Application of optical sensor array in partial discharge signal location of GIS/GIL

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Abstract. The optical sensor array inside the high-voltage equipment can effectively realize the on-line measurement of the high-voltage switch operation state, significantly improve the efficiency and accuracy of SF6 Electrical equipment fault diagnosis, and effectively guarantee the safety and reliability of equipment operation. Firstly, the structure and performance of the micro optical sensor are analyzed, and the system model and data processing unit of the optical sensor array are given. Furthermore, the influence characteristics of single sensor and array sensor Gaussian noise on signal are given, and the noise elimination strategy of observation signal based on Kalman filter is given. The results show that: the optical sensor has a good focusing ability for the optical signal, the light of the sensor array is reflected and propagated many times in the GIS/GIL of the high voltage switch-gear, and the internal partial discharge signal is located more accurately. The research results of this paper can provide important technical support for the GIS/GIL fault monitoring and early warning of the gas insulated electrical equipment on the transmission line.

1. Introduction

As an excellent insulation and arc extinguishing medium, SF6 gas is widely used in SF6 gas insulated circuit breaker and gas insulated sub station. Among all kinds of electrical equipment, such as GIS, transformer, mutual inductor, power cable, most of the high-voltage switches with the SF6 gas as insulating medium have gradually entered the maintenance period since they were put into operation. The content of SF6 decomposition products can characterize the operation status of high-voltage equipment. The detection of decomposition products is very important, and the application of optical detection method to detect decomposition products has gradually become the mainstream detection method[1-3].

Optical sensor has the advantages of long service life and high detection sensitivity, but it is difficult to achieve miniaturization because it needs to set optical path, circuit, mechanical structure and other components. Study the feasibility of miniaturization sensor, explore the research of optical sensor based on micro nano machining technology, and realize the miniaturization of sensor. Carry out theoretical simulation and research work[4,5]. Combined with Fourier transform infrared spectrometer, the absorption characteristics of decomposition products and the spectral absorption cross interference characteristics of background SF6 gas were studied. Gaussian interface program is used to optimize the molecular structure, and then simulate the molecular IR absorption spectrum to obtain high-precision absorption spectrum, which provides data support for the further research of the project. The actual measurement results and theoretical spectral absorption data are analyzed, and the appropriate absorption wavelength is selected by comparing the gas absorption line strength[6,7].

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According to the selected gas absorption spectrum, combined with the optical properties of the material, the substrate material is studied to determine the optimal material for this project. According to the components of corrosive gas in SF6 high pressure equipment, the corrosion resistance and passivation treatment technology of micro gas absorption tank were studied. The finite element method is used to analyze the influence of the cross-section structure and length parameters of the micro gas absorption cell on the light field distribution, and to determine the optimal structure parameters of the micro gas absorption cell when the evanescent field ratio is optimal. Based on this, this paper first analyzes the structure and performance of the micro optical sensor, and gives the system model and data processing unit of the optical sensor array. The influence characteristics of single sensor and array sensor Gaussian noise on signal are given, and the noise elimination strategy of observation signal based on Kalman filter is given. The results show that: the optical sensor has a good focusing ability for the optical signal, the light of sensor array is reflected and propagated many times in the GIS/GIL of high voltage switchgear, and the internal partial discharge signal is located accurately. The research results of this paper can provide important technical support for GIS/GIL fault monitoring and early warning of transmission line gas insulated electrical equipment.

2. Partial discharge measurement of GIS true simulation device

The GIS true type defect simulation device should be able to realize the following functions: 1) it has four typical insulation defects: free metal particles, bubble defects in solid insulation parts, needle / plate and plate / plate electrode discharge; 2) it has good sealing performance, the SF6 gas pressure inside the device can be adjusted, and it has a gas inlet to realize the real-time measurement of decomposition gas composition and content; 3) it has a video monitoring device to realize the real-time measurement The partial discharge signal acquisition port can be connected with various PD monitoring devices. The design of GIS true defect simulator is shown in Figure 1.

![Fig.1 Design of GIS defect simulator](image1)

![Fig.2 3D model of GIS defect simulation device](image2)

Figure 1 shows that the whole design of GIS true type defect simulation device can achieve the above functions. At the same time, four basin type insulators are designed to isolate the air chamber into five intervals to ensure the independence of each structural component [8,9]. The typical defect simulation device and high voltage bushing are independent gas chambers to avoid the influence of
micro decomposition gas under the discharge condition of the defect simulation gas chamber on the insulation performance. The three-dimensional modeling of the whole design scheme of GIS true defect simulation device is shown in Figure 2.

Figure 2 shows that the device is compact and portable. Meanwhile, the high-voltage bushing makes the external high voltage safer and has no corona interference [10]. Through the high-voltage bushing, two voltage types, DC and AC, can be effectively connected. The decomposition characteristics and partial discharge law of SF6 gas under different voltage types are studied respectively. The GIS true type defect simulation device is a special device designed according to the actual application requirements, so compared with the traditional GIS equipment, it needs to carry out more precise electric field distribution checking calculation [11], including the electric field checking calculation of basin insulator and high voltage bushing, the electric field distribution calculation of Central conductor surface and the refined electric field distribution checking of typical insulation defects. The appearance of typical insulation defects is shown in Figure 3.

Figure 3 shows that the air gap discharge model, suspension discharge model, tip discharge model and suspended particle discharge model are set inside the defect simulation device, and the external connection with the video receiving device can realize the real-time monitoring of the partial discharge of defects. Firstly, according to the test data of pulse current method, the typical discharge pulses of air gap discharge, suspension discharge, particle discharge and tip discharge are shown in Figure 4. It can be seen from the figure that under the four typical discharge conditions, the partial discharge signals present different characteristics. The electric pulse patterns of air gap discharge and suspension discharge have significant symmetry; the pulse patterns of particle discharge and tip discharge have certain randomness, which is mainly related to the structural characteristics of insulation defects. The air gap and suspension structures are relatively stable, while the particle and tip structures have certain randomness.

Further using XD5352 UHF partial discharge tester, channel C is the test spectrum of external UHF sensor, and channel D is the test spectrum of internal sensor. The test results are shown in Figure 5. The figure shows that under various defect modes, the change trend of partial discharge signals in a cycle measured by external and internal UHF Sensors is basically consistent, but the signal amplitude
measured by internal sensors is significantly higher than that of external sensors, because the internal sensors are closer to the discharge source in space; on the other hand, the signals under various defect states are quite different. It shows that UHF sensor test signal can also effectively distinguish all kinds of typical insulation defects.

(a) typical air gap discharge  (b) typical suspension discharge

(c) typical particle discharge  (d) typical tip discharge

Figure 5. Test data of UHF

Figure 5 shows that with the increase of applied voltage, the amplitude of PD signals of pulse current method and UHF also increases, which is mainly due to the enhancement of electric field intensity of metal particles and metal tips by applied voltage, and the saturation effect of PD signals with the increase of applied voltage.

3. Kalman filtering for denoising of one dimensional observation signal

In the process of sensor receiving optical signal, it is necessary to de noise the signal. In this paper, the signal detection technology in non-Gaussian environment is adopted[12]. In coherent structure DSSS system, the optical discrete received signal after A/D sampling can be expressed as:

\[ r(k) = \sqrt{2Ed} (kT_s - \tau r) c(kT_s - \tau r) \cos(\omega r kT_s + \phi) + n(kT_s) \]  

(1)

Since the frequency and phase of the carrier component of the signal are known at the receiving end, the single branch observation of the received signal after demodulation is as follows:

\[ X_i = \nabla c(i) + W_i \]  

(2)

Under the assumption that the amplitude of the non local Gaussian noise detector is very optimal, we can get the following results:

\[ T_{LO}(X) = \left( \frac{d^\nu \phi_X(X/\theta)}{d\theta^\nu} \bigg|_{\theta=0} \right) / (\phi_X(X/0)) \]  

(3)

Where: \( \nu \) is the order of the first nonzero derivative term of the probability density function \( \phi_X(X/\theta) \) at \( \theta = 0 \). And the first derivative of is:

\[ \frac{d \phi_X(X/\theta)}{d\theta} = -\prod_{i=1}^{n} f_w(X_i - \theta, \nu) \cdot \sum_{i=1}^{n} \frac{f_w(X_i - \theta, \nu)}{f_w(X_i - \theta, \nu)} \]  

(4)

The statistic function of the local optimal detector in the additive non Gaussian noise model is obtained:

\[ T_{LO}(X) = -\sum_{i=1}^{N} c_i \cdot g_i(X_i) = -\sum_{i=1}^{N} c_i \cdot \frac{f_w'(X_i)}{f_w(X_i)} \]  

(5)

Where: \( g_i(X) = f_w'(X_i) / f_w(X_i) \) is the nonlinear function in the local optimal detector.
Figure 6. Non Gaussian noise model

Figure 7. Effect of Kalman filter as to non Gaussian noise interference

Figure 6 and Figure 7 show that the optical signal \((N=1)\) of the main sensor is smooth and stable. When the number of sensors is greater than \(N\), the signal superposition occurs due to the mutual interference between light rays, that is, the non Gaussian noise interference model appears\([13]\). The non Gaussian noise interference model can be effectively processed by Kalman filter.

At present, the optical sensor is used to measure the known partial discharge position, and the ranging error is 0.05m. A large number of test data statistics show that the measurement error variance of the laser rangefinder is \(R=0.0025\), the data measured by the rangefinder for the \(k\) th time is not 100% accurate, there is measurement noise \(V(k)\), and the measurement equation is \(Z(k) = X(k) + V(k)\). The state equation and observation equation of the system are as follows:

\[
X(k) = AX(k-1) + GW(k-1)
\]

\[
Z(k) = HX(k) + V(k)
\]  (6)

Where \(X(k)\) is the distance (height value) of one-dimensional variable, \(A=1\), \(H=1\), and the variances of \(W(k)\) and \(V(k)\) are \(Q\) and \(R\). After the system is established, the Kalman filter can be used to deal with the noise \(w(k)\) and \(V(k)\). Suppose that to estimate the actual height at the \(k\)-th moment, the height at the \(k\)-th moment should be predicted according to the height at the \(k\)-1st moment\([14]\). The state space model of Kalman filter describes the dynamic system as follows:

\[
\hat{X}(k+1|k) = \Phi \hat{X}(k|k)
\]  (7)

The covariance matrix was further predicted:

\[
P(k+1|k) = \Phi P(k|k) \Phi^T + \Gamma Q \Gamma^T
\]  (8)

The filter gain matrix is obtained:

\[
K(k + 1) = P(k + 1|k) H^T [HP(k + 1|k) H^T + R]^{-1}
\]  (9)

Status update:
\[
\hat{X}(k+1|k) = \hat{X}(k+1|k) + K(k+1)\varepsilon(k+1)
\]
(10)

\[
\varepsilon(k+1) = Y(k+1) - H \hat{X}(k+1|k)
\]
(11)

Covariance matrix update:

\[
P(k+1|k+1) = [I_n - K(k+1)H]P(k+1|k)
\]
(12)

\[
\hat{X}(0|0) = \mu_0, P(0|0) = P_0
\]
(13)

Figure 8. Effect of Kalman filter as to non-Gaussian noise interference

Figure 9. Effect of Kalman filter as to non-Gaussian noise interference

Figure 10. Optical path of observation sensor (N=3)
4. Analytical analysis of optical sensor performance parameters

The number and location of optical sensors in GIS need theoretical analysis. When the above variables are fixed, it is necessary to consider the optimization algorithm and data processing method to determine the location of partial discharge. The optical sensor is placed at each key position in the GIS cavity. The optical sensor emits light with a certain frequency band and scans continuously. After receiving the position information of partial discharge signal, the light feeds it back to the background information processing system. The position information of partial discharge can be obtained by synthesizing the position information of each sensor. The optical path of the three observation sensors is shown in Figure 10. Figure 10 shows that the light is reflected many times inside the GIS cavity, and the optical sensor can effectively capture the position information of the light. The optical focusing function at the sensitive surface of one of the optical sensors is shown in Figure 11. The visible light is effectively focused on the center of the sensor, and the light gradually weakens at the center. The collimation characteristics of the sensor for light can improve the positioning accuracy of partial discharge signal. Figure 12 shows the 3D ray Atlas of the light inside the GIS equipment, and the visible light has the same characteristics inside the GIS It has good ergodicity and high collimation. On the other hand, the Kalman filtering algorithm flow proposed in this paper is applied to locate the partial discharge position, and the positioning effect is shown in Figure 13. Figure 13 shows that the predicted partial discharge positions of the five sensors have little deviation from their actual positions, and the deviation decreases gradually in each iteration. Moreover, there is oscillation deviation in the process of partial discharge location path search, but they all vibrate around the actual trajectory, which shows the effectiveness and practicability of the proposed localization algorithm. In the process of Kalman filtering algorithm, the iterative calculation can be realized by the following algorithms: (1) data input and parameter definition; (2) input the position coordinates of each sensor node; (3) record the light distribution of the optical sensor along its path; (4) integrate the sensor position matrix and mass matrix to calculate the overall diffusion matrix of the optical sensor system; (5) use the linear method (6) using the visual program template to display the curve of the solution of the transient problem.

Figure 11. The optical focusing function at the sensitive surface of one of the optical sensors

Figure 12. 3D ray Atlas of the light inside the GIS equipment
Figure 13 shows that with the increase of the running time of the iterative program, the error between the actual value and the predicted value of PD target distance first increases and then decreases, and finally tends to 0, which indicates that the proposed Kalman filtering algorithm process has good convergence characteristics. On the other hand, the cross section of GIS can body is meshed to determine the location of sensors in two-dimensional space.

Figure 13. Error between the actual value and the predicted value of PD target distance

Figure 14. Observation sensor matrix network

Figure 15. Positioning effect of 3*4 order sensor array

The coordinates of the light propagation path can be calculated by fitting the effective positions of the nodes. The above figure shows a matrix network of 3*4 sensors. Each sensor has the effect of a
single sensor network as shown in Figure 14. The positioning effect of 3*4 order sensor array is shown in Figure 15. The increase of the number of sensors can effectively improve the detection accuracy of partial discharge signal position.

5. Conclusion
Firstly, the structure and performance of the micro optical sensor are analyzed, and the system model and data processing unit of the optical sensor array are given. Furthermore, the influence characteristics of single sensor and array sensor Gaussian noise on signal are given, and the noise elimination strategy of observation signal based on Kalman filter is given. The results show that: the optical sensor has a good focusing ability for the optical signal, the light of sensor array is reflected and propagated many times in the high voltage switchgear GIS/GIL, the internal partial discharge signal is accurately located, and the positioning accuracy can be controlled at about 15cm, and the increase of the number of sensors can effectively improve the detection accuracy of partial discharge signal position. The results show that the proposed Kalman filtering algorithm process can effectively eliminate the Gaussian background noise, and with the increase of the iterative program running time, the error between the actual value and the predicted value of PD target distance first increases, then decreases, and finally tends to zero, which indicates that the proposed Kalman filtering algorithm process has the good convergence characteristics.

References
[1] Huang Guangbin, Zhu Qinyu, Siew C K. Extreme learning machine: theory and applications[J]. Neurocomputing, 2006, 70(1-3): 489-501.
[2] Liu Guohua, Zhang Yujun, Zhang Kai, et al. Research on online correction algorithm with neural network multi-environment factors for CO detection of motor vehicle exhaust[J]. Infrared Millim Waves, 2018, 37(6): 704-710( in Chinese).
[3] Chen Chen, Zhang Yujun, He Ying, et al. Performance simulation analysis of NDIR sensor for vehicle exhaust[J]. Infrared Technology, 2017, 39(6): 567-573(in Chinese).
[4] Chen Miao, Huang Zhengwei, Wang Yi. Development of multicomponent measurement by single light source and optical path based on a infrared gas analyzer of NDIR principle[J]. Analytical Instrumentation, 2017(3): 20-25(in Chinese).
[5] Ji Shengchang, Zhong Lipeng, Liu Kai, et al. Research status and development of SF6 decomposition components analysis under discharge and its application[J]. Proceedings of the CSEE, 2015, 35(9): 2318-2332(in Chinese).
[6] Wada J, Ueta G, Okabe S. Evaluation of breakdown characteristics of N2 gas for non-standard lightning impulse waveforms under non-uniform electric field - breakdown characteristics for single-frequency oscillation waveforms[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2012, 19(1):263-273.
[7] QIU Yuchang, SHI Wei, ZHANG Wenyuan. High voltage engineering[M]. Xi’an:Xi’an Jiaotong University Press, 1995:11-14
[8] Cao Jing, Zhang qin, Yang Yinjian. Corona discharge characteristic for fittings of high altitude ac transmission line[J]. High Voltage Engineering, 2011, 37(12): 2924-2928.
[9] Li X, Zhao H, Jia S, et al. Study of the dielectric breakdown properties of hot SF6-CF4 mixtures at 0.01-1.6MPa[J]. Journal of Applied Physics, 2013, 114(5):053302.1-053302.7.
[10] MA Bin, ZHOU Wenjun, WANG Tao, et al. Corona Discharge of the Severe Non-uniform Electric Field Based on the UV-light Imaging Technology[J]. High Voltage Engineering, 2006, 32(7):13-16.
[11] YAN Zhang, ZHU De-heng. Technology of high voltage insulation[M]. Beijing,China:Electric Power Industry Press, 2002:64-69
[12] SHEWCHUK J R. Refinement algorithm for triangular mesh generation[J]. Computational
Geometry: Theory and Applications, 2002, 22: 21-74.

[13] Khaled M. Computation of breakdown phenomena in non uniform air gaps[D]. Zurich, Switzerland: Switzerland Federal Institute of Technology. 1975.

[14] Shi Cheng, Ma Guoming, Mao Naiqiang, et al. Study on fiber ultrasonic location technology of partial discharge in transformer based on wavelength division multiplexing/time-division multiplexing technology[J]. Proceedings of the CSEE, 2017, 37(16): 4873-4879 (in Chinese).