Enhanced Bowtie UHF Antenna for Detecting Partial Discharge in Gas Insulated Substation

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***Abstract*-UHF method to detect partial discharge (PD) phenomenon has been proven to be an effective way. Many types of UHF antenna have been developed in order to achieve a better sensitivity and accuracy in certain bandwidth (300 MHz – 3.0 GHz) for detecting the ultra-high frequencies generated by partial discharge. Bowtie antenna is proven to be sensitive, accurate and easily designed and fabricated. This paper focuses on the enhancement of bowtie antenna to achieve better performance in detecting partial discharge using UHF method. Characteristics of antenna both on the simulation result prior to the fabrication and measurement using a network analyzer show the good agreement. Experiment was carried out in a gas insulated switchgear (GIS) model with a protrusion on the conductor as PD source and antenna located at different positions with applied voltage range from 20 – 25 kV. EM wave intensity and frequency captured by antenna were observed. The relation between the distances of PD source to antenna, either from one spacer aperture to others, or distance from one spacer aperture were investigated. Antenna mounted 55 cm from the closest spacer aperture to the PD source can still detect EM wave intensity very well. The lowest EM wave peak envelope intensity measured at 30.03 mV from the same spacer aperture compared to 1.952 mV peak-peak EM wave intensity from internal GIS UHF sensor demonstrates a sufficient sensitivity performance.**

***Index Terms*—bowtie antenna, partial discharge, UHF, protrusion, EMW intensity, transmission rate, cut off frequency.**

I. Introduction

The insulation system of high voltage equipments plays an important role in the power system operation. Assessments and diagnosis of the insulation condition of equipments become primary requirement in simple, reliable and economic way. Ultra high frequency (UHF) method is known widely and regarded as effective and powerful tool to assess and diagnose the existence of partial discharge (PD) activities [1]-[4]. UHF method has good sensitivity in certain bandwidth.

This work focuses on bowtie antenna as UHF PD signal detector, which is considered easily adjust to accommodate specific operating bandwidth or to be scaled accordingly for certain application [5]-[7]. Experiment was carried out in a 66 kV GIS model tank. PD source was protrusion on the high voltage (HV) conductor, modelled with a 50 mm needle and attached to the GIS HV conductor.

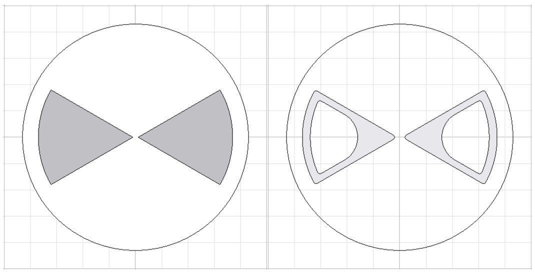
This paper is organized into 5 parts: section 1 the introduction, section 2 presents the antenna design and fabrication, section 3 describes experimental set up and measurement of PD EM wave, section 4 shows relation between the PD source to various antenna positions completed with the EM wave intensity observations, and lastly; section 5 the conclusion and further discussion.

II. Antenna Design and Fabrication

Finite-difference time-domain (FDTD) method is widely known as a numerical method for its application in antenna design and simulation [8]-[10]. In prior research, FDTD was applied to simulate and analyze the design and performance of bowtie antenna as PD detection [8]. The bowtie antenna was designed based on an original model, Fig. 1(a). The simulation and analysis has summarized the primary design parameters of antenna as follow:

- Flare angle
- Wings radius
- Gap distance
- Thickness of antenna
- Dielectric constant of substrate
- Effective current distribution

The geometry dimensions are basically identical with the exception of curvature at the apex and the edge of antenna. The defects at bowtie antenna result in two peaks at different peak wavelength [14]. The inner defect was controlled as variable due to the FDTD analysis of current distribution at higher frequency range [8].



(a) (b)

Fig. 1 Antenna model: (a) original bowtie model and (b) enhanced bowtie model.

The proposed antenna geometry and the fabricated bowtie antenna (Fig. 2) are as follows:

- Flare angle = 60°
- Wings radius = 36.0 mm
- Gap distance = 2.0 mm
- Substrate relative dielectric constant = 4.2
- Radius curvature of defect = 10.0 mm
- Inner radius of defect = 33.0 mm
- Radius curvature of apex = 2.5 mm
- Radius curvature of edge = 2.5 mm

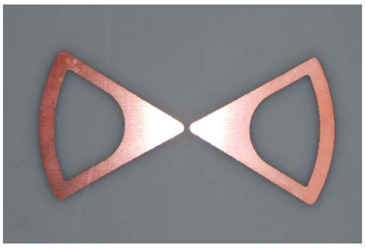


Fig. 2 Enhanced bowtie antenna fabricated on a printed board.

The network analyzer measurement (Fig. 3) on the modified antennas shows that the enhanced bowtie antenna has lower return loss (RL) compared to the original model from 300 kHz up to 3.8 GHz. The RL of the enhanced antenna has 2 points of resonant frequencies at 1.05 GHz and 3.1 GHz. The highest RL response is around -37 dB; while the original model only reaches -20 dB.

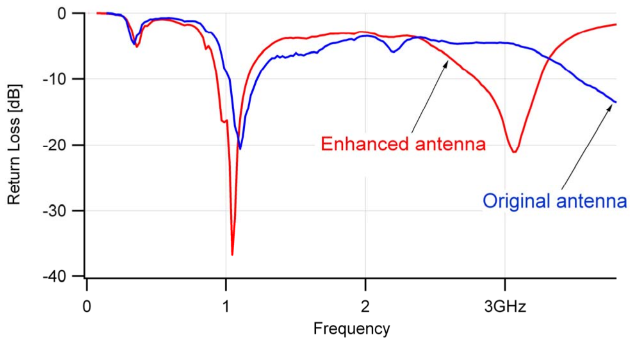


Fig. 3 S_{11} parameter measured by network analyzer

The rise of boresight level of enhanced antenna might be due to the presence of hole defect which allows more electron to concentrate at the region near the centre tip corresponding to the polarization of electric field and the travel trajectory of the electrons associated to the effective path length of the electron movement in the upper and bottom edges of bowtie antenna [16].

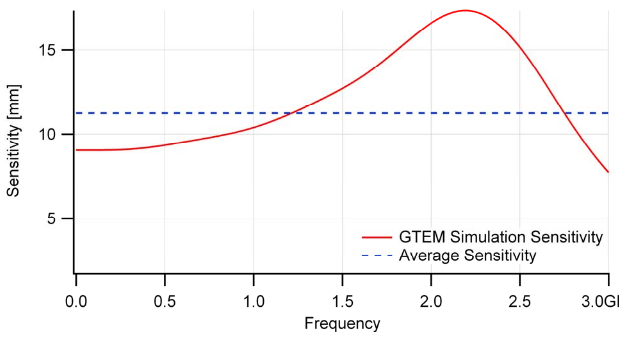


Fig. 4 GTEM simulation for antenna sensitivity check

Prior to the fabrication, GTEM simulation was carried out to estimate the sensitivity of antenna. A plane wave of 1 V/m was generated to the antenna and the output of antenna was calculated. Fig. 4 illustrated the GTEM simulation result. For frequency range 300 kHz to 3.0 GHz, the highest sensitivity is 16.5 mm (red solid line) at 2.14 GHz with average 11.25 mm (blue dash line), which satisfies the requirement for UHF coupler of no less than 6 mV/Vm^{-1} [15].

III. Experimental Setup

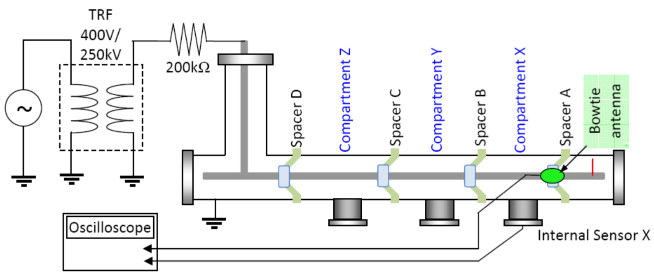


Fig. 5 Experimental set up

Experiment configuration is shown in Fig. 5. The model 66 kV GIS testing facility consists of 5 chambers in a straight line configuration filled with SF6 at 0.05 MPa [11]-[12]. A 50 mm needle was attached to the conductor as PD source

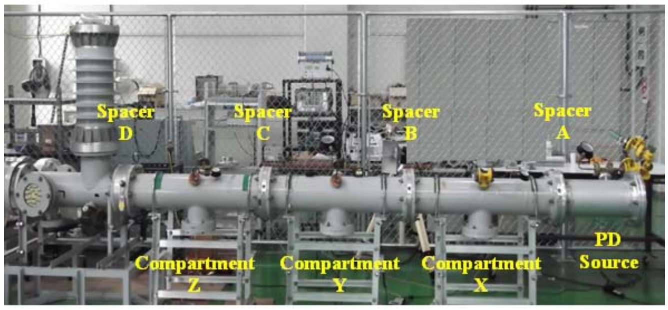


Fig. 6 GIS configuration

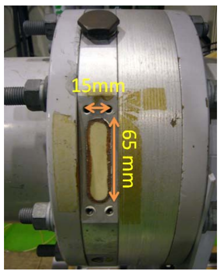


Fig. 7 Spacer aperture

and PDIV was measured at 14 kV. The gap distance between the needle tip to outer tank conductor of GIS tank was set 10 mm.

The UHF signals emitted by PD source were observed using the enhanced bowtie antenna and compared to the internal sensor at compartment X (Fig. 6 and Fig. 7) using a 1 GHz oscilloscope with sampling rate 5.0 GS/s.

The output signal detected with the bowtie antenna was amplified with 36 dB gain. A 25 kV testing voltage was applied to GIS by a single phase 400 V/250 kV testing transformer through a 200 kΩ resistor. The distance between two spacer apertures was 1000 mm. The distance from PD source to the first aperture was 380 mm.

The enhanced bowtie antennas were mounted at 4 locations: spacer aperture A, B, C and D. The sensitivity of the antenna was also tested at various distances from spacer aperture A to 10, 300 and 550 mm.

IV. Measurement Result and Discussion

A. Spacer position

PD UHF signal obtained from each spacer position was measured and processed as peak envelope [13] as shown in Fig. 8.

In this case, the antenna was set in an antenna amplifying box and attached closely to the spacer aperture. The maximum measurement of EMW intensity at spacer A, B, C and D are 223 mV, 172 mV, 115 mV and 83 mV. Transmission rate was thus calculated by equation (1) with EMW intensity at spacer A as reference.

$$\text{Transmission\_rate} = \frac{V_{max}(\text{Spacer}_{position})}{V_{max}(\text{Spacer}_A)} \ldots\ldots \quad (1)$$

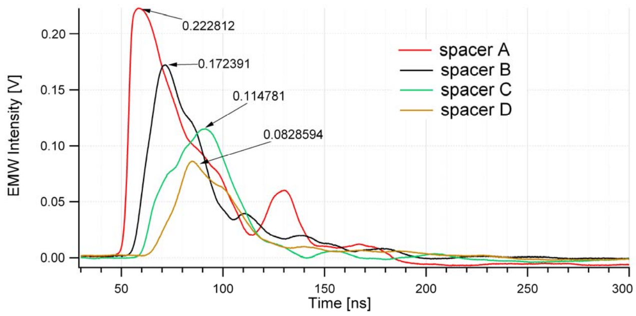


Fig. 8 UHF signal measurement by enhanced bowtie antenna at spacer A, B, C and D

As described in the figure 9 below, the transmission rate is decreased as linear function of position with average

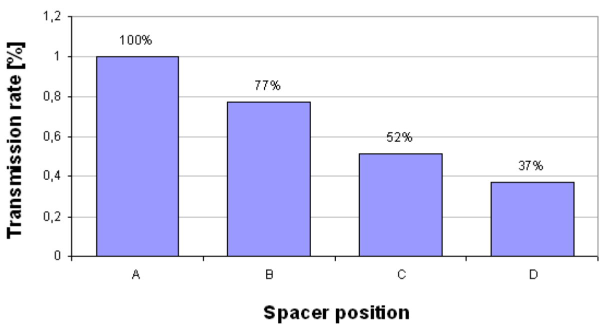


Fig. 9 Transmission rate of PD induced EMW at different spacer position

decrement of 21.4% per meter. This decrement can only be achieved when the EMW propagates inside the GIS tank which acts as a tubular waveguide.

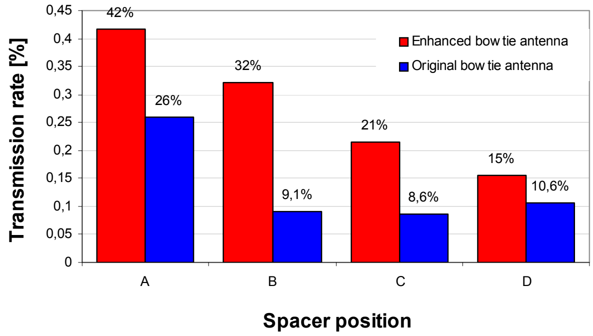


Fig. 10 Transmission rate of PD induced EMW at different spacer position of enhanced and original bowtie antenna comparison

Fig. 10 illustrates the comparison of transmission rate between the enhanced and original bowtie antenna. Both transmission rates were calculated with reference to EMW intensity of internal sensor at compartment X.

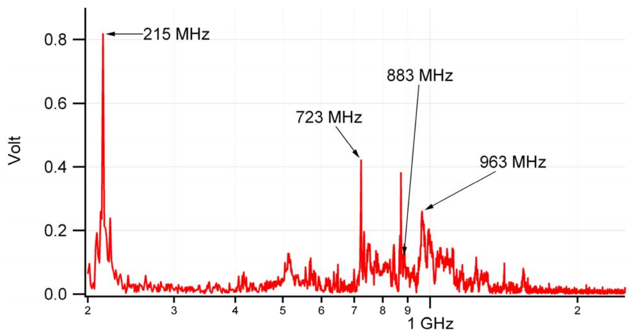


Fig. 11 Frequency spectrum of UHF signal measured by enhanced bowtie antenna

The enhanced antenna has higher rate at each spacer position with a consistent linear negative correlation with the function of distance from the PD source location. The original antenna measured lower transmission rate but the correlation did not appear linear and at spacer D tended to increase.

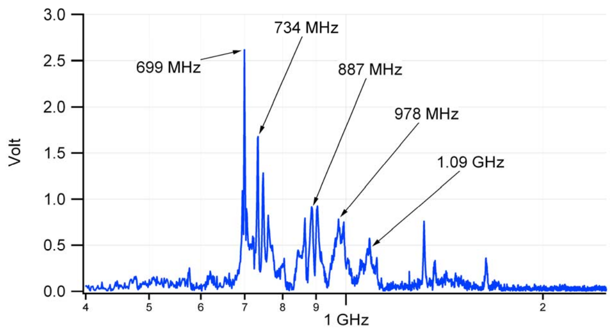


Fig. 12 Frequency spectrum of PD UHF signal measured by internal sensor at compartment X

The frequency analysis was extracted from the measurement signal by FFT analysis. The dominant frequencies were 215 MHz, 723 MHz, 883 MHz and 963

MHz (Fig. 11). The lowest frequency 214.84 MHz corresponded to external noise since it was less than the cut off frequency inside the GIS tank and absence of this frequency from internal sensor measurement (Fig. 12).

The dimension of GIS results in the cut off frequency of 681 MHz. The transverse electric (TE) modes in this GIS configuration are shown in Table 1 as equation (2).

Due to the spacer aperture size, the leakage frequency is 1.153 GHz as calculated using equation (3) which was considered as slot array antenna.

- TE cut off frequency:

$$f_{m,n} = \frac{c}{\pi \cdot (r_i + r_o) \cdot \sqrt{\varepsilon_r}} \cdot m,$$

For $m = 1,2,3,...$ and $n = 1$ ....(2)

- Spacer aperture penetration frequency:

$$f_c = \frac{c}{4 \cdot l},$$

Aperture size $w \times l = 15\text{mm} \times 65\text{mm}$ ....(3)

TABLE I
TE MODE CALCULATION DUE TO GEOMETRY OF GIS

Mode	Cut off Frequency
TE11	680.9 MHz
TE21	1.362 GHz
TE31	2.043 GHz
TE41	2.724 GHz

The result that shows the antenna still measured the frequency lower than leakage frequency from the spacer aperture can be interpreted as follows; the spacer with higher relative permittivity might improve the UHF signal level further [15] and the equation (3) does not take the relative permittivity into account.

Comparison of physical distance of aperture and calculation of Time of Arrival (TOA) of EMW signal difference between the each position of antenna confirmed the acceptable value. The differences of TOA of UHF signal at the spacer aperture with internal sensor as reference is approximately 4 ns and results in 1.2 m which is close the exact distance between spacer (1.0 m).

B. Distance from spacer aperture A

In this case, the antenna was set in the same condition and located at various distance from spacer A's aperture: closely attached to the aperture, 300 mm and 550 mm from the aperture. UHF signal measurement as function of distances from spacer A as variable shows that at 0, 300 and 550 mm the antenna still performed good PD detection sensitivity of 30, 63 and 34.8 mV EMW intensity at 5.5, 63 and 66 pC, respectively (Fig. 13). The charge was estimated using the comparison of EMW intensity of enhanced bowtie antenna and the internal sensor at compartment X with the calibration testing of internal sensor at X position with the same PD source to the conventional charge measurement using capacitor and detecting impedance.

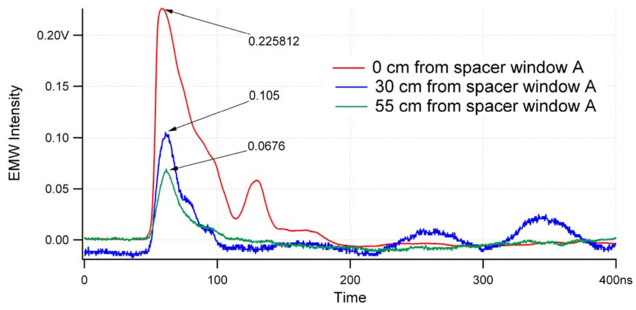


Fig. 13 UHF signal measurement by enhanced bowtie antenna at different distances from spacer A's aperture

The transmission rate was calculated with reference to the internal sensor, and then the results were averaged and recalculated with reference to the closest distance. Transmission rate falls to 48% and 30% at distances 300 mm and 550 mm as shown in Fig. 14.

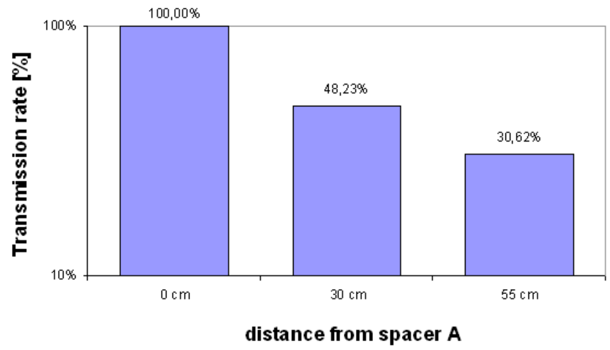


Fig. 14 Transmission rate of PD induced EMW at different distances from spacer A's aperture

Note that the average decrement of transmission rate is 127% per meter. In this experiment, the increment of the distance from the spacer aperture enlarged the scattering direction of EMW, so it would certainly reduce the attenuation of UHF signals.

Unlike in the spacer position experiment, the GIS tank behaved as a huge waveguide that enables EMW to travel inside in a relative stable intensity. Even 3380 mm from the PD source, the enhanced antenna still has 37% transmission rate compared to 55 mm from spacer A's aperture.

The FFT of UHF signals showed the same result as in previous experiment. It was also confirmed from the FFT result that the antenna has lower bandwidth starting from approximately 210 MHz. FFT analysis can only be performed up to 2 GHz. The higher frequency bandwidth could not be presented due to the limitation of the oscilloscope.

V. Conclusion and Further Discussion

A newly developed enhanced bowtie antenna was designated to detect the UHF signal from 300 MHz up to 3.0 GHz emitted by PD source from the GIS model. GTEM simulation showed that the antenna satisfied the application requirement as UHF PD detector.

Enhanced bowtie antenna was able to improve the gain of S11 parameter 15 dB lower than the original model. The noise detection (214 MHz) confirmed that antenna has lower frequency band level.

The experiment of UHF PD detection using the enhanced bowtie antenna with 36 dB gain has been proven successfully at different spacer locations and various distances from spacer aperture A. The best position to mount the antenna is at the nearest distance from the spacer aperture.

Further experiment shall be carried out with various type of PD source, and penetration (leakage) frequency through spacer aperture shall be confirmed in detail.

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References

[1] M. Hikita, S. Ohtsuka and S. Matsumoto, "Recent Trend of The Partial Discharge Measurement Technique Using UHF Electromagnetic Wave Detection Method," IEEJ Transaction on Electrical and Electronics Engineering, vol 2, issued 5, pp. 504-5-9, 2007.

[2] Maruyama, S. Hoshino et. Al., "Sensitivity Characteristics of Various UHF Sensors Attached Outside a GIS Tank," The International Conference on Condition Monitoring and Diagnosis, Japan, 2010.

[3] J. S. Pearson, B. F. Hampton and A. G. Sellars, "A Continuous UHF Monitoring for Gas Insulated Substations," IEEE Trans. on Electrical Insulation, vol. 26, no. 3, pp. 169-478, June, 1991.

[4] R. Kurrer and K. Feser, " The Application of Ultra High Frequency Partial Discharge Measurement to Gas Insulated Substations," IEEE Trans. Power Delivery , vol. 13, no. 3, pp. 777-782, July, 1998.

[5] A.A. Lestari, A.G. Yarovoy, L.P. Ligthart, "An efficient Ultra-Wideband Bowtie Antenna," Proceeding European Microwave Conference, London, UK, pp. 120-132, September 2001.

[6] B. Allen, M. Dohler, E. E. Okon, W. Q. Malik, A. K. Brown, D. J. Edwards "Ultra-wideband Antennas and Propagation for Communications and Radar Imaging" John Wiley & Sons © 2007.

[7] Chen, Y. L., C. Ruan, and L. Peng, "A novel ultra-wideband bowtie slot antenna in wireless communication systems," Progress In Electromagnetics Research Letters, vol. 1, 101–108, 2008.

[8] J. Muslim, A. Susilo, K. Nishigouchi, Y. Z. Arief, U. Khayam, Suwarno, M. Lozako, M. Hikita "Improvement of Bowtie UHF Antenna for detecting Partial Discharge in Gas Insulated Substation" International Conference on Electrical Engineering and Informatics (ICEEI), pp. 217-224, Malaysia, July, 2013.

[9] P. Silvester, "Finite-element analysis of planar microwave networks," IEEE Trans. Microwave Theory Tech., vol. MTT-21, pp. 104–108, Feb. 1973.

[10] A. Reineix and B. Jecko, "Analysis of microstrip patch antennas using finite difference time domain method," IEEE Trans. Antennas Propagat., vol. 37, pp. 1361–1369, Nov. 1989.

[11] W. A. Putro, Sriyono, K. Nishigouchi, U. Khayam, Suwarno, M. Kozako, M. Hikita, K. Urano, Chen Min "PD Pattern of Various Defects Measured by UHF External Sensor on 66 kV GIS Model," conference Proceeding of CMD, Bali, Indonesia, 2012.

[12] W. A. Putro, Sriyono, K. Nishigouchi, U. Khayam, Suwarno, M. Kozako, M. Hikita, K. Urano, Chen Min "Influence of Spacer Aperture Size on PD-Induced Electromagnetic Wave Measured with UHF External Sensor in 66 kV GIS Model," conference Proceeding of CMD, Bali, Indonesia, 2012.

[13] Li Li-Xue et. al., "Partial Discharge Diagnosis on GIS based on Envelope Detection," WSEAS Transaction, 2008.

[14] Kebo He, Ji Chen, Zhaoyu Zhang, "Bowtie Nanoantennas with Void Defects," Photonics Global Conference (PGC), pp. 1-3, Singapore, December, 2012.

[15] M. D. Judd, O. Farish, J. S. Pearson and B. F. Hampton, "Dielectric Windows for UHF Partial Discharge Detection," IEEE Trans. on Dielectric and Electrical Insulation, vol. 8, no. 6, pp. 953-958, December, 2001.