Research on operation characteristics of UHV converter valve hall based on intelligent image processing and 3D modeling technology

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Abstract. There are many power equipments in the UHV valve hall, including the converter transformer, converter valve tower, all kinds of bushing, tubular bus. The operation condition monitoring of the above main equipment mainly includes electrical performance parameter measurement, oil and gas insulation medium performance parameter measurement and other means. This paper mainly introduces a monitoring method for the operation status of converter valve hall from the perspective of image processing technology. The technology mainly includes: 1) the application of intelligent image processing technology to identify and classify the database of infrared thermal imager and ultraviolet imager; 2) the real-time on-line measurement for the insulation distance of typical fittings through Kalman filter technology, including the measurement of the hottest temperature The insulation distance between partial discharge point and zero potential grounding point; 3) the electric field simulation model of typical main equipment in valve hall is established based on three-dimensional modeling technology of finite element method, and the surface electric field distribution of key main equipment fittings is obtained. Combined with the image database information, insulation distance information and typical main equipment electric field distribution information, the operation state parameters are effectively obtained, and the intelligent algorithm is applied to automatically evaluate its operation state, discover the latent fault and locate the positive fault, so as to provide effective data support and the protection strategy for the main equipment operation and maintenance.

1. Introduction
There are many main equipment in UHV converter valve hall, including converter transformer, wall bushing, converter bushing, converter valve tower, various tubular bus. The above equipment is well manufactured, expensive and plays a key role[1,2]. The operation status of the above main power equipment is directly related to the power conversion quality of the whole converter valve hall. At present, the operation and maintenance of UHV converter valve hall is mainly carried out through electrical monitoring devices. For the power equipment of oil paper insulation system, such as the main insulation system of converter transformer, the on-line real-time monitoring of dielectric loss angle value and on-line detection of transformer oil decomposition gas can be carried out. For the main power equipment insulated by SF6 gas, the technical means such as SF6 decomposition gas detection are mainly used[3,4]. The main gases monitored include the HF and CF4 gas composition changes with time. For the epoxy resin composite corrugated paper insulation power equipment, the on-line real-time monitoring of the tangent value of loss angle and the application of UHF and pulse
current methods are mainly used to monitor the local discharge level, including the converter transformer bushing, through wall bushing and other power equipment[5-7]. For the converter valve tower, the core component of the converter valve hall, the real-time online operation status of the core component is reflected by monitoring the internal temperature curve and the converter IGBT unit temperature.

However, the above monitoring means need to participate in the acquisition of real-time signals by human, and the acquired data stream information is easy to introduce external interference. At the same time, there are limitations in fault data processing and operation and maintenance strategy formation. Therefore, it is urgent to propose a convenient, fast and effective auxiliary means of operation condition monitoring. In view of this, this paper puts forward an innovative method to monitor the operation status of converter valve hall from the perspective of image processing technology. The technology mainly includes: 1) using intelligent image processing technology to identify and classify the infrared thermal imager and ultraviolet imager database; 2) using Kalman filtering technology to measure the insulation distance of typical fittings in real time, including measuring the insulation distance between the hottest temperature, partial discharge point and zero potential grounding point; 3) using 3D modeling technology based on finite element method The electric field simulation model of typical main equipment in valve hall is established, and the surface electric field distribution of key main equipment fittings is obtained. Combined with image database information, insulation distance information and electric field distribution information of typical main equipment, the operation state parameters are effectively obtained, and the intelligent algorithm is applied to automatically evaluate its operation state, so as to discover latent faults and locate positive faults. The application of intelligent image processing technology is shown in Figure 1.

In Figure 1, the probability density function network structure suitable for infrared and ultraviolet image database is constructed firstly, then the image database is input into fuzzy neural network for batch processing, and finally the distribution of electric field and thermal field of image database is output. The research results of this paper can provide effective data support and protection strategy for the operation and maintenance of main equipment, and have certain engineering and application value.

2. Intelligent image processing technology based on genetic algorithm and BP neural network
The specific steps of BP neural network prediction algorithm optimized by genetic algorithm are as follows: Step 1: set the population size as $P$. The initial population of $P$ individuals is randomly generated $W=(W_1, W_2, ..., W_P)^T$, and given a data selection range, because the determination of the initial population has a great influence on the global optimization of GA, the linear interpolation function is used to generate the real vector $W_1, W_2, ..., W_S$ of individual $w_i$ in the population as a chromosome of genetic algorithm. The length of chromosome is as follows[8]:

$$S = RS_1 + S_1S_2 + S_1 + S_2$$

Where $R$ is the number of input layer nodes, $S_1$ is the number of hidden layer nodes, and $S_2$ is the number of output layer nodes. Each individual in the population represents the initial value of a BP neural network, and a gene value $W_i$ in the individual $W_i$ represents a connection weight or threshold.
of the neural network. In order to get high-precision weight and shorten the length of chromosome string, floating-point coding method is used.

Step 2: determine the individual evaluation function. Given a BP neural network evolution parameter, the chromosome obtained in the first step is used to assign the weights and thresholds of BP neural network, and the training samples are input to train the neural network to achieve the set accuracy to obtain the network training output value. Then the fitness value fitnessi and average fitness value of individual Wi in population W are defined as[9,10]:

$$\text{fitness}_i = \sum_{j=1}^{M} (\hat{y}_{ij} - y_j)^2 (i = 1, 2, ..., P) \quad (2)$$

$$f = \frac{1}{P} \sum_{i=1}^{P} \text{fitness}_i \quad (3)$$

Where $\hat{y}_{ij}$ is the training output value, $y_j$ is the expected value of training output, $M$ is the number of phase points in the reconstructed phase space, $P$ is the population size. Step 3: Using roulette selection operator, that is to say, the selection strategy $p_i$ based on fitness proportion is used to select the chromosomes in each generation of the population:

$$p_i = \frac{f_i}{\sum_{i=1}^{P} f_i} (i = 1, 2, ..., P) \quad (4)$$

Where $f_i = 1 / \text{fitness}_i$, $P$ is the population size. Step 4: because the individual uses real number coding, so the crossover operation method uses real number crossover method. The cross operation of the k-th gene $w_k$ and the l-th gene $w_l$ at the j position is as follows:

$$\begin{align*}
  w_{kj} &= w_{kj} (1 - b) + w_j b \\
  w_{lj} &= w_{lj} (1 - b) + w_j b
\end{align*} \quad (5)$$

Where $B$ is a random number of $[0, 1]$. Step 5: mutation operation: select the j-th gene of the i-th individual for mutation operation:

$$w_{ij} = \begin{cases} 
  w_{ij} + (w_{ij} - w_{\text{max}}) f(g) r \geq 0.5 \\
  w_{ij} + (w_{\text{min}} - w_{ij}) f(g) r < 0.5
\end{cases} \quad (6)$$

$$f(g) = r_2 (1 - g / G_{\text{max}})$$

Where: $w_{\text{max}}$ and $w_{\text{min}}$ are the upper and lower bounds of gene $w_{ij}$, $r$ is the random number of $[0, 1]$, $r_2$ is a random number, $g$ is the current iteration number, and $G_{\text{max}}$ is the maximum evolution algebra.

Step 6: decompose the optimal individual of genetic algorithm into connection weights and thresholds of BP neural network, train BP neural network prediction model with BP algorithm, and obtain the optimal solution of chaotic time series prediction. The fuzzy neural network can be learned by the hybrid algorithm of BP algorithm and least square estimation, so as to adjust the parameters of the system[11,12]. The forward phase is calculated to the fourth layer, and the error signal is transmitted...
backward in the reverse phase. The BP algorithm is used to update the antecedent parameters. The topology structure of deep learning based on fuzzy neural network is shown in Figure 2. Firstly, the weights and thresholds of the probability density function are set, and then the image database of the power equipment collected by the UHV valve hall is used for deep learning training to obtain the weights and thresholds of the probability density function after iterative adjustment, and finally the electric field and potential distribution cloud images of the image database are output.

3. E-field simulation of converter valve hall based on 3D finite element modeling technology
Taking the ±800kV Zhundong Chongqing DC transmission project as an example, the project is a bipolar DC system. The system consists of two complete monopoles, each complete monopole is composed of two 12 pulsating converters with equal voltage at each end in series, and the converter transformer is single-phase and two windings. Any pair of 12 pulsating converters out of operation in each complete monopole will not affect the incomplete monopole operation of the remaining converters. The rated current of the system is 800kV, the rated current is 4750A, and the rated transmission capacity is 3800MW. The ±800kV UHV converter bushing is used in Zhundong converter station and Chongqing converter station. One end of the converter bushing is located outside the valve hall, and the other end is located inside the valve hall. The valve hall includes converter valve tower, converter transformer bushing and adjacent electrical equipment, as shown in Figure 3.

![Fig.3 Actual operating environment in UHV valve hall](image-url)
Taking the rectifier side as an example, the AC voltage of UHV AC side enters the valve hall through the converter bushing. The voltage waveform through the converter bushing is the superposition of DC component, AC component and transient component. The simulation results show that the voltage ripple is 40kV and current ripple is 80A, which is much smaller than the fundamental DC component. Generally, the maximum temperature of valve hall is +55℃, the minimum temperature is +10℃, and the maximum humidity is 60%. Figure 4 shows actual power equipment in UHV valve hall. It can be seen that under the actual operation environment, the surface of bushing forms uneven temperature distribution, and the highest temperature point is near the top grading ring and grounding flange.

Figure 4 shows the site photos of actual power equipment in the UHV valve hall, including typical power equipment such as UHV converter valve tower, UHV converter bushing, UHV through wall bushing, support insulator, tubular bus and large pressure equalizing cover. The above equipment has a large current flow under the operating conditions, so it will produce a more significant heating effect. In general, local hot spots will appear under the conditions of poor contact of metal conductor, inherent defects of IGBT in converter valve tower and solid insulation cracks in bushing[13]. The main components of the equipment in the UHV converter valve hall, including converter valve tower, converter bushing, tube bus and its voltage equalizing device, were observed in close range. It can be seen that the structure of converter valve tower is complex, and a metal shell is arranged on its outer surface, which is used for electromagnetic shielding protection of precision converter components.
inside the valve tower. At the same time, the infrared imager is used to scan and analyze the surface temperature distribution of the converter valve tower, focusing on the power semiconductor devices inside the converter valve tower and its simulation technology. The infrared thermal imager was used to observe the above key power equipment, as shown in Figure 5.

Figure 5 shows that the electric equipment in the valve hall has obvious temperature field differential distribution under the action of applied current. The local hot spots mainly appear in the contact area of metal conductor, and the surface temperature of large pressure equalizing cover is higher than other areas. At the same time, in the converter valve tower, due to the repeated interruption of IGBT and other semiconductor devices, there will be obvious local overheating area, and the above temperature hot spot is also the area where the valve hall power equipment is prone to failure in the actual operation process. Furthermore, considering that the power equipment in converter valve hall is subjected to high voltage for a long time during operation, the high electric field intensity area is easy to appear on the surface of each large power fitting, especially at the corner of tubular bus. The high temperature area and high electric field intensity area can basically coincide at the same position. The corona phenomenon on the surface of power equipment fitting observed by UV imager is also analyzed. Detailed observation is shown in Figure 6. Figure 6 shows that the ultraviolet imager of the power equipment in the valve hall can effectively observe the weak corona discharge on the surface of typical fittings, which may be caused by the burr, dirt and other foreign matters on the surface of fittings[14]. If there is no severe corona discharge, it indicates that there is no significant insulation defect on surface of substation fittings, but how to accurately locate the three-dimensional distribution of temperature hot spots and ultraviolet defects spatial positioning is convenient to find the defect location as soon as possible for on-site maintenance and repair of power equipment. Now, Kalman filtering technology is used to measure the insulation distance of typical fittings on-line in real time.

![Fig.6 Observation results of power equipment ultraviolet imager](image1)

![Fig.7 Optical path of six observation sensors](image2)
4. The measured online insulation distance of typical fittings based on Kalman filtering technology

Optical sensors are arranged in the interior space of high-voltage power valve hall, the number and location of which 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. Optical sensors are placed at each key position in the high-voltage power valve hall. The optical sensors emit light of certain frequency band and scan continuously. After receiving the position information of partial discharge signal, the light will feed 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 six observation sensors is shown in Figure 7. Figure 7 shows that each observation sensor has a certain observation radius, and each observation radius overlaps with each other, and the probability of observation position is higher in the area with more times of superposition. There are some differences between the actual position of the observation point and the evaluation distance, but the positioning is basically accurate.

![Fig.8 Comparison of filtering effect before and after Kalman filtering technology](image)

![Fig.9 Real time on-line measurement and track tracking of insulation distance of typical fittings](image)

Figure 8 shows that when Kalman filtering technology is not used, the jump of the distance estimation deviation at the key position is more severe in 0~160s. After using the Kalman filtering technology, the jump amplitude of the estimation deviation is reduced, which is basically controlled at the same error level, indicating that the Kalman filtering technology has a better noise control level. At the same time, the track tracking effect of real-time on-line measurement of insulation distance of typical fittings is shown in Figure 9, which shows that the observation distance always jumps around the real path, which proves that the algorithm proposed in this paper has the characteristics of gradual convergence.
5. The 3D modeling of typical power equipment in UHV converter valve hall

Figure 10 shows the surface temperature distribution of UHV converter bushing. The figure shows that the hot spots of UHV converter bushing are mainly distributed in the outlet sleeve under operating conditions. The main reason is that the inside of the sleeve is transformer oil inside the converter transformer, and the oil is in direct contact with the transformer winding, so the temperature is high. At the same time, there is also a high temperature area in the water cooling area of the converter valve tower. Firstly, 3D modeling is carried out for the UHV converter bushing, as shown in Figure 11.

![Fig.10 Surface temperature distribution of UHV converter bushing](image)

![Fig.11 Three dimensional model of UHV converter bushing](image)

![Fig.12 Three dimensional model of UHV converter transformer](image)

Figure 11 shows that three-dimensional model of UHV converter casing includes end pressure equalizing cover, tail pressure equalizing ring and converter body. In the three-dimensional model, the grading ring, wall and inner shield structure at the end of casing and middle flange are considered
simultaneously. The converter bushing in Figure 11 includes indoor and outdoor parts. The hollow silicone rubber insulators at both ends are connected through the middle flange and pass through the wall. Furthermore, the three-dimensional model of the core power equipment converter transformer in the converter valve hall is constructed, as shown in Figure 12. The figure shows that the internal structure of the converter transformer is complex, including the upper and lower magnetic shunt, aluminum shield plate and other key components. At the same time, the three-dimensional internal model of UHV converter transformer is shown in Figure 13.

Figure 13 shows that UHV converter transformer has the characteristics of large size ratio, many parts and complex structure, which brings great difficulties to the grid generation and electric field calculation of 3D model. In particular, the thickness of the internal shield plate is only 3 mm, so it is necessary to adopt a special mesh generation method to minimize the number of nodes and elements in the finite element calculation model.

Figure 14 shows that the casing equipotential line is obviously divided into two parts by the middle wall, and the overall potential distribution is not symmetrical. It can be seen that the valve hall wall has a certain distortion effect on the overall potential and electric field distribution of the bushing, and the wall effect should be considered in the calculation by using the three-dimensional model. The maximum electric field intensity outside the bushing is located on the surface of the high voltage
grading ring of the outgoing lines at both ends, and its maximum electric field intensity is 2653V/mm. Considering that the external air breakdown field intensity is about 3000 V/mm, the grading ring basically meets the requirements of field intensity control. The structure of the grading ring at the high voltage end of the bushing can effectively shield the connecting device between the conductive rod in the center of the bushing and the wires in and out of the bushing, control the maximum field strength at a low level, and avoid the occurrence of corona discharge[15]. Under the large grading ring is the contact part between silicone rubber hollow insulator and high potential fittings. The grading ring should be used to effectively shield the three contact points to avoid corona ablation of silicone rubber under the action of high field strength. Due to the hot spot of temperature in the equalizing cover inside the converter valve hall, the surface electric field intensity distribution of the large equalizing cover is focused, as shown in Figure 15. Figure 15 shows that the internal structure of the large pressure equalizing cover in the valve hall is relatively complex, and there is a flexible contact connection between the tubular bus of the rigid structure and the pressure equalizing cover, which has good anti-seismic and anti displacement capacity. At the same time, it can be seen that the high field strength is mainly concentrated in the lower end of the equalizing cover, with the value of 2386V/mm, and there are small regional high field strength areas in the flexible contact area. On the other hand, the three-dimensional electric field distribution of typical three contact area and low-voltage ring in the UHV converter valve hall in Figure 16 shows that a good shielding area is formed between the low-voltage grading ring and the wall, so that the three contact points between the hollow composite insulator and the grounding flange are in the low field strength area, but the highest field strength appears on the surface of the low-voltage shielding ring, about 900V/mm, which is far less than the air breakdown field strength. At the same time, the highest electric field intensity on the surface of the hollow composite insulator appears in the front of the low-voltage shielding ring, which is mainly due to the modulation effect of the internal shielding layer structure of the through wall bushing on the external electric field distribution.

![High voltage grading ring model](image1)

(a) High voltage grading ring model

![3D electric field distribution](image2)

(b) 3D electric field distribution

Fig. 15 3D electric field distribution of large grading ring in UHV converter valve hall
6. Conclusion

1) Intelligent image processing technology is applied to identify and classify the database of infrared thermal imager and ultraviolet imager; 2) real time on-line measurement of insulation distance of typical fittings is carried out through Kalman filtering technology, including measuring the insulation distance between the hottest point of temperature, partial discharge point and zero potential grounding point; 3) typical main equipment of valve hall is established based on three-dimensional modeling technology of finite element method. The electric field simulation model is prepared to obtain the surface electric field distribution of key equipment fittings. Combined with the image database information, insulation distance information and typical main equipment electric field distribution information, the operation state parameters are effectively obtained, and the intelligent algorithm is applied to automatically evaluate its operation state, discover the latent fault and locate the positive fault, so as to provide effective data support and protection strategy for the main equipment operation and maintenance.

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