Analysis of Monitoring System of Partial Discharge Electromagnetic Interference in Ultra-high Voltage Substation Environment

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Abstract. In order to solve the existing noise reduction measures in substation is not comprehensive, and the lack of substation on-site interference measures, the monitoring system of partial discharge electromagnetic interference in ultrahigh voltage (UHV) substation environment is studied. First of all, the ultrahigh frequency (UFH) interference information in substation is analyzed. Then signal suppression measures are adopted according to the interference signals in the substation. Finally, the UFH monitoring system is established based on the random pulse interference signal elimination method based on fuzzy clustering analysis. The results show that the electromagnetic interference monitoring system of partial discharge in the environment of UHV substation studied in this research can significantly improve the detection and localization of partial discharge, and can have more choices in determining the frequency band, which is helpful to improve the accuracy of time delay measurement so as to improve the accuracy of localization. The result of this research provides a good guidance for solving electromagnetic interference problems in UHV substations in China.

Keywords: Electromagnetic interference; Time domain analysis; Fuzzy cluster analysis; Spectral characteristics.

1. Introduction
In recent years, with the continuous rapid growth of various industries in China, the demand for electric energy for economic construction, industrial production and people's daily life is increasing day by day. At the same time, the voltage grade and capacity of transformers in the power system also increase accordingly [1]. The requirement of high-power quality and stability of power system makes the insulation structure of transformer more reliable and compact.

Various types of power transformers with high voltage and large capacity are the hubs of power transmission and conversion in the power grid, and their installation location is usually the key control point of power transmission and distribution. The security, reliability and stability of power consumption by power users are largely dependent on the running state of the transformer [2]. Therefore, the condition monitoring and fault pre-diagnosis of transformer are of great significance. In addition, effective
monitoring of transformer insulation can, to a large extent, ensure the safe and stable operation of the power grid. Partial discharge (PD) is an important symptom of insulation deterioration in the long running process of GIS, transformer, capacitor and other high voltage power equipment. PD is a non-penetrating discharge phenomenon caused by local defects such as air bubbles, cracks and electrode burrs in the manufacturing, transportation and operation of insulation medium of high-voltage power equipment, which is an important factor leading to insulation deterioration, and may lead to accidents if not found and treated for a long time. Due to the complex operation environment and insulation structure of power equipment, PD monitoring equipment is often in a strong electromagnetic environment, and various interference signals will seriously affect the detection results of PD [3]. Substation is a strong electromagnetic interference environment. All kinds of radio communication, radar pulse, rectifying and reversing pulse of power electronic equipment, corona on the bus, all kinds of discharges on the end and surface of the outlet tube of all kinds of high voltage equipment, and all kinds of interference pulse on the equipment grounding network all have adverse effects on the reliable operation and correct diagnosis of the local monitoring device. Electromagnetic interference is a key technical bottleneck that has long troubled the promotion and application of partial discharge online monitoring technology. Field operation experience shows that the current monitoring device's interference identification ability and anti-interference level are far from being able to adapt to the complex electromagnetic interference environment in substation field [4]. Partial discharge detection has obvious advantages in detecting insulation faults in power equipment, and it is more effective in detecting sudden faults than medium loss testing, oil chromatography and gas analysis. Therefore, the effective detection of partial discharge is of great significance to the safe and stable operation of power equipment.

In conclusion, in order to strengthen the interference identification ability and anti-electromagnetic interference (EMI) performance inspection and assessment of the EMI monitoring device, solve the problem of false alarm and omission of the monitoring device, and give full play to the effectiveness of the status monitoring system, it is necessary to establish and perfect the standard specification of EMI testing. In this research, the random pulse interference signal elimination method based on fuzzy clustering analysis is proposed to establish the electromagnetic interference monitoring system. The high frequency interference signal is analyzed and the suppression measures are introduced. A set of electromagnetic interference monitoring system is established to analyze the background noise and local UHF time-domain and spectral characteristics. It is hoped that this research can provide a good idea for electromagnetic interference monitoring.

2. Methodology

2.1. Analysis of UHF interference signal in substation

There are various interference signals in partial discharge measurement, and according to their time-domain waveform characteristics, they can generally be divided into three categories: continuous periodic interference, pulse interference and white noise [5-7]. Continuous periodic interference includes interference caused by power system carrier communication and high-frequency protection signals, and radio interference. The waveform of such interference is usually a high frequency sine wave with a fixed resonant frequency and band width. The interference signal of mobile phone communication is a kind of common interference signal in substation, and basically comes from the nearby mobile phone base station. Its time-domain waveform features are as follows: the communication interference signal is square wave modulated sine wave. From the long-time window, wave segments similar to square wave will appear, and the interval between each wave segment is a certain time. After testing, it shows that the energy of communication interference signals is mainly distributed in several frequency bands, which belong to narrowband signals. The spectrum of mobile phone communication signals is shown in figure 1.
Pulse interference signals include: corona discharge of power supply line or high voltage terminal; pulse interference caused by closing or breaking of switches and thyristor rectifiers in the power grid; interference caused by discharge of other non-test equipment in the power system; and interference caused by poor grounding of test line or adjacent place. In the time domain, this kind of interference is a sharp pulse signal with a short duration, but in the frequency domain, it is a broad band signal with multiple frequency components.

White noise includes all kinds of random noise. Theoretically, the power spectrum of white noise interference is constant and distributed in the whole frequency band. In practice, if the spectrum is continuous and flat in the wider band, it can be considered as white noise.

2.2. Suppression measures of UHF interference signal in substation

The multi-source discharge separation method based on dynamic frequency selection and frequency division measurement can be used in four background environments: low background noise level, high background noise, high background noise and strong system interference. According to the field test, the conditioning work of the signal sensor set by the system should be put in the narrow-band frequency selection mode. After the receiver is adjusted to the narrow-band mixing operation mode, the frequency search is carried out automatically within the range of 300M ~ 1.8ghz. According to the principle of maximum signal peak/signal mean value, the center detection frequency with the highest SNR is found, and the receiver to maintain the detection at this frequency is set. Receiver working mode can also be manually set by software. The flow chart of dynamic frequency division signal separation technology is shown in figure 2.
The elimination method of random pulse interference signal based on fuzzy clustering analysis is based on objective function. By optimizing the iterative algorithm, the clustering center is obtained. The specific algorithm steps are as follows:

Firstly, the cluster index set is determined: $J=la$, and $J$ is the characteristic parameter of single pulse signal.

**Figure 2.** Flow chart of dynamic frequency division signal separation technique
Secondly, \( X = (x_1, x_2, \ldots, x_n) \) is set as \( n \) collections of typical UHF signal samples, as shown in equation (1):

\[
\mathbf{u}_{ik} = \begin{bmatrix}
    u_{11} & u_{12} & \cdots & u_{1n} \\
    u_{21} & u_{22} & \cdots & u_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    u_{n1} & u_{n2} & \cdots & u_{nn}
\end{bmatrix}
\]

(1)

\( p_i (i = 1, 2, \ldots, c) \) is used to represent the \( i \)th category of cluster prototype vector. \( c \) is the number of classes to partition, \( 2 \leq c \leq n \), and fuzzy clustering objective function \( J_m \):

\[
J_m(U, P) = \sum_{k=1}^{n} \sum_{i=1}^{c} (u_{ik})^m (d_{ik})^2
\]

(2)

Among them, \( m \) is called a weighted exponential. In the above target function, the distance between sample \( x_k \) and the \( i \)th category of clustering prototype \( p_i \):

\[
(d_{ik})^2 = \| x_k - p_i \|
\]

(3)

Thirdly, the number of clustering categories \( c \) is given. After initializing the clustering prototype \( P \), the optimal fuzzy classification matrix and clustering center are determined by iterative calculation of equations (4) and (5). The signals are classified into \( c \) classes according to the optimal fuzzy classification matrix.

\[
u_{ik} = \frac{1}{\sum_{j=1}^{c} \left( \frac{d_{ik}}{d_{jk}} \right)^{m-1}}\]

(4)

\[
p_i = \frac{x \sum_{k=1}^{n} (u_{ik})^m}{\sum_{k=1}^{n} (u_{ik})^m}
\]

(5)

In this research, 1000 groups of data are selected as fuzzy clustering samples from a large number of on-site uhf online monitoring data of a 500kV transformer. Six characteristic parameters are extracted. Through monitoring, it shows that when initial phase, average amplitude of pulse and pulse number are selected as clustering characteristic parameters, data points form dense clusters with obvious classification effect. Therefore, this research adopts these three characteristic parameters as clustering indicators.
2.3. Establishment of local EMI monitoring system

UHF test system includes partial discharge simulation system, UHF test system and conventional pulse current test system. The results of pulse current measurement are mainly used as a reference for UHF detection system. Partial discharge simulation system consists of pressurization system and test model. Among them, the test power supply of the pressurization system is output from the auto voltage regulator and connected to the high-voltage test transformer through the isolation transformer. Rated voltage of the test transformer $U_{N} = 50kV$, rated power $S_{N} = 5kVA$, and magnitude of partial discharge under $50kV$ is less than $5pC$. The isolation transformer can restrain the high harmonics and improve the quality of power supply.

The test model includes simulation transformer tank, and typical partial discharge model. The analog transformer tank is a metal shielding chamber with $350 \times 240 \times 200cm$, and the casing is grounded.

Discharge parts are mostly in some oil gaps, oil wedges, air gaps, suspended potential metal body, conductor sharp angle and solid surface. These discharges can be classified into four basic types: bubble discharge in oil, pin discharge in oil, suspension discharge and surface discharge. Therefore, four typical partial discharge models as shown in figure 4 are established in this research to simulate the above-mentioned discharge types.

![Typical partial discharge model in oil](image)

(a) Discharge needle plate (b) Bubble discharge in oil (c) Suspended discharge (d) Creeping discharge

Figure 4. Typical partial discharge model in oil

Local EMI monitoring system consists of a sensor consisting of a standard horn antenna and a short probe monopole antenna with a corresponding amplifier, $50 \Omega$ rf coaxial cable, digital oscilloscope, computer and analysis software, as shown in figure 5.
3. Results and discussion

3.1. Background noise

Typical time-domain waveform and average power spectral density of simulated internal and external background noise are measured by two UHF detection systems in the laboratory. The average power spectral density (PSD) is the superimposed average of the power spectral density of 100-time domain waveforms acquired by FFT transformation. The specific characteristic peak distribution of the background noise signal spectrum detected by the two systems is shown in Table 1.

| Ch1           | Frequency/GHz | 0.5~0.66 | 0.85~0.96 | 1.8 | 2.6 | 3.3 | 0.3 | 5   | 5.7 |
|---------------|---------------|----------|-----------|-----|-----|-----|-----|-----|-----|
|               | Characteristic peak amplitude/ dBm | -66      | -46       | -62 | -76 | -72 | -72 | -68 | -73 |

| Ch2           | Frequency/GHz | 1.25 | 1.8 | 3.3 | 5   | 6.2 | -   | -   | -   |
|---------------|---------------|------|-----|-----|-----|-----|-----|-----|-----|
|               | Characteristic peak amplitude/ dBm | -62  | -52 | -54 | -49 | -61 | -   | -   | -   |

The distribution characteristics of the spectra measured by the two sensors don't change much, but the level increases significantly, as shown in Table 2.

| Ch1           | Frequency/GHz | 0.5~0.66 | 0.85~0.96 | 1.8 | 2.6 | 3.3 | 4.3 | 5   | 5.7 |
|---------------|---------------|----------|-----------|-----|-----|-----|-----|-----|-----|
|               | Characteristic peak amplitude/ dBm | -53      | -22       | -46 | -59 | -67 | -57 | -54 | -63 |

| Ch2           | Frequency/GHz | 1.25 | 1.8 | 3.3 | 5   | 6.2 | -   | -   | -   |
|---------------|---------------|------|-----|-----|-----|-----|-----|-----|-----|
|               | Characteristic peak amplitude/ dBm | -39  | -28 | -27 | -24 | -26 | -   | -   | -   |

As shown in Table 1 and Table 2, the simulated transformer oil tank has a good shielding effect on external interference signals, especially the shielding effect on high frequency signals is better than that on low frequency signals. Installing sensors inside the transformer tank not only improves the detection sensitivity, but also improves the system's ability to resist external interference effectively.

3.2. Time domain and spectral characteristics of UHF in typical partial discharge

The typical partial discharge model is placed inside the shielding box, and the model is discharged by applying high pressure of machining frequency. At the same time, standard horn and short probe monopole antenna sensor are used to detect UHF signal, which is amplified by the amplifier and connected to the oscilloscope. The oscilloscope is set to collect 100-time domain waveforms for each sample of various models in the "Normal" trigger mode. The power spectrum data are obtained by FFT transform and all the data are superimposed and averaged. The value of apparent discharge is measured
synchronously by conventional partial discharge test system. Table 3 shows the high-voltage amplitude
of external construction frequency recorded in the test, the average apparent discharge power of the test
article and the average amplitude of UHF signal. The Ch1 data in the table are the measurement results
of the standard gain horn sensor. The data of Ch are the measurement result of the unipolar probe sensor.

### Table 3. Test voltage, average apparent discharge and amplitude

| Partial discharge model       | Power frequency voltage (kV) | Average apparent discharge (pC) | UHF Signal mean amplitude (mV) |
|------------------------------|-----------------------------|--------------------------------|-------------------------------|
| The needle plate electrode    | 4.5                         | ~100                            | 85                            |
| Bubble in the oil            | 2                           | ~50                             | 34                            |
| Suspended discharge          | 8.9                         | ~150                            | 386                           |
| Creeping discharge           | 5.7                         | ~120                            | 73                            |

The waveform of UHF signal generated by pin plate discharge is characterized by high amplitude at
the initial part and pulse duration of about 300 ~ 400ns. The signal time domain waveform measured by
different sensors is quite different. The amplitude of time domain waveform detected by the unipolar
probe is relatively low, which is about 70% of that of the standard horn antenna. However, the SNR is
relatively high, the rise time of waveform is steeper, and the width of half-wave pulse is narrower.

Considering that the signal rising edge measured by the unipolar probe is approaching the
establishment time of the detection instrument, it is necessary to modify it. For this reason, equation (6)
is used to compensate the detection result of the unipolar probe:

$$tr_m = \sqrt{tr_d^2 + tr_s^2}$$  \hspace{1cm} (6)

In the equation, $tr_s$ is the true rise time of the signal; $tr_d$ is the establishment time of the measuring
instrument. The establishment time of the measuring instrument is determined by its bandwidth
characteristics, which can be expressed by equation (7).

$$tr_d = 0.35/f_{3dB}$$  \hspace{1cm} (7)

In the equation, $f_{3dB}$ is the upper limit frequency of the 3dB bandwidth of the instrument is measured.
It shows that the establishment time of 6GHz analog bandwidth oscilloscope is 58ps. After correction
of the measured value by formula (6), the rising edge of the actual discharge signal of the pin plate
reached 55ps respectively, and the width of the single pulse was roughly 150 ~ 200ps. This result is
about 10 times faster than the partial discharge waveform parameters measured by uhf detection system.
This means that no matter partial discharge detection and localization are carried out, there are more
choices in determining the frequency band, especially helpful to improve the accuracy of time delay
measurement so as to improve the accuracy of localization. Therefore, the characteristic parameters of
the discharge time domain waveform and spectrum of each model are summarized in table 4.
Table 4. Time domain and spectral characteristics of typical discharge

| Variant                      | Discharge needle plate | Bubble discharge | Suspended discharge | Creeping discharge |
|------------------------------|------------------------|------------------|---------------------|-------------------|
|                              | Ch1        | Ch2        | Ch1      | Ch2        | Ch1      | Ch2        | Ch1      | Ch2        |
| Pulse duration (ns)          | 300–400   | 400–500   | About 450 | 300–400   |
| Half wave width of first pulse (ns) | 0.31    | 0.176    | 0.24     | 0.153     | 0.35     | 0.183     | 0.2      | 0.18      |
| The rising edge of the first wave (ps) | 130    | 55       | 100      | 39        | 140      | 76        | 170      | 95        |
| Spectrum distribution (GHz)   | 0.4-2     | 1-6       | 0.3-3.5  | 2-4       | 0.2-1.3  | 0.4-4     | 0.3-2    | 0.5-6.5   |
| Major energy distribution (GHza) | 0.5-1   | 1.6-1.8  | 0.5-1.2  | 1.7       | 0.4-0.9  | 2.2-7     | 0.5-1.4  | 1-3       |

Then the sensitivity of different discharge models is analyzed by using two UHF antenna sensors and corresponding detection system. The measurable minimum apparent discharge of the measurement system under laboratory conditions is equivalent to 34.8pC in sensitivity. When the average amplitude of the signal detected by the unipolar probe sensor is 61mV, the average apparent discharge power is 100pC, equivalent to 1.64pc /mV. Its background noise level is about 6.3mv, equivalent to 10pC, and its equivalent sensitivity is about 20pC. The equivalent sensitivity of UHF detection of four typical partial discharge types calculated by this method is shown in table 5.

Table 5. Detection of the equivalent sensitivity of typical discharge under UHF

| Discharge type              | Discharge needle plate | Bubble discharge | Suspended discharge | Creeping discharge |
|-----------------------------|------------------------|------------------|---------------------|-------------------|
|                             | Ch1        | Ch2        | Ch1      | Ch2        | Ch1      | Ch2        | Ch1      | Ch2        |
| Equivalent sensitivity (pC) | 34.8       | 20.7       | 10.1     | 3.0        | 5.4      | 5.1        | 31.6     | 40.9       |

According to the above results, the electromagnetic wave signal radiated by partial discharge has a certain energy distribution within the frequency range of 1G-5GHz. By receiving this part of signal component, it not only has the equivalent detection sensitivity that meets the engineering requirements, but also has a higher detection signal-to-noise ratio. The time domain waveform of the measured signal has a shorter rise time and the pulse width of the single oscillation is narrower.

4. Conclusion

In order to solve the current phenomenon of electromagnetic interference in partial discharge in the environment of UHV substation, as well as the problems of false and missing partial discharge on-site, the interference signal of partial discharge electromagnetic in the environment of UHV substation is analyzed. Then, according to the existing types of interference signals, the suppression method of UHF interference signals in substation is proposed, and a UHF monitoring system is established. Typical time-domain waveform and average power spectral density of simulated internal and external background noise are measured by two UHF detection systems. The monitoring results show that the monitoring system can provide more signal bands for selection and help to improve the accuracy of time delay measurement so as to improve the accuracy of positioning.

The study in this research can better monitor the detection of partial discharge electromagnetic interference signals in the environment of UHV substation, which can solve the problem of five guarantees and missing report in substation. However, the study in this research is in the result of simulation study, without a complete discussion of various complex situations in reality. It is hoped that the follow-up work can be carried out further research.
Acknowledgments
The research is supported by the Science and Technology Projects of State Grid:” Deep study on the technology of field hand-over test for UHV AC reactor, AC transformer and AC instrument transformer”

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