Study on the mixing and separation of UHF signals with multiple insulation defects in GIS

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Abstract. In order to explore the mixing characteristics of ultra-high frequency (UHF) partial discharge (PD) signals in GIS, simulation tools and Antenna Theory concerning the electromagnetic field (XFDTD) have been adopted in investigating the mixed features of UHF signals in GIS environment. Simulation results and theoretical analysis in this paper demonstrate that convolution is the basic relationship between PD current signal and the single UHF PD signal; the PD mixing signals are the linear and instantaneous mixture of single PD signals and they are also the linear and convolution mixture of PD current signals. The reverse process of those mixing modes are also been discussed based on blind sources separation and find out that it is an over complete blind source separation problem to gain single UHF PD signal from mixed one. Moreover, it can be approximated to conventional blind source separation when the layout of ultra-high frequency sensors is compact.

1. Introduction
Based on the UHF PD, studies on GIS partial discharge mostly pay attention to partial discharge fault location and partial signal spread features nowadays\cite{1-3}, but there are rare researches focus on mixing features about UHF PD.

With the researches about pattern recognition of GIS PD signal more and more deeply, the recognition on mixed partial discharge signal getting attention\cite{4}. Now the research analysis about the recognition on mixed partial discharge signal mainly can be divided into the following two points: 1) make the comparison in the distribution area of mixed PD signal features and the distribution area of single PD signal features, then find out the single PD signal form existing in mixed PD signals; 2) fault parts of single PD signal excavated from mixed PD signal through blind source separation theory, and then the recognition result of mixed PD signal can come true \cite{5} by identifying the components extracted from the system.

In the first point, it is so hard to conduct feature analysis. It required more and more experience of data processing. The second point getting attention due to clear point and thinking step by step, but the mixed mode of PD signal are the predictions or just defaults for a mixed mode in the current system researches, while the mixed features of PD signal have not been droved and exemplified. We have carried out in-depth research and analysis on GIS mixed PD signal pattern recognition and provide a basis for studies in the future, it has a great significance to study the mixed features of UHF PD signal and its inverse process.
In this paper, the theory analyzing and formula derivation of its mixed modes of PD signals are carried out according to the antenna theory. Then, the reverse process of PD signal mixing process is analyzed through the blind source separation theory quote in this paper. At last, one software called XFDTD for electromagnetic simulation is adopted to demonstrate the results.

2. Mixed Relations among Various Signals of PD Fault Linear Mixing.

It is the essence of GIS PD fault, that under anomalous high field strength, the insulating medium will be transfixxed, then a discharge current path occurred in the GIS, and a high-frequency pulse current signals is produced. A discharge current path can be seem as an antenna and radiate electromagnetic wave, which comes from the high frequency pulse current signal to GIS cavity.

UHF sensor is designed on the basis of the antenna system, and mixed features got from receives signals composed of the basic antenna [6]. Therefore, we take the example like doublet antenna, it supposes that the one electromagnetic wave and the two electromagnetic wave overlap in area D; Number one doublet antenna is in the area D; A is one point in antenna one; E1 and E2 are electric field intensities which produced by number one and number two electromagnetic waves at A; EA is the real electric field strength about point A. Z-axis is defined to be the axis of symmetrical doublet antenna, the symmetry point of the axis is considered to be the initial point. Finally, according the right-hand screw rule, the x-axis and y-axis can be fixed. The direction vector \( \vec{e}_x \), \( \vec{e}_y \) and \( \vec{e}_z \) can be defined in this axis.

\[
\begin{align*}
E_1 &= e_{11}(t)\vec{e}_x + e_{12}(t)\vec{e}_y + e_{13}(t)\vec{e}_z \\
E_2 &= e_{21}(t)\vec{e}_x + e_{22}(t)\vec{e}_y + e_{23}(t)\vec{e}_z
\end{align*}
\]

Based on the electromagnetic theory, the electric field component consistent with the axis of the symmetrical dual antenna can generate inductive electromotive power in the antenna only, the induced current can be lead out subsequently. \( E_{i1}=e_{11}(t) \), \( E_{i2}=e_{21}(t) \) are the z-axis points of \( E_1 \), \( E_2 \) and \( i_1(t) = e_{11}(t)/Z_L \) is the induced current at the point A, \( i_2(t) = e_{21}(t)/Z_L \), \( Z_L \) is the hinder of the antenna. And

\[
\begin{align*}
E_A &= E_1 + E_2 \\
&= [e_{11}(t) + e_{21}(t)]\vec{e}_x + [e_{12}(t) + e_{22}(t)]\vec{e}_y + [e_{13}(t) + e_{23}(t)]\vec{e}_z \\
&= \sum_i e_i(t)\vec{e}_i
\end{align*}
\]

As a result, electromagnetic wave one and two, work on the antenna at the same time, the same part composed axis of symmetrical doublet antenna is

\[
i_A(t) = \frac{E_A}{Z_L} = \frac{e_{11}(t) + e_{21}(t)}{Z_L} = i_1(t) + i_2(t)
\]

It can be seen that the mixed signal gotten by the antenna is the linear superposition of electromagnetic wave one and two's instantaneous values. So the nonlinearity characteristics of signal amplifier and other auxiliary components didn't get attention, the mixing signal obtained through UHF sensor signal is the conclusion of signal instantaneous values which are worked out by two electromagnetic waves.

Mixing properties of the PD signals are as follows: If PD fault occurs in GIS, there are unaccountable approaches which excited inspired electromagnetic wave to approach UHF sensor. The \( s(t) \) can be represented the fault signal of PD’s discharge current, with regard to the source signal, \( a(t)s(t-\tau) \) is the current signal corresponding to the electromagnetic wave each path, there \( \tau \) means the time lag, \( 0<\tau\leq+\infty \), attenuation coefficient in this system is \( a(t) \). The derivation process can be seen in Fig.1
The single partial discharge signal $x(k)$ are formed by UHF sensors. The relationship between $x(k)$ and $s(k)$ are demonstrated as follows:

$$x(k) = \sum_{\tau=0}^{\infty} a(\tau) s(k-\tau) = a(k) * s(k) \quad (4)$$

Here * stands for the convolution algorithm, $a(k)$ indicates the impulse response from the source signal $s(k)$ to the of UHF sensor. The number of non-zero elements consisted of $s(k)$ is much less than the number of $x(k)$. According to equation (4), it can be concluded that single PD signal is the convolution algorithm of the discharge current signal with the impulse response.

When the number of Signal source of blocking discharge current in GIS is $n$, mixed PD signal UHF signals $u_j(k)$ got from UHF sensor $j$ can be taken as follows:

$$u_j(k) = \sum_{i=1}^{n} \left[ \sum_{\tau=0}^{\infty} a_{ij}(\tau) s_i(k-\tau) \right]$$

$$= \sum_{\tau=0}^{\infty} \left[ a_{ij}(k) * s_i(k) \right]$$

$$= \sum_{i=1}^{n} x_{ij}(k) \quad (5)$$

Here $x_{ij}(k)$ is the single PD signal about PD signal source $s_i$, and it is worked out by sensor $j$. Vector $a_{ij}(k)$ is an impulse response of PD signal source $s_i$ to sensor $j$. So it can be concluded that the blended PD signal is a linear instantaneous mixture of single PD signal and a linear convolution mixture of PD current signals. The mixed model is shown in Fig. 2.

In a word, white noise signal has its unique characteristics, and it can't replace the mixed features of PD signals.

3. Inverse Process for Mixing Process

Demonstrated in Fig.2, a single PD signal is a convolution and deconvolution process of PD current signal, and its corresponding pulse function.
Based on (4) and deconvolution formula of discrete signal, we get that

\[a(k) = \left[ x(k) - \sum_{\tau=0}^{\text{num}} a(\tau) s(k-\tau) \right] / s(0)\]

\[s(k) = \left[ x(k) - \sum_{\tau=0}^{\text{num}} s(\tau) a(k-\tau) \right] / a(0)\]

(8)

There \(s(0)=x(0)/a(0)\), \(a(0)=x(0)/s(0)\), \(\text{num}+1\) is a discrete number of \(x(k)\).

Mixed PD signal is linear instantaneous mixture between single PD signals. In the field of blind source separation, blind deconvolution is signal processing theory. The linear instantaneous mixing of single PD signal is called mixed PD signal. If it is in the field of blind source separation, blind deconvolution is a kind of signal processing theory devoted to solving these problems. It mainly because the blind deconvolution technology is mature, they are not repeated here any more.

Based on (5), the coefficient of mixed PD signal is 1, which is a single PD signal. Because the distance between the point of failure and the sensor is various. Even for the same kind of PD fault, different sensors have different time to capture a single PD signal. When varied partial discharge faults coexist, we can't think of them as the same signal. If we think that the value of the signal number \(s\) of PD current is \(n\), and the number of UHF Sensors can be \(m\), so for a single PD signal, its signal number \(x_{ij}\) can be \(m \times n\), so it's better than \(m\). So we can say that the number of source signals looks better than the number of mixed signals. Because the source signal is a super complete blind source separation problem [8].

The transmission distance of UHF signal is limited because it decays rapidly in sulfur hexafluoride gas and it can lasts only a few microseconds. Sensors that can capture effective UHF signals have relatively short distances between them. The partial discharge fault of UHF sensor will produce some single partial discharge signals, the time difference between these signals can cause less attention, and they are related to the sampling interval (for example, the location of UHF sensor is outside the same insulator). \(x_{ij}(k)\) can be shown as:

\[x_{ij}(k) = c_{ij} x_i(k)\]

(9)

Here, \(x_i(k)\) is acquired by UHF sensor. It is a single PD signal belonging to \(s_i\) of PD current source, and \(c_{ij}\) is its real coefficient. In this way, the mixed signal can be written as follow:

\[u_j(k) = \sum_{i=1}^{n} x_{ij}(k) = \sum_{i=1}^{n} \left[ c_{ij} x_i(k) \right]\]

(10)

At the same time, a single PD signal changes from \(n\) to \(mn\). When \(m \geq n\), it has become the traditional blind source separation problem according to the linear instantaneous hybrid model.

Through related research and exploration, the traditional blind source separation algorithm can separate single PD signal from mixed PD signal successfully. In a word, each mixed mode of PD signal and their inverse process can be seen in Fig.3.
4. Simulation Analysis

In the research field of XFDT, we have established the GIS straight tube structure, and its cross section is shown in Figure 4. The PD fault source is simply expressed as monopole antenna, we think that UHF sensor is bipolar antenna. For the excitation source S1 and S2, we use gauss pulse signal, their pulse width is 2ns, when we connect S2 to antenna 2, its time delay is 100ns. The partial discharge signal obtained when the excitation source waveform and the separated and combined sources on the receiving antenna work is shown in Figure 5.

Fig. 4 Cross section of GIS simulation model
Figure 5 shows that $S_1$ and $S_2$ are the waveforms of excitation sources 1 and 2 respectively; $X_1$ and $X_2$ are the only partial discharge signals gradually generated when excitation sources 1 and 2 are placed separately in the receiving antenna; $X$ is the mixed partial discharge signals generated when two excitation sources are placed in the receiving antenna at the same time.

By this way, we compare the waveform of excitation signal with the corresponding monitoring signal. At last, we find out that the digital gap of non-zero sampling point is larger, which is consistent with the digital gap in (4). Or it can be said, the individual partial discharge signal is the result of the partial discharge current signal acting together with the corresponding impact response.

The corresponding comparison results of $X_1 + X_2$ and $X$ both got from Fig. 5 is demonstrated in Fig. 6. There is a conclusion that waveforms of $X_1 + X_2$, It is very similar to $X$, and its corresponding similarity factor is 0.999999; in addition, the signal to interference ratio of $X_1 + x_2$ and $X$ achieves 248.7dB. The conclusion is that we can think it to be $X_1 + X_2$.

We carry out a simulation experiment. We connect the single and mixed partial discharge signals in the L-shaped structure and the straight tube structure composed of insulator, and then we calculate the instantaneous value of the single partial discharge signal and its similarity coefficient and the sum of the signal to interference ratio between the mixed partial discharge signals. The calculation results can be seen in Tab. 1.

| Structure                        | Similarity factor | SIR[dB]  |
|---------------------------------|------------------|---------|
| Straight barrel(including insulators) | 0.999999999994512 | 260.21  |
| L-shaped structure              | 1.0              | 236.2   |
In short, the partial discharge of mixed signals in GIS is the sum of the instantaneous values of each individual partial discharge signal. Single PD signal can be regarded as the convolution of PD current signal and a function.

5. Summary
For GIS system, we can see that the signal PD signal is the linear convolution between PD current signal and its impulse response. The partial discharge of mixed signals in GIS system is a mixture of the instantaneous value of a single partial discharge signal and it is the linear convolution of the partial discharge current signal.

We studied the single PD signal in the mixed PD signal, which is a problem of over complete blind source separation. This point of view has been discussed before. When the distance of the mixed PD signal obtained by UHF sensor is relatively small, it can be approximately equivalent to a typical problem of blind source separation.

Based on the theory of blind source separation, we analysed and compare it. At last, we find that the pattern recognition of partial discharge signal mainly includes two aspects: the first is that the discharge current signal contained in the mixed signal can be deduced by the calculation of iterative blind deconvolution; the second is that we can get the discharge current signal from the mixed partial discharge by using the over complete blind source separation theory. Each individual PD signal is estimated in the signal, and the necessary pattern recognition is carried out for the single PD signal.

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