Investigation of Partial Discharge Localization Method in Time Domain in GIS

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Abstract: It’s needed to locate the PD source for identifying the insulation defect which induces PD to happen and eventually causes insulation breakdown in gas insulated switchgear (GIS). A simple and obvious way of PD localization is the time of flight method which is widely used as a part of UHF method. But in application, the time of flight method can hardly be applied effectively and will induce errors if the initial pulse of the PD signal is small and blurry or its signal-to-noise ratio (SNR) is too low. For improving the accuracy of PD localization, the characteristics of electromagnetic wave (EM-wave) propagation route in GIS were investigated in this paper. The simulation and experiment results show that the EM-wave signals induced by PD in GIS are related with EM-wave propagation routes, which were decided by the location of PD source and detector’s position. As a result, a PD localization method in time domain based on EM-wave propagation route was proposed. The experiment results show that the proposed method can locate the PD well and effectively in the case that the initial pulse of PD signals is very small and blurry when PD source locates near the outer conductor of GIS.

Key-Words: GIS, partial discharge, UHF, localization, electromagnetic wave, propagation route

1 Introduction
The existence of small defects such as fixed protrusion or free moving particles in gas insulated switchgear (GIS) can induce partial discharge (PD) which will deteriorate insulation condition and eventually cause insulation breakdown when GIS are in service. Thus, the detection of PD is very important for early detection of insulation defects, preventing insulation failure and improving the power supply reliability [1-4]. Standardized method of PD detection defined by IEC 60270[5] is the best way used in the factory, but there are some limitations such as interference from electromagnetic noise is difficult to be discriminated and PD localization is not possible when it is used for on-site PD detection in GIS. To solve these problems, Ultra High Frequency (UHF) method has been introduced and widely used for on-site testing of GIS recently [6-10]. UHF method based on detecting the UHF band (300MHz to 3GHz) electromagnetic wave signal emitted by the PD pulse is relatively free from external noises and has good sensitivity during on-site testing. The additional and valuable advantage of this technique is the capacity of locating PD source in GIS.

It’s needed to locate the PD source for finding the insulation defect when PD happened in GIS. Time of flight method is widely used for locating PD in GIS for the merits such as simple principle, easy implementation and good veracity [11-13]. But if the initial pulse of the PD signal is small and blurry or its signal-to-noise ratio (SNR) is too low, the time of flight method can hardly be applied effectively and will induce errors. Inputting UHF signal by a monopole probe protruding through the outer conductor of GIS and detecting the signal by UHF coupler which mounted directly in line with the source probe, it was found that the initial pulse of signal was small and a much larger signal occurred a short time later which can be explained by the propagation of the normal electric field around the inner surface of the outer conductor [14]. Yet the phenomena and characteristic of EM-wave propagation route have not been researched thoroughly. Will the propagation route be affected by PD source position? What is the relationship between the signal waveform and UHF sensor position?

For improving the accuracy and validity of PD localization, the characteristics of EM-wave propagation route in GIS were investigated in this paper. The relationships between the EM-wave signals in GIS and the positions of PD source and detector were analyzed by constructing relatively simulation models and experiment system. As a result, a partial discharge localization method in time domain based on EM-wave propagation route was proposed which can locate the PD source well...
when the initial pulse of PD signal is small and blurry.

2 Time of Flight Method

Time of flight method is a simple and obvious way of locating PD source in GIS. As shown in Fig 1, when PD signal propagating in GIS, the time of it arriving at UHF sensors are different as the lengths of the propagation routes are different, so the time of flight technique locates the PD source by calculating the time difference between the wave fronts of PD signal arriving at two UHF sensors. The distance between PD source and UHF sensor can be calculated by the following equation [13]:

\[ X_1 = \frac{X - (X_2 - X_1)}{2} = \frac{X - c_0 \cdot \Delta t}{2} \]  

(1)

Where X is the distance between two sensors, X1 and X2 are the relative distance between PD source and two sensors, c0 = 0.3 m/ns, \( \Delta t \) is the time difference which is determined by the initial pulses of signals detected by two sensors.

Equation (1) is always used to locate PD source in time of flight method. The time of signal initial pulse is used as reference time to calculate the time difference \( \Delta t \). But if the initial pulse of the PD signal is small and blurry or its SNR is too low, the \( \Delta t \) can not be easily identified and the time of flight method can hardly be applied effectively and will induce errors.

3 The Characteristics of EM-wave Propagation Route

3.1 Theory

GIS can be regarded as a coaxial waveguide with the radius of inner conductor and outer conductor are a and b, as shown in Fig 2. It is known from EM-wave theory that not only TEM mode but also TE and TM modes can exist in coaxial waveguide. But TE and TM modes have cut-off frequencies and can only propagate at frequencies above their own cut-off frequency while TEM mode can propagate at any frequency. The cut-off frequency of high order mode can be approximately obtained by the following equation [15]:

\[ f_{c_{mn}} = k_{c_{mn}} / (2\pi \sqrt{\mu\epsilon}) \]  

(2)

Where \( \mu \) is the medium permeability, \( \epsilon \) is the medium permittivity; \( k_{c_{mn}} \) is the cut-off wave number of each high order mode.

TEM mode propagating velocity which relates with the light speed \( c = 1/\sqrt{\mu\epsilon} \) in coaxial waveguide and the transmitting speed of high order modes can be expressed as the following equation [16]:

\[ u_{g_{mn}} = u_p \sqrt{1 - (f_{c_{mn}} / f)} \]  

(3)

Where \( u_p = 1/\sqrt{\mu\epsilon} \) is the phase speed of EM-wave, it is equal with the light speed c.

EM-waves are emitted to the space around PD source in all directions when PD happens in GIS. The EM-wave propagates in GIS in such way that it transmits to the waveguide wall in a certain angle and reflected in the same angle. Considering that the incidence angle is related with the radial position of PD source in GIS, the EM-waves propagation routes are analyzed as PD source locating near inner conductor or outer conductor.

(a) PD near inner conductor (b) PD near outer conductor

When PD source locates near the inner conductor of GIS, the EM-waves propagation routes from PD source to sensor was showed in Fig 3(a). The incidence angle \( \theta_i \) in the transverse section is small as the PD source is near the center. One EM-wave component arrives at the sensor in most direct path while other EM-wave components propagate to the...
sensor by reflecting on the waveguide wall. But the situation is different when PD source locates near the outer conductor, as shown in Fig 3(b). The incidence angles $\theta_i$ in the transverse section are different and become larger as the PD source is near the edge. While one EM-wave component transmits to sensor in direct path and another component reflected to sensor by the waveguide wall, two identical EM-wave components propagate to sensor by reflecting around the inner surface of outer conductor as $\theta_i$ is close to 90 degree.

### 3.2 Simulation

The simulation model shown in Fig 4 was built and simulated by FDTD method. The inner conductor radius $a$ and outer conductor radius $b$ were set to 5cm and 24cm, the length of the chamber was 2m and two end ports were set as absorbing boundary. PD source was set near inner conductor (PD 1) and near outer conductor (PD 2). Three probes were set at the positions of $\phi=0^0$, $\phi=90^0$ and $\phi=180^0$ on the inner surface of outer conductor with 1m distance apart from PD source respectively.

![Fig.4 PD simulation model](image)

The PD current can be approximated described by a Gaussian function as follows [14]:

$$i(t) = I_0 e^{-\left(t-t_0\right)^2 / 2 \sigma^2}$$  \(4\)

Where $I_0$ is the peak value of current pulse, $\sigma$ is the time attenuation constant.

![Fig.5 Partial discharge current pulse](image)

In this paper, the amplitude of PD current pulse $I_0$ was set to 10mA, $\sigma$ was set to 0.17ns and $t_0$ was set to 0.9ns, as shown in Fig 5. PD current flowed in the radial direction and the path length was 10mm. The electric field signals of PD1 and PD2 detected by probes were shown in Fig 6.

![Fig.6 Electric field signals of PD detected by probes](image)

As shown in Fig 6(a), the initial pulses of signals detected by probes are all big and clear. It can be explained by that the first pulse arriving at sensor is TEM mode because it propagates faster than high order modes and TEM mode is big while PD source locating nears the inner conductor. The arriving times of initial pulses are about 3.5ns and the initial time of PD pulse is about 0.2ns, the time difference is about 3.3ns with 1m distance between the two probes. Hence, the propagation rout of initial pulse was consistent with the direct path.

Fig 6(b) shows that the signals detected by three probes are different and the initial pulses of signals are all small and hard to be identified. It means that the regular time of flight method can’t be used properly. This is because that TEM mode is small as PD source locates near the outer conductor. But after several pulses there were peak pulses appeared both in the signals detected by probe 1 and probe 3 while...
the signal of probe 2 has not apparent peak pulse. This phenomena can be explained by that probe 1 and probe 3 located at the positions of $\phi=0^0$ and $\phi=180^0$, the two identical EM-wave components emitted by PD source traveling around the inner surface of the outer conductor in opposite directions and arrived at the probes synchronously by traveling the same distance and produce peak pulses while arrived at probe 2 with traveling different distance which was set at $\phi=90^0$ position.

The first peak pulses of signals detected by probe 1 and probe 3 appear at different times which are about 6.6ns and 4.7ns and the time difference is about -1.9ns. The distances of EM-wave traveled from PD source to two probes can be calculated as $l_1=\sqrt{(2\pi - b)^2 + 1} \approx 1.81m$ and $l_3=\sqrt{\left((\pi - b)^2 + 1\right)} \approx 1.25m$. The time difference $\Delta t=\left(l_1-l_3\right)/c_0=1.87\text{ns}$, and this calculation result matches the simulation result well.

The analyses above indicate that the initial pulse can be discriminated clearly and the propagation route is direct path when PD source locates near the inner conductor. The initial pulse of signal is small and hard to be identified when PD source locates near the outer conductor, but peak pulses will appear in the signal when sensor locates at the position of $\phi=0^0$ or $\phi=180^0$ and the propagation route of peak pulse is traveling around the inner surface of outer conductor.

4 PD Localization Method

4.1 PD Locating Method

The initial pulse of EM-wave signal is small and hard to be discriminated when PD source locates near the outer conductor, so the regular time of flight method as shown in function (1) is hard to use to locate the PD source. But it can be seen from above analysis that there are peak pulses appearing in the signals when sensor located at the position of $\phi=0^0$ or $\phi=180^0$ and the time instant of the first peak pulse accord with the path of propagating around the inner surface of the outer conductor from PD source to the sensor.

Therefore, the PD source can be located according to the time difference of the first peak pulses.

In the PD localization system such as shown in Fig 1, the equations of peak pulse time difference can be expressed as follows:

\[
\begin{align*}
\sqrt{(n\pi r)^2 + X_2^2} - \sqrt{(n\pi r)^2 + (X_1)^2} &= c_0 \cdot \Delta t \\
X_1 + X_2 &= X
\end{align*}
\]

Where $n=1, \phi=180^0$ 
$n=2, \phi=0^0$

Solving the equations (5), then get

\[
X_1 = \frac{X}{2} + \frac{1}{2} \sqrt{(c_0 \Delta t)^2 + \left(\frac{4(n\pi r c_0 \Delta t)^2}{X^2 - (c_0 \Delta t)^2}\right)} \quad \Delta t < 0; \quad (6)
\]

\[
X_1 = \frac{X}{2} - \frac{1}{2} \sqrt{(c_0 \Delta t)^2 + \left(\frac{4(n\pi r c_0 \Delta t)^2}{X^2 - (c_0 \Delta t)^2}\right)} \quad \Delta t > 0;
\]

Where $X$ is the distance between two sensors, $X_1$ and $X_2$ are the relative distance between PD source and two sensors, $c_0=0.3m/ns, r$ is the inner radius of the outer conductor, $t$ is the time difference between the first peak pulses of signals detected by two sensors.

Hence, PD localization method in time domain based on the characteristics of EM-wave propagation route is proposed as follows. It is necessary to identify the PD source radial position at first for locating PD source correctly. The characteristics of EM-waves are different according with the PD source position as analysis above. The EM-wave signal at different $\phi$ position can be detected by moving the external UHF sensor. If the characteristic of EM-wave match the EM-wave characteristic of PD source locating near the outer conductor, the equation (6) can be applied to locate the PD source, else the equation (1) will be used for PD localization.

4.2 Laboratory Test

To check the validity of the PD localization method in time domain based on EM-wave propagation route, the actual GIS PD locating test system was constructed as shown in Fig 7. The radius of the inner conductor was 5cm and the inner radius of the outer conductor was 24cm. The GIS chamber was filled with 0.4MPa SF$_6$ gas. A needle was fixed on the outer conductor of the GIS which is 0.7m apart from the left spacer. Two external UHF sensors were used to locate the PD source. The signals detected by external sensors were amplified by two UHF amplifiers respectively (gain 40dB) and transmitted to the digital oscilloscope (Aglient 54853A) with the maximum sampling rate of 20GS/s through 5m coaxial cable with the characteristic impedance of 50Ω.
interval of $\varphi=180^\circ$ as shown in Fig 7. The sensors were moved by keeping the interval angle unchanged and stopped when the signal amplitude became the largest. The sensors were at the positions of $\varphi=0^\circ$ and $\varphi=180^\circ$ relative to the position of PD source. The signals were shown in Fig 8.

As shown in Fig 8, there are peak pulses appearing in certain intervals in both signals and the corresponding peak pulses of two signals appeared at different times. According to the EM-wave characteristic of PD, it can be identified that PD source located near the outer conductor. The position of sensor 1 is at $\varphi=180^\circ$ relative to PD source position as the first peak pulse of sensor 1 signal appeared earlier than sensor 2 signal.

For locating the position of PD source, sensor 2 was moved to another spacer (the right spacer) and at the position of $\varphi=180^\circ$ as shown as the dashed circuitry in Fig 7. The signals detected by sensors were shown in Fig 9.

As shown in Fig 9, there are peak pulses appearing in certain intervals in both signals and the corresponding peak pulses of two signals appeared at different times. According to the EM-wave characteristic of PD, it can be identified that PD source located near the outer conductor. The position of sensor 1 is at $\varphi=180^\circ$ relative to PD source position as the first peak pulse of sensor 1 signal appeared earlier than sensor 2 signal.

For locating the position of PD source, sensor 2 was moved to another spacer (the right spacer) and at the position of $\varphi=180^\circ$ as shown as the dashed circuitry in Fig 7. The signals detected by sensors were shown in Fig 9.

5 Conclusion

1) The propagation routes of EM-waves excited by PD source in GIS are related with the radial position of PD source and sensor position $\varphi$.

2) The initial pulse of PD signal is big and clear when PD source locates near the inner conductor of GIS. The propagation route of the initial pulse is accord with the direct path between sensor and PD source.

3) The initial pulse of PD signal is so small and blurry that it is hard to discriminate when PD source locates near outer conductor. So, the initial pulse time is hard to be identified and the regular time of flight method can’t be used properly. But there are peak pulses appeared when sensor at $\varphi=0^\circ$ and $\varphi=180^\circ$, the propagation route of the peak pulse accord with traveling around the inner surface of outer conductor.

4) A PD localization method in time domain based on the characteristics of EM-wave propagation route was proposed. The experiment results show that it can locate the PD effectively in the case that the initial pulse of PD signals is small and hard to be identified when PD source near the outer conductor of GIS.

References:


