$$

$$= a_\phi \frac{\hat{I} dz}{4\pi} e^{-j\beta r}[\frac{j\beta}{r} + \frac{1}{r^2}]\sin\theta$$

Electric field E is:

(5) $$dE = \frac{1}{j\omega\varepsilon}\nabla\times(dH) = a_r dE_r + a_\theta dE_\theta$$

Scalar form of dA is as follows:

(6) $$dE_r = \frac{I\,dz}{4\pi}e^{-j\beta r}[\frac{2\eta}{r^2} + \frac{2}{j\omega\varepsilon r^3}]\cos\theta$$

(7) $$dE_\theta = \frac{I\,dz}{4\pi}e^{-j\beta r}[\frac{j\omega\mu}{r} + \frac{\eta}{r^2} + \frac{1}{j\omega\varepsilon r^3}]\sin\theta$$

where: η – wave impedance, $\eta = \sqrt{\mu/\varepsilon}$

In near field region, since $e^{-j\beta r}$ approximately equals to 1, so expressions of H and E will be:

(8) $$H \cong a_\phi \frac{I\,l\sin\theta}{4\pi r^2}$$

(9) $$E \cong \frac{I\,l}{j\omega 4\pi\varepsilon r^3}(a_r 2\cos\theta + a_\theta\sin\theta)$$

Therefore, radiation intensity in near field region could be calculated as follows.

(10) $$S = \frac{1}{2}[E\times H^*] = -j\frac{I^2 l^2}{32\pi^2 r^5\omega\varepsilon}\sin^2\theta\, a_r$$

It is concluded that the radiation intensity is identity in the whole sphere surface, so the relationship between energy of UHF signal (could be calculated by surface integral of S) and current I is quadratic function.

Principle of IEC60270 is shown in figure 2. The type of detection impedance is *RC*. When test unit C_x generates a PD with charge quantity q, a voltage pulse Δu will be acquired. In theory, Δu is a pulse wave with right angle, but in practical, Δu should be described as follows:

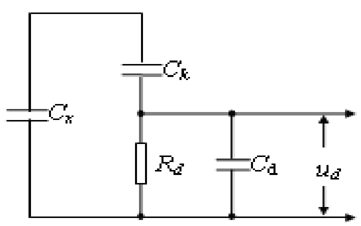


Fig.2 partial discharge RC detection circuit

(11) $$\Delta u = U_m(1 - e^{-\alpha_f t})$$

(12) $$U_m = q/[C_x + C_k C_d/(C_k + C_d)]$$

where: U_m – the amplitude of voltage pulse,

α_f – attenuation constant of PD.

Therefore, detected current could be calculated.

(13) $$\Delta i = I_m(1 - e^{-\alpha_f t})$$

(14) $$I_m = \frac{U_m}{R_d} = q/R_d[C_x + C_k C_d/(C_k + C_d)]$$

Where: I_m – the amplitude of current pulse

If $k_c = R_d[C_x + C_k C_d/(C_k + C_d)]$, then

(15) $$I_m = q/k_c$$

Current pulse I_m is radical current source I, so

(16) $$S = \frac{1}{2}[E\times H^*] = -j\frac{(\frac{q}{k_c})^2 l^2}{32\pi^2 r^5\omega\varepsilon}\sin^2\theta\, a_r$$

It is concluded that the relationship between energy of UHF signal S and charge quantity q is quadratic function.

(17) $$U = k_t E$$

where: U – the UHF electric field incident on the sensor, k_t – a parameter determined by the position and shape of antenna, so

(18) $$U = \frac{k_t l(a_r 2\cos\theta + a_\theta\sin\theta)}{j\omega 4\pi\varepsilon r^3 k_c}Q$$

If $k = \frac{k_t l(a_r 2\cos\theta + a_\theta\sin\theta)}{j\omega 4\pi\varepsilon r^3 k_c}$, so

(19) $$U = kQ$$

It is concluded that the relationship between the UHF electric field incident on the sensor U and apparent discharge quantity is linear and slope of the line is determined by shape and position of antenna as well as the PD source.

3 Experiments

3.1 Measurement system

The measurement system showed in Figure 3 is used to measure PD by IEC60270 and UHF technique. The metal protrusion located at the HV electrode is arranged in air as PD source. The distance between metallic protrusion and the plate is 10, 15 and 20mm. The distance between sensor and test unit is 50cm.

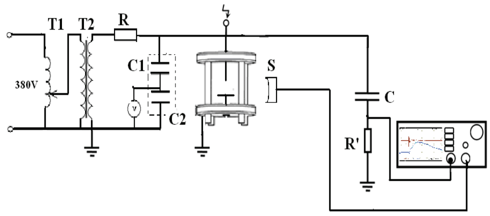


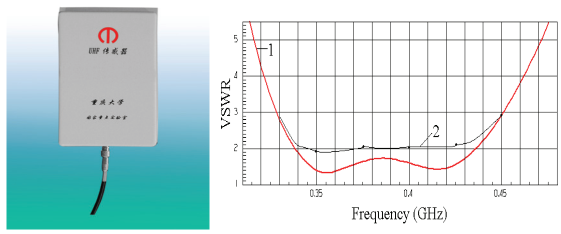
Fig. 3 Measurement system

T1 – 0-380V Induction voltage regulator; T2 – 100kV/0.5A, n=1000:1, Testing transformer without corona; C1/C2 – 2000pF/2μF Capacitive voltage divider; R – 10kΩ Protective resistance, S – microstrip patch antenna ,C – Coupling capacitance, R' – Impedance

3.2 Microstrip patch antenna

Different sensors have different performance in the UHF measurement. The authors devised a microstrip patch antenna as the UHF sensor. The bandwidth is 340-430MHz, centre frequency is 390MHz. Its performance parameters as below:

(a) Antenna (b) VSWR



(c) Pattern（400MHz） (d) Gain（400MHz）

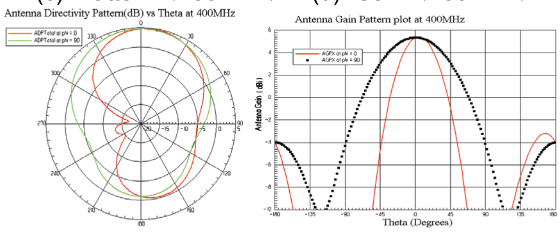


Fig. 4 Microstrip patch antenna parameters

3.3 Acquirement of data

A transformer with variable output (0–100 kV) was used to energize the PD sources under 50Hz AC conditions. UHF PD signals are acquired by a microstrip patch antenna and apparent charge quantity is calculated by taking the peak value of the IEC60270 pulse. Apparent charge quantity and UHF signals were captured simultaneously with the oscilloscope triggered on the UHF signals. The bandwidth of oscilloscope is 500MHz and sampling rate is 2.5Gs/s.

Changing the output of transformer, the PD will change with it. Under every testing voltage, five hundred apparent charge quantities and waveforms of UHF signals were recorded. The following figure shows the recorded signals of UHF and IEC60270 techniques.

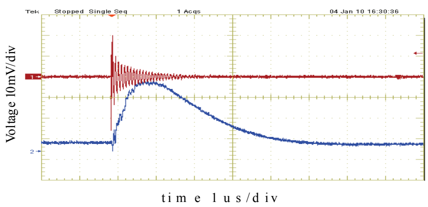


Fig. 5 Signals of UHF and IEC60270 signals

3.4 Tools for analyzing acquired data quantitatively

In order to determine the relationship between UHF signal and its apparent charge quantity, the authors calculate the amplitude value, peak-peak value, energy and the square of apparent charge quantity. The energy of UHF signal could be calculated by formula 20.

$$E_{RF} = \frac{\Delta t}{R}\sum_i V_i^2 \qquad (20)$$

where: V_i – voltage of the *i*th sampling point, R – the load impedance.

The marching way of measurement system is DC 50Ω, so the value of R = 50Ω. Because the sampling rate is 2.5Gs/s, the value of Δt is 0.4ns.

Regression analysis was applied to all data, so coefficient of determination R^2, which is an important index in field of statistical test to verify reliability of regression equations and determine the regression level of data, will be used to analyze the regression quantitatively. The value of coefficient of determination ranges from 0 to 1, the greater value means the better regression. The formula is as follows:

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{n} W_i(\hat{y}_i - \overline{Y})^2}{\sum_{i=1}^{n} W_i(Y_i - \overline{Y})^2} \qquad (21)$$

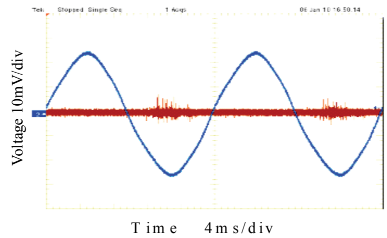
where: Y_i – observed values, $\overline{Y}$ – the mean value of Y_i, $\hat{y}_i$ – regression value. SSR – regression sum of squares, which represents the influence degree of independent variable on dependent variable. SST – total sum of squares, which indicates the total dispersion between all observed values and their mean values.

4 Reruslts and discussion

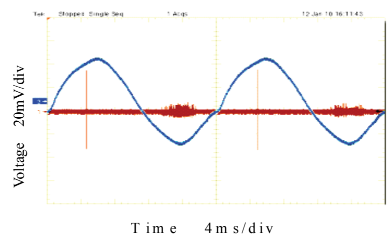
4.1 PD of metal protrusion in air

The PD of metal protrusion is typical corona discharge. Metal protrusion is connected to HV and adjusted the distance between protrusion and plate to 20mm. When voltage is increased to 5.1kV, PD signals start to be acquired as shown in figure 6(a). Under 5.1kV, PD signals are detected only in the negative half cycle with large quantity and smaller amplitude. With the increasing of voltage, PD starts to occur in the positive half cycle with small quantity and much higher amplitude compared with the negative half cycle. When voltage increases to 7.0kV, the UHF signal in positive half cycle is higher enough to be captured easily, as shown in figure 6(b). But this is contrary when metal protrusion is connected to low-voltage, as shown in figure 7.

(a) UHF signal of PD under 5.1kV



(b) UHF signal of PD under 7.0kV



(c) Waveforms of UHF signal of PD both in positive and negative half cycle under 7.0kV

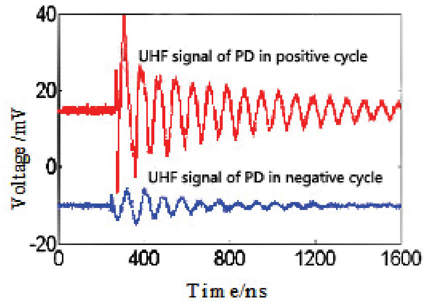


Fig. 6 UHF signal of PD when needle connected HV

From figure 6 we could conclude that the PD phenomenon and the waveform of UHF signal are different in different half cycle of voltage, as shown in figure 6(c). So the relationship between UHF signal and apparent quantity will be different in different half cycle.

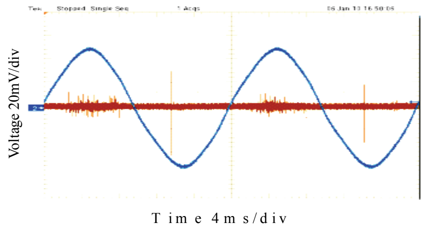


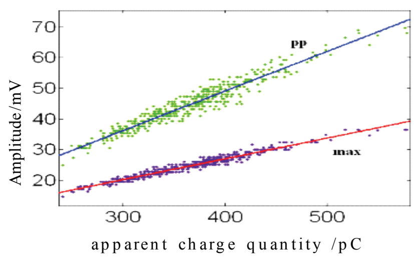
Fig. 7 UHF signal of PD when plate connected HV

Next the authors try to analyze the PD of both positive half cycle and negative half cycle with the needle connected with HV as below. There is contrary when needle is connected to low-voltage.

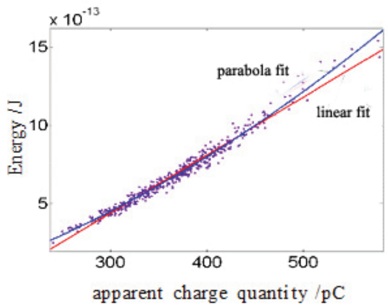
4.2 The relationship between UHF signal and apparent charge quantity in positive half cycle

The relationship of amplitude (max) and peak-peak (pp) value of UHF signal relative to apparent charge quantity is shown in Figure 8(a).

(a) Amplitude and peak-peak value relative to apparent charge quantity



(b) Energy relative to apparent charge quantity



(c) Energy relative to square of apparent charge quantity

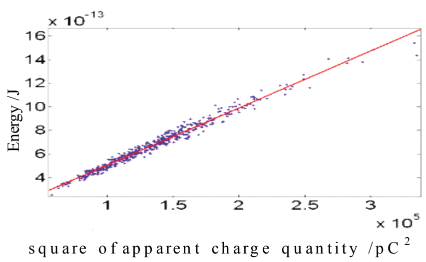


Fig. 8 Relationship between UHF signal and apparent charge quantity

The relationship between energy and apparent charge quantity is shown in figure 8(b). From the figure and data in table 1 we could know the relationship is not linear but square-law. For linear regression, the value of coefficient of determination is 0.9734, but 0.9791 for regression of square-law. The relationship of energy of UHF signal relative to square of apparent charge quantity is shown in figure 8(c). In theory, this relationship is identical with square-law in figure 7(b).

Table 1 shows the coefficients of determination of all calculated parameters under different voltage. It is concluded that linear relationship does exist between energy of UHF signal and square of apparent charge quantity.

Table 1. Value of coefficient of determination R^2

R^2	max	pp	Energy		$q2$
			linear	square	
7.0kV	0.9471	0.9224	0.9767	0.9777	0.9783
9.0kV	0.9557	0.9284	0.9734	0.9791	0.9777
10.0kV	0.9496	0.9218	0.9585	0.9760	0.9760

4.3 The relationship under different voltages

In this section, the authors investigate how relationship between energy of UHF signal and square of apparent discharge quantity changes with the change of voltage. Figure 9 shows its relationship under 7.0kV, 9.0kV and 10.0kV. We find that the variation of voltage has no impact on the regression curve, that is, data from different voltages regress to the same line.

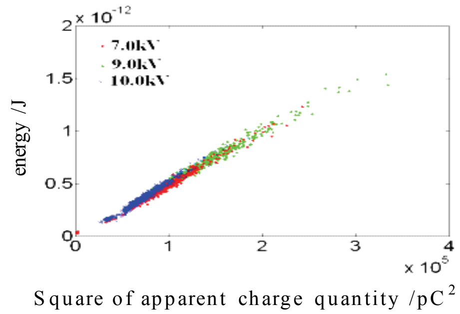


Fig. 9 Relationship between energy of UHF signal and apparent discharge quantity under different voltages

4.4 The relationship under different distance between protrusion and plate

The relationships under different distances between protrusion and plate are shown in figure 10. It shows that when the distance is 20 or 15mm, the relationship is still linear though the slope of regression line is different. However, when the distance is decreased to 10mm, the PD phenomena starts to change and the linear relationship is not so clear though energy of UHF signal still increases with apparent discharge quantity.

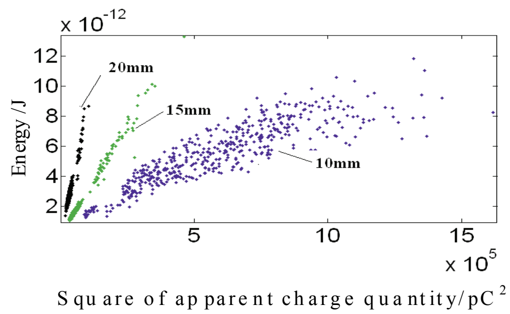


Fig.10 Relationship between energy of UHF signal and apparent discharge quantity under different distances

Normally, as the gap distance gets larger, the discharge quantity gets smaller. Because the PD of needle plate gap is limited in small range around the big curvature electrode.

When the gap distance increases in non-uniform electric field, the accumulation of anion gets relatively more, which hinders the development of the PD signals. For these reasons, as the gap distance gets larger, the discharge quantity gets smaller.

4.5 The relationship in negative half cycle

The relationship between amplitude of UHF signal and apparent discharge quantity on the distances of 10, 15, 20mm under 7.0 kV are shown in figure 11. We find it different from that of positive half cycle. First, apparent charge quantity is much smaller in identical testing condition. In general, it is less than 100pC. Second, there is no regression curve describing the relationship. The only relationship could be concluded is that apparent charge quantity increases with decrease of distances between protrusion and plate.

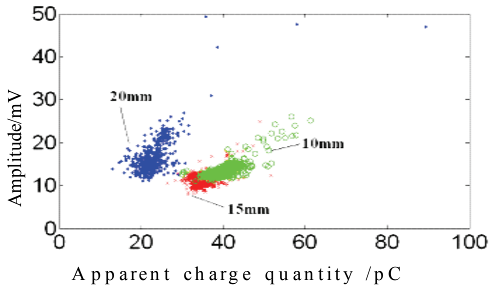


Fig. 11 Relationship between amplitude and apparent discharge quantity in negative half cycle

5 Conclusions

In this study, the authors investigated the relationship between the parameters of UHF signal and apparent discharge quantity. Reasoned by theory and experiment results, it indicated that the best regression curve with the biggest value of coefficient of determination is energy of UHF signal relative to square of apparent discharge quantity.

The waveforms and chararacteristics of PD in positive and negative are different. When Metal protrusion is connected to HV, the relationship between energy of UHF signals and apparent charge quantity in positive half cycle is quadratic function. Moreover, under different voltages, it regresses to an identical line. However, there is no corresponding relationship in nagative half cycle. And also,as the gap distance gets smaller, the discharge quantity gets larger, but the linear relationship between energy of UHF signal and square of apparent discharge quantity gets more obscure.

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REFERENCES

[1] Masayuki Hikita, Shinya Ohtsuka and Satoshi Matsumoto. Recent Trend of the Partial Discharge Measurement Technique Using the UHF Electromagnetic Wave Detection Method. IEEJ Trans. Electrical and Electronic, 2007, 2(1): 504-509.

[2] M. D. Judd, O. Farish and B. F. Hampton. Excitation of UHF Signals by Partial Discharges in GIS. IEEE Trans. Dielectr. Electr. Insul, 1996, 3(4): 213-228.

[3] Raymond Bell, Chris Charlson, Shaun Paul Halliday et al. High-voltage Onsite Commissioning Tests for Gas-insulated Substations Using UHF Partial Discharge Detection. IEEE Trans. Power Delivery, 2003, 18(4):. 1187-1191.

[4] Ju Tang; Qian Zhou; Ming Tang et al. Study on mathematical model for VHF partial discharge of typical insulated defects in GIS, IEEE Trans. Dielectr. Electr. Insul., 2007, 14(1): 30–37.

[5] A. J. Reid, M. D. Judd, B. G. Stewar et al. Identification of multiple defects in solid insulation using combined UHF and IEC60270 PD measurement. In 9th IEEE International Conference on Solid Dielectrics, 2007.

[6] A. J. Reid, M. D. Judd, B. G. Stewar et al. Correlation between UHF energy and IEC60270 apparent charge for selected partial discharge source geometries. In 15th International Symposium on High Voltage Engineering, 2007.

[7] B.G. Stewart, A. J. Reid, M. D. Judd and R. A. Fouracre. UHF and IEC60270 Correlation Analysis of Radiated Frequency Band Measurements on Resin Insulation Void Samples. 2007 Electrical Insulation Conference and Electrical Manufacturing Expo, 2007, 138-141.

[8] A. G. Sellars, S.J. MacGregor and O. Farish. Calibrating the UHF technique of partial discharge detection using a PD simulator, IEEE Trans. Dielectr. Electr. Insul., Vol. 3, No. 4, pp. 46-53, 1995.

[9] N. Kock, B. Coric, and R. Pietsch. UHF PD detection in gas-insulated switchgear—Suitability and sensitivity of the UHF method in comparison with the IEC 270 method. IEEE Electr. Insul. Mag, 1996, 12(6): 20–26.

[10] A. J. Reid, L. Yang, M. D. Judd, B. G. Stewar et al. An integrated measurement strategy for simultaneous fault identification: Combining the UHF and IEC60270 techniques. In 14th International Symposium on High Voltage Engineering, 2005.

[11] A. J. Reid, M. D. Judd, B. G. Stewart et al. Frequency distribution of UHF energy from PD sources and its application in combined UHF and IEC60270 measurements. In IEEE Conference onElectrical Insulation and Dielectric Phenomena, 2006.

[12] G.P. Cleary, M.D. Judd. UHF and current pulse measurements of partial discharge activity in mineral oil. IEE Proc. Measurement Technology. 2006, 153(2): 47-54.

[13] Shinya Ohtsuka, Takashi Teshima, Satoshi Matsumoto, et al. Relationship between PD induced electromagnetic wave measured with UHF method and charge quantity obtained by PD current waveform in model GIS. 2006 Annual Report Conference on Electrical Insulation and Dielectric Phenomena,, 2006, 645-618.

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