IEEE Access
Multidisciplinary Rapid Review Open Access Journal

Received February 26, 2020, accepted March 2, 2020, date of publication March 9, 2020, date of current version March 17, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2979290

A Method to Construct Early-Warning and Emergency Response System for Sulfur Hexafluoride Leakage in Substations

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This work was supported by the National Natural Science Foundation of China under Grant 51775029, the Chinese Universities Scientific Fund under Grant PYBZ1809, and the School of Mechatronics Education and Innovation Fund 2019-2020.

ABSTRACT Sulfur hexafluoride (SF_6) gas leakage in populous urban areas, once occurring, can cause death from suffocation if its concentration largely exceeds 1000ppm and oxygen concentration is low than 19 vol-%. Leakage that cannot be detected and responded to with prompt and effective measures can even lead to large death tolls. Presently, few systematic technical approaches to monitoring, early-warning, consequence prediction, and emergency response of SF_6 leakage have been reported. In this paper, a method for constructing the early-warning and emergency response system for SF_6 leakage in substations is proposed. Firstly, the concentration distribution of leaked SF_6 gas at different leakage points within the substation space is analyzed using CFD simulation to determine the coordinates of sensitive areas where the exceeding of the threshold value of SF_6 concentrations is first detected and thus to ascertain sensor monitoring points. By altering leakage locations and leakage orifice diameters within the substation space, the data concerning the coupling relationship between leakage time, leakage orifice diameter, and concentration are obtained, and a prediction model of diffusion concentration of SF_6 leakage in substations is established through regression. Based on the prediction model, an emergency response system for SF_6 leakage in substations is constructed; additionally, in combination with safety management data of substations, the files required for emergency responses to SF_6 leakage can be identified immediately after occurrence, which provide a guidance for on-field personnel to take emergency responses and safety prevention measures. In this paper, a case study of a substation leakage event is presented to describe the method to construct an early-warning and emergency response system for leakage in substations, as well as the application of the method. The results of this research can provide a theoretical basis for early-warning and emergency response to SF_6 leakage, thereby improving the inherent safety levels of substations.

INDEX TERMS Sulfur hexafluoride, leakage, early-warning, emergency response, CFD.

I. INTRODUCTION

Sulfur hexafluoride (SF_6) is widely used in electric equipment of substations [1]. In the occurrence of SF_6 leakage in substation's main transformer chamber, the concentration of SF_6 within the space can rapidly exceed 1000ppm, and oxygen concentration will be lower than 19 vol-%, predisposing work and maintenance personnel to suffocation [2]. Serious SF_6 leakages in substations established in populous areas may cause massive injuries or even deaths if it is not promptly detected, and effective prevention and control measures are not taken. Therefore, it is imperative to study the early-warning and emergency response system for substation leakages.

A large multitude of studies on early-warning for leakage have been conducted by research institutions and scholars, while studies focusing on the early-warning and emergency response system for SF_6 leakage in substations have been few. Li *et al.* [3] developed an STM32-based monitoring and warning system capable of detecting SF_6 leakage volume in the high-voltage distribution cabinet to ensure the safety of maintenance and inspection personnel working indoors.

The associate editor coordinating the review of this manuscript and approving it for publication was Giambattista Gruosso.

TABLE 1. Comparison of the method in this paper with existing methods.

	Existing methods	The method in this paper
1	No description of how the sensor set points were obtained.	Set up the sensor according to the determined method, leakage can be detected at the first time
2	It is not possible to predict the time required for a leaked gas to reach a dangerous concentration.	A concentration prediction model is established, which can be used to predict the time required for a leaked gas to reach a dangerous concentration
3	The construction method of the emergency recovery device is not mentioned	The construction method of the emergency recycling device is proposed.
4	Lack of emergency measures	An emergency disposal system is established, and required files can be found through the file identification function

To address low measurement accuracy, poor real-time performance and other problems with gas leakage detection relying on electrochemical or negative corona discharge technologies, Shu *et al.* [4] designed a new type of photonic crystal fiber (PCF) based SF_6 detector, and utilized the harmonic detection method and computer wireless transmission network to construct a real-time monitoring system. Saeed and Alim [5] proposed an alternative method for gas leakage detection by incorporating a small autonomous robot, which performs leakage detection through navigating small areas. Once leakage is detected, a wireless signal will be sent to a receiver module comprised of a LCD display. Zhu *et al.* [6] designed a wireless sensor network based early-warning system for underground pipeline safety. When pipeline leakage occurs, the system is able to locate the coordinates of the leakage points and report to the monitoring center. Gupta *et al.* [7] proposed what is called the Leak Analytics System (LAS), which utilizes a probabilistic approach to determine the location and the rate of leakage in low-pressure gas distribution networks, providing a powerful, economical and real-time on-line monitoring system for networks of this kind. Baroudi *et al.* [8] discussed the latest state of the art in leak detection systems (LDSs) and data fusion methods for pipeline monitoring. When pipeline leakage occurs, the system can locate the coordinates of the leakage points and report to the monitoring center. Zeng *et al.* [9] proposed a method for constructing a real-time monitoring and early-warning model of ethylene oxide reactor leakage. Based on this method, a corresponding quantitative calculation software was developed, a real-time monitoring system was constructed, and multiple parameter inputs changed in real-time according to the actual production process to realize real-time monitoring of leakage risk. Ding *et al.* [10] designed a dynamic evacuation guide system, wherein gas sensors are deployed to monitor the leaking of harmful gases, such as H_2S and CO, and the gas diffusion area is also estimated dynamically based on sensor data. The evacuation route can be updated according to the real-time situation. Hsia and Guo [11] developed a security system with a multi-agent architecture, which has multiple sensors and communication interfaces. If an event occurs, the system can provide not only an early-warning but also guidance for rapid evacuations. An analysis of existing literature reveals that studies focusing on the setting of sensors' monitoring points, prediction of gas concentrations, early-warning, and emergency response to SF_6 leakages have been few and unsophisticated. Specifically, existing studies have the following problems: (1) sensors are mounted in arbitrary positions, with the inability to detect SF_6 leakage immediately after occurrence; (2) there is a lack of a prediction model that effectively predicts the concentration distribution of leaked SF_6 in sensitive areas (i.e., areas where the concentration of SF_6 reaches 1000ppm in the minimum amount of time); (3) there is an absence of an early-warning and emergency response system for leakage, resulting in the inability to reduce or avoid losses caused by leakage events by prompt warning and effective response measures.

Thus, to construct an early-warning and emergency response system for SF_6 leakage in substations, the following problems should be addressed: (1) determining sensor setting points in areas sensitive to SF_6 concentration: Immediate detection of leakages within a space is required in order to obtain SF_6 concentration in sensitive areas; (2) constructing a prediction model of SF_6 diffusion concentrations in substations: The concentration distribution of SF_6 leakages within a space can be predicted; (3) the method to construct early-warning and emergency response system modules for SF_6 leakage in substations: the early-warning and emergency response system module for SF_6 leakage in substations should be developed, and the method to construct early-warning and emergency response system adapted to different substation specifications should be proposed in order to ensure personnel injury or death is avoided through timely evacuation and the implementation of effective measures [12]–[14].

This paper proposes a systematic method for constructing a substation sulfur hexafluoride leakage warning and emergency response system, which can be used to solve the problems existing in current research, as shown in Table 1. According to this method, a substation sulfur hexafluoride leakage warning and emergency response system has been established. The core of this method is calculating the concentration distribution of SF_6 leakage according to simulation results, constructing a concentration prediction model, and establishing a system based on the concentration prediction model. System warning accuracy will be improved. By applying this system, SF_6 leakage can be detected as soon as possible, and timely warnings can be

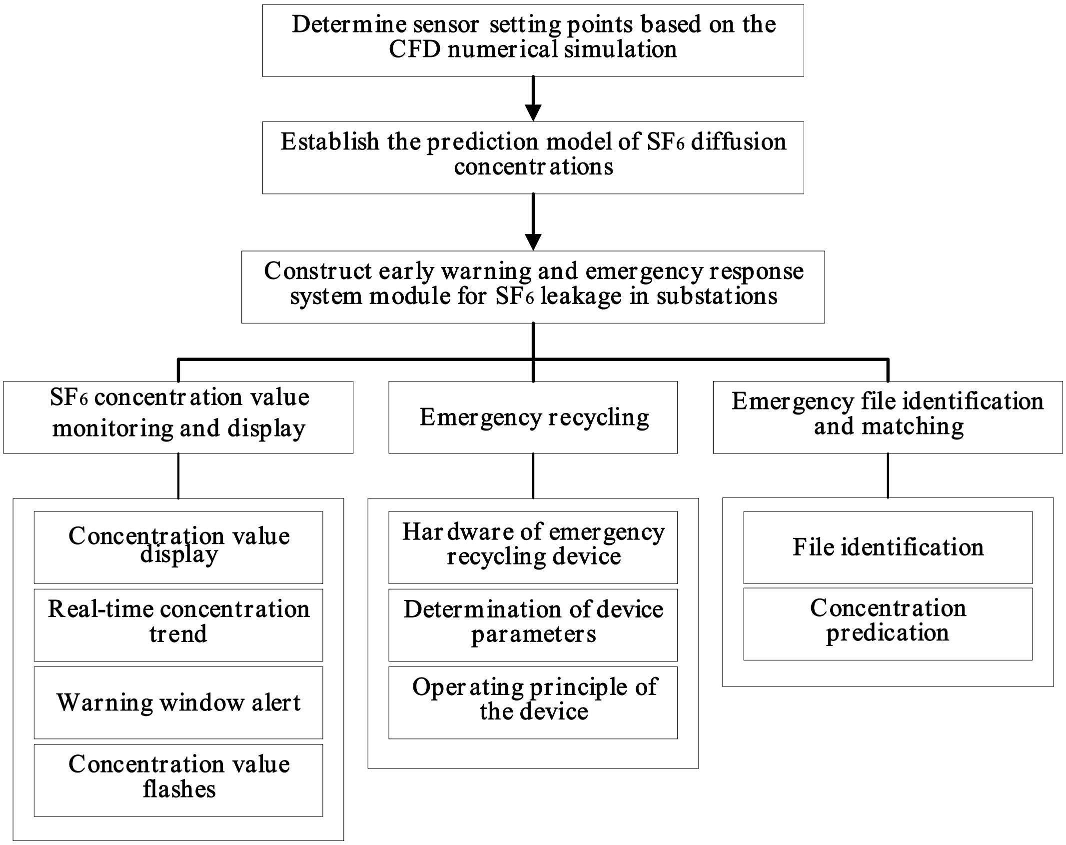


FIGURE 1. Method to construct the early-warning and emergency response system for SF_6 leakage in substations.

given. The SF_6 gas can be recycled immediately so that the indoor SF_6 concentration can drop below the dangerous value as soon as possible. Based on safety management data, technical files that should be referenced immediately for emergency measures can be presented; emergency measures could be rapidly formulated by taking account of the SF_6 diffusion conditions obtained from the concentration prediction model.

II. OVERVIEW OF THE METHOD TO CONSTRUCT THE EARLY-WARNING AND EMERGENCY RESPONSE SYSTEM FOR SF_6 LEAKAGE IN SUBSTATIONS

In this paper, an early-warning and emergency response system for SF_6 leakage in substations is constructed through the following steps, as shown in Figure 1.

A. OVERVIEW OF THE METHOD TO DETERMINE SENSOR SETTING POSITIONS BASED ON CFD NUMERICAL SIMULATION

To determine sensor setting positions sensitive to SF_6 concentrations, this paper adopts the following method: First, the substation's main transformer chamber was studied in order to determine its primary structure and size, a 3D model of the chamber was created and then meshed, followed by determining possible leakage locations and leakage orifice diameters. Next, the sensor monitoring points were set, and the diffusion of SF_6 leakages was simulated using the FLUENT software [15], the results of which were used to determine the setting points of sensors.

B. OVERVIEW OF THE METHOD TO CONSTRUCT THE PREDICTION MODEL FOR SF_6 DIFFUSION CONCENTRATION IN SUBSTATIONS

The method to construct the prediction model for SF_6 diffusion concentration in substations is as follows: based on the simulation data of sensor setting points, factors influencing the distribution of gas concentrations like leakage orifice diameter, leakage duration, leakage location, ambient temperature and wind speed were fitted into a regression to construct a prediction model of diffusion concentration of SF_6 in substations.

C. OVERVIEW OF THE METHOD TO CONSTRUCT THE EARLY-WARNING AND EMERGENCY RESPONSE SYSTEM MODULE FOR SF_6 LEAKAGE IN SUBSTATIONS

Based on the analysis of requirements of the early-warning and emergency response system for SF_6 leakage in substations, the system functions can be allocated into the following modules: a SF_6 concentration monitoring and display module, an emergency recycling module, and an emergency file identification and matching module, as shown in Figure 1. The function of each module is shown as follows:

① the SF_6 concentration monitoring and display module: the module monitors and displays the real-time values of

SF_6 concentrations generated by sensors, and initiate textual, digital, sound and lightning alerts when SF_6 concentration reaches the warning value.

② the emergency recycling module: when SF_6 leakage exceeds the limitation, the emergency recycling device will be started to recycle SF_6 gas within the main transformer chamber of the substation, to contain the SF_6 concentration below the hazardous value.

③ the emergency file identification and matching module: based on safety management data, technical files that should be referenced immediately for emergency measures are identified, and emergency measures are rapidly formulated by taking account of the SF_6 diffusion conditions obtained from the concentration prediction model.

III. CASE-BASED DESCRIPTION OF SYSTEM CONSTRUCTION METHOD AND ITS APPLICATION

In this paper, a case study of a substation is presented to describe the methodology of constructing the early-warning and emergency response system for SF_6 leakage in substations and its applications.

A. DETERMINATION OF SENSOR SETTING POSITIONS BASED ON CFD NUMERICAL SIMULATION

1) MODELING

In the main transformer chamber, locations, where the leakage is likely to occur, are the three valves on the pipe connecting the transformer and heat exchanger, as shown in Figure 2. The 3D model of the main transformer chamber was constructed and meshed, followed by importation into the FLUENT software.

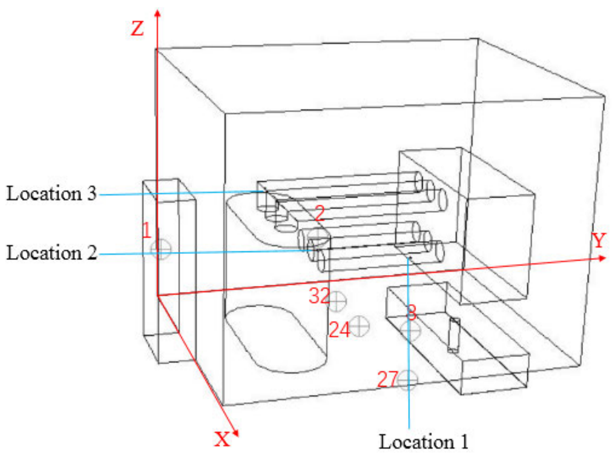


FIGURE 2. Diagram of the main transformer chamber.

2) SETTING SENSOR MONITORING POINTS

A total of 38 sensor monitoring points were established on plane 0.1 and 1.5 meters above the ground in the main transformer chamber. The heights of the monitoring points were determined based on the following facts: ① as a heavy gas, SF_6 tends to accumulate onto the ground following leakage, and thus the monitoring of SF_6 concentration should be carried out near the ground; ② the plane on which most people's respiration occurs is about 1.5 meters above the ground, and thus the SF_6 concentrations on that level should be monitored to avoid deaths from suffocation.

3) DETERMINATION OF SENSOR SETTING POINTS

Taking leakage location and leakage orifice diameter as variables, numerical simulation has been conducted to study the diffusion situation of SF_6 leakage in the main transformer chamber under the influence of different variables. Based on different leakage locations and leakage orifice diameters, six monitoring points were determined, which can first detect that sulfur hexafluoride concentrations exceeding 1000 ppm. The method to determine the six locations is CFD simulation. There will be three possible leakage locations, which can be obtained according to a risk analysis for the main transformer chamber. Thirty-eight points are assumed to be selected to install sensors. For each location, leakage simulation should be conducted and the SF_6 concentration at those 38 points can be monitored. The points can be arranged according to the order detecting the SF_6 concentration exceeding 1000ppm. There will be three orders for the three leakage locations. Each point will be given a value according to its order, and there will be three values that can be obtained. For example, the value of the first point in order is 1. The values for the same point should be summed. The six monitoring points which have the smallest sum can be selected to install sensors. They were point 8 (8, 5, 1.5), point 27 (8, 5, 0.1), point 24 (4, 5, 1.5), point 32 (2, 5, 0.1), point 2 (0, 5, 1.5) and point 1 (0, 0, 1.5), whose locations in the main transformer chamber are shown in Figure 2.

B. CONSTRUCTION OF THE PREDICTION MODEL OF DIFFUSION CONCENTRATIONS OF SF_6 IN SUBSTATIONS

When regressing the model, factors like leakage orifice diameter, leakage duration, leakage location, ambient temperature and wind speed should be considered. However, as SF_6 leakages occur in the main transformer chamber which is a windless environment with stable temperatures, the effects of ambient temperature and wind speed on SF_6 concentration can be neglected. Thus, the regression only needs to take into account of the effects of leakage orifice diameter, duration and location.

The fitting toolbox of the MATLAB software was used for regressing and fitting the experimental data obtained from the monitoring system [16]–[19]. After grouping the leakage locations, the regression equation (where x is the leakage orifice diameter, y is leakage duration, and z is SF_6 concentration) between leakage diameter (mm), leakage duration, and the SF_6 concentrations detected at various sensor points could be obtained.

Take the formula for data fitting monitored by monitoring point 32 as an example, as shown in Table 2. The formulas in Table 2 can be obtained by using the Fourier function and Polynomial function in the fitting toolbox. The Fourier function and Polynomial function are used to approximate the curve to be fitted. The principle is the common least

TABLE 2. Regression models.

Leakage orifice diameter (mm)	Time- and gas leakage orifice diameter-induced change in leaking gas concentration
x=0.5	$z=a0+a1\times\cos(a\times y)+a2\times\sin(a\times y)+a3\times\cos(2\times a\times y)+a4\times\sin(2\times a\times y)+a5\times\cos(3\times a\times y)+a6\times\sin(3\times a\times y)+a7\times\cos(4\times a\times y)+a8\times\sin(4\times a\times y)+a9\times\cos(5\times a\times y)+a10\times\sin(5\times a\times y)+a11\times\cos(6\times a\times y)+a12\times\sin(6\times a\times y)+a13\times\cos(7\times a\times y)+a14\times\sin(7\times a\times y)+a15\times\cos(8\times a\times y)+a16\times\sin(8\times a\times y)$
x=1	$z=b0+b1\times\cos(b\times y)+b2\times\sin(b\times y)+b3\times\cos(2\times b\times y)+b4\times\sin(2\times b\times y)+b5\times\cos(3\times b\times y)+b6\times\sin(3\times b\times y)+b7\times\cos(4\times b\times y)+b8\times\sin(4\times b\times y)+b9\times\cos(5\times b\times y)+b10\times\sin(5\times b\times y)+b11\times\cos(6\times b\times y)+b12\times\sin(6\times b\times y)+b13\times\cos(7\times b\times y)+b14\times\sin(7\times b\times y)+b15\times\cos(8\times b\times y)+b16\times\sin(8\times b\times y)$
x=2	$z=c0+c1\times\cos(c\times y)+c2\times\sin(c\times y)+c3\times\cos(2\times c\times y)+c4\times\sin(2\times c\times y)+c5\times\cos(3\times c\times y)+c6\times\sin(3\times c\times y)+c7\times\cos(4\times c\times y)+c8\times\sin(4\times c\times y)+c9\times\cos(5\times c\times y)+c10\times\sin(5\times c\times y)+c11\times\cos(6\times c\times y)+c12\times\sin(6\times c\times y)+c13\times\cos(7\times c\times y)+c14\times\sin(7\times c\times y)+c15\times\cos(8\times c\times y)+c16\times\sin(8\times c\times y)$
x=5, 10, 15	$z=d00+d10\times x+d01\times y+d20\times x^2+d11\times x\times y+d02\times y^2+d21\times x^2\times y+d12\times x\times y^2+d03\times y^3$
x=20, 25, 50	$z=e00+e10\times x+e01\times y+e20\times x^2+e11\times x\times y+e02\times y^2+e30\times x^3+e21\times x^2\times y+e12\times x\times y^2+e03\times y^3+e40\times x^4+e31\times x^3\times y+e22\times x^2\times y^2+e13\times x\times y^3$

TABLE 3. Comparison of fitting effects(x = 0.5).

Leakage location	Time- and gas leakage orifice diameter-induced change in leaking gas concentration	R
Location 1	$z=a0+a1\times\cos(a\times y)+a2\times\sin(a\times y)+a3\times\cos(2\times a\times y)+a4\times\sin(2\times a\times y)+a5\times\cos(3\times a\times y)+a6\times\sin(3\times a\times y)+a7\times\cos(4\times a\times y)+a8\times\sin(4\times a\times y)+a9\times\cos(5\times a\times y)+a10\times\sin(5\times a\times y)+a11\times\cos(6\times a\times y)+a12\times\sin(6\times a\times y)+a13\times\cos(7\times a\times y)+a14\times\sin(7\times a\times y)+a15\times\cos(8\times a\times y)+a16\times\sin(8\times a\times y)$	0.9898
	$z=f1\times y^8+f2\times y^7+f3\times y^6+f4\times y^5+f5\times y^4+f6\times y^3+f7\times y^2+f8\times y+f9$	0.9711
	$z=g1\times\sin(g2\times y+g3)+g4\times\sin(g5\times y+g6)+g7\times\sin(g8\times y+g9)+g10\times\sin(g11\times y+g12)+g13\times\sin(g14\times y+g15)+g16\times\sin(g17\times y+g18)+g19\times\sin(g20\times y+g21)+g22\times\sin(g23\times y+g24)$	0.9705
Location 2	$z=a0+a1\times\cos(a\times y)+a2\times\sin(a\times y)+a3\times\cos(2\times a\times y)+a4\times\sin(2\times a\times y)+a5\times\cos(3\times a\times y)+a6\times\sin(3\times a\times y)+a7\times\cos(4\times a\times y)+a8\times\sin(4\times a\times y)+a9\times\cos(5\times a\times y)+a10\times\sin(5\times a\times y)+a11\times\cos(6\times a\times y)+a12\times\sin(6\times a\times y)+a13\times\cos(7\times a\times y)+a14\times\sin(7\times a\times y)+a15\times\cos(8\times a\times y)+a16\times\sin(8\times a\times y)$	0.9781
	$z=f1\times y^8+f2\times y^7+f3\times y^6+f4\times y^5+f5\times y^4+f6\times y^3+f7\times y^2+f8\times y+f9$	0.5576
	$z=g1\times\sin(g2\times y+g3)+g4\times\sin(g5\times y+g6)+g7\times\sin(g8\times y+g9)+g10\times\sin(g11\times y+g12)+g13\times\sin(g14\times y+g15)+g16\times\sin(g17\times y+g18)+g19\times\sin(g20\times y+g21)+g22\times\sin(g23\times y+g24)$	0.6069
Location 3	$z=a0+a1\times\cos(a\times y)+a2\times\sin(a\times y)+a3\times\cos(2\times a\times y)+a4\times\sin(2\times a\times y)+a5\times\cos(3\times a\times y)+a6\times\sin(3\times a\times y)+a7\times\cos(4\times a\times y)+a8\times\sin(4\times a\times y)+a9\times\cos(5\times a\times y)+a10\times\sin(5\times a\times y)+a11\times\cos(6\times a\times y)+a12\times\sin(6\times a\times y)+a13\times\cos(7\times a\times y)+a14\times\sin(7\times a\times y)+a15\times\cos(8\times a\times y)+a16\times\sin(8\times a\times y)$	0.9958
	$z=f1\times y^8+f2\times y^7+f3\times y^6+f4\times y^5+f5\times y^4+f6\times y^3+f7\times y^2+f8\times y+f9$	0.8955
	$z=g1\times\sin(g2\times y+g3)+g4\times\sin(g5\times y+g6)+g7\times\sin(g8\times y+g9)+g10\times\sin(g11\times y+g12)+g13\times\sin(g14\times y+g15)+g16\times\sin(g17\times y+g18)+g19\times\sin(g20\times y+g21)+g22\times\sin(g23\times y+g24)$	0.9319

square principle, which makes the curve pass through these interpolation nodes, and makes it optimal in a certain sense.

In Table 2, one location will have five formulas and five sets of coefficients, and there will be 15 formulas and 15 sets of coefficients for three locations. Six monitoring points have been selected to install sensors to warn the SF_6 concentration exceeding 1000 ppm. Therefore, 90 formulas and 90 sets of coefficients can be acquired.

The comparison of several methods has been performed in Tables 3-5.

These fitting equations can be further incorporated into the prediction model of SF_6 diffusion concentration in substations. With known leakage location and leakage orifice diameter, the model can be used to derive the concentration distribution of SF_6 in the main transformer chamber at any leakage time.

C. CONSTRUCTION OF THE EARLY-WARNING AND EMERGENCY RESPONSE SYSTEM FOR SF_6 LEAKAGE IN SUBSTATIONS AND ITS APPLICATION

1) CONSTRUCTION OF THE EARLY-WARNING AND EMERGENCY RESPONSE SYSTEM FOR SF_6 LEAKAGE IN SUBSTATIONS

Based on the prediction model of diffusion concentration of SF_6 leakage in substations in a combination of safety management data, an early-warning, and emergency response system for SF_6 leakage in substations was constructed. The system comprises of 3 modules: a SF_6 concentration monitoring and display module, an emergency recycling module, and an emergency file identification and matching module. The operating principle of the system is shown in Figure 3: the SF_6 concentration monitoring and display module monitors the indoor SF_6 concentrations. If the SF_6 concentration exceeds an alert value, the system immediately issues a warning and initiates the emergency recycling module to reduce the indoor SF_6 concentration below a hazardous value. Upon receiving the warning signal, the on-duty personnel immediately identify technical data that should be referenced and predict the concentration distribution of SF_6 leakage in sensitive areas of the main transformer chamber using the emergency file identification and matching module; on that basis, the personnel further develop emergency response measures and perform maintenance the soonest possible in order to mitigate the consequences of the accident and avoid the occurrence of personnel injury or death. The functions and construction methods of each module will be separately described in the following section.

a: SF_6 CONCENTRATION MONITORING AND DISPLAY

The SF_6 concentration monitoring and display module comprises of sensors, database, and the KingSCADA software, which includes functions like concentration value display,

TABLE 4. Comparison of fitting effects(x = 1).

Leakage location	Time- and gas leakage orifice diameter-induced change in leaking gas concentration	R
Location 1	z=b0+b1×cos(b×y)+b2×sin(b×y)+b3×cos(2×b×y)+b4×sin(2×b×y)+b5×cos(3×b×y)+b6×sin(3×b×y)+b7×cos(4×b×y)+b8×sin(4×b×y)+b9×cos(5×b×y)+b10×sin(5×b×y)+b11×cos(6×b×y)+b12×sin(6×b×y)+b13×cos(7×b×y)+b14×sin(7×b×y)+b15×cos(8×b×y)+b16×sin(8×b×y)	0.9964
	$z=h1\times y^8+h2\times y^7+h3\times y^6+h4\times y^5+h5\times y^4+h6\times y^3+h7\times y^2+h8\times y+h9$	0.9842
	z=i1×sin(i2×y+i3)+i4×sin(i5×y+i6)+i7×sin(i8×y+i9)+i10×sin(i11×y+i12)+i13×sin(i14×y+i15)+i16×sin(i17×y+i18)+i19×sin(i20×y+i21)+i22×sin(i23×y+i24)	0.9941
Location 2	z=b0+b1×cos(b×y)+b2×sin(b×y)+b3×cos(2×b×y)+b4×sin(2×b×y)+b5×cos(3×b×y)+b6×sin(3×b×y)+b7×cos(4×b×y)+b8×sin(4×b×y)+b9×cos(5×b×y)+b10×sin(5×b×y)+b11×cos(6×b×y)+b12×sin(6×b×y)+b13×cos(7×b×y)+b14×sin(7×b×y)+b15×cos(8×b×y)+b16×sin(8×b×y)	0.9912
	$z=h1\times y^8+h2\times y^7+h3\times y^6+h4\times y^5+h5\times y^4+h6\times y^3+h7\times y^2+h8\times y+h9$	0.7558
	z=i1×sin(i2×y+i3)+i4×sin(i5×y+i6)+i7×sin(i8×y+i9)+i10×sin(i11×y+i12)+i13×sin(i14×y+i15)+i16×sin(i17×y+i18)+i19×sin(i20×y+i21)+i22×sin(i23×y+i24)	0.8053
Location 3	z=b0+b1×cos(b×y)+b2×sin(b×y)+b3×cos(2×b×y)+b4×sin(2×b×y)+b5×cos(3×b×y)+b6×sin(3×b×y)+b7×cos(4×b×y)+b8×sin(4×b×y)+b9×cos(5×b×y)+b10×sin(5×b×y)+b11×cos(6×b×y)+b12×sin(6×b×y)+b13×cos(7×b×y)+b14×sin(7×b×y)+b15×cos(8×b×y)+b16×sin(8×b×y)	0.995
	$z=h1\times y^8+h2\times y^7+h3\times y^6+h4\times y^5+h5\times y^4+h6\times y^3+h7\times y^2+h8\times y+h9$	0.9492
	z=i1×sin(i2×y+i3)+i4×sin(i5×y+i6)+i7×sin(i8×y+i9)+i10×sin(i11×y+i12)+i13×sin(i14×y+i15)+i16×sin(i17×y+i18)+i19×sin(i20×y+i21)+i22×sin(i23×y+i24)	0.9948

TABLE 5. Comparison of fitting effects(x=2).

Leakage location	Time- and gas leakage orifice diameter-induced change in leaking gas concentration	R
Location 1	z=c0+c1×cos(c×y)+c2×sin(c×y)+c3×cos(2×c×y)+c4×sin(2×c×y)+c5×cos(3×c×y)+c6×sin(3×c×y)+c7×cos(4×c×y)+c8×sin(4×c×y)+c9×cos(5×c×y)+c10×sin(5×c×y)+c11×cos(6×c×y)+c12×sin(6×c×y)+c13×cos(7×c×y)+c14×sin(7×c×y)+c15×cos(8×c×y)+c16×sin(8×c×y)	0.9969
	$z=j1\times y^8+j2\times y^7+j3\times y^6+j4\times y^5+j5\times y^4+j6\times y^3+j7\times y^2+j8\times y+j9$	0.9615
	z=k1×sin(k2×y+k3)+k4×sin(k5×y+k6)+k7×sin(k8×y+k9)+k10×sin(k11×y+k12)+k13×sin(k14×y+k15)+k16×sin(k17×y+k18)+k19×sin(k20×y+k21)+k22×sin(k23×y+k24)	0.9962
Location 2	z=c0+c1×cos(c×y)+c2×sin(c×y)+c3×cos(2×c×y)+c4×sin(2×c×y)+c5×cos(3×c×y)+c6×sin(3×c×y)+c7×cos(4×c×y)+c8×sin(4×c×y)+c9×cos(5×c×y)+c10×sin(5×c×y)+c11×cos(6×c×y)+c12×sin(6×c×y)+c13×cos(7×c×y)+c14×sin(7×c×y)+c15×cos(8×c×y)+c16×sin(8×c×y)	0.8708
	$z=j1\times y^8+j2\times y^7+j3\times y^6+j4\times y^5+j5\times y^4+j6\times y^3+j7\times y^2+j8\times y+j9$	0.5225
	z=k1×sin(k2×y+k3)+k4×sin(k5×y+k6)+k7×sin(k8×y+k9)+k10×sin(k11×y+k12)+k13×sin(k14×y+k15)+k16×sin(k17×y+k18)+k19×sin(k20×y+k21)+k22×sin(k23×y+k24)	0.5658
Location 3	z=c0+c1×cos(c×y)+c2×sin(c×y)+c3×cos(2×c×y)+c4×sin(2×c×y)+c5×cos(3×c×y)+c6×sin(3×c×y)+c7×cos(4×c×y)+c8×sin(4×c×y)+c9×cos(5×c×y)+c10×sin(5×c×y)+c11×cos(6×c×y)+c12×sin(6×c×y)+c13×cos(7×c×y)+c14×sin(7×c×y)+c15×cos(8×c×y)+c16×sin(8×c×y)	0.9918
	$z=j1\times y^8+j2\times y^7+j3\times y^6+j4\times y^5+j5\times y^4+j6\times y^3+j7\times y^2+j8\times y+j9$	0.9845
	z=k1×sin(k2×y+k3)+k4×sin(k5×y+k6)+k7×sin(k8×y+k9)+k10×sin(k11×y+k12)+k13×sin(k14×y+k15)+k16×sin(k17×y+k18)+k19×sin(k20×y+k21)+k22×sin(k23×y+k24)	0.9904

real-time concentration trend, warning window alert, and concentration value flashes. The module is constructed through the following steps:

① *Database for Data Storage*: Sensors set in accordance with the sensor setting points determined by CFD data simulation monitor and collect the indoor SF_6 concentrations, and send the data to the SQL server database for storage; in addition, a monitoring interface of the main transformer chamber is generated based on actual conditions of the chamber and sensor locations.

② *Data Display*: The database and the software are connected by the IO Server application, which reads the SF_6 concentration data in a real-time manner and transmits the data to the monitoring interface of the main transformer chamber, where the monitoring display panel and the real-time trending curve are generated. The monitoring display panel displays SF_6 concentrations collected by various sensors, while the real-time trending curve displays the real-time changes of SF_6 concentrations around sensors over time.

③ *Warning:* The alert values are set for the warning groups and flashing texts. When SF_6 concentration detected by a sensor exceeds a preset alert value, the warning window will immediately issue a warning and display information related to the warning sensor. The warning window is shown in Figure 4. The SF_6 concentration value displayed in the monitoring interface of the main transformer chamber will constantly flash red lights as a reminder that the SF_6 concentration will reach a hazardous value.

b: EMERGENCY RECYCLING

The emergency recycling module relies on an emergency recycling device to fulfill its functions. The hardware components, suction parameter setting, and operating principle of the module are shown as follows:

① *Hardware Components of the Emergency Recycling Device:* The emergency recycling device is installed at the cooling ventilation grille beneath the main equipment layer of the underground substation. Its hardware is comprised of

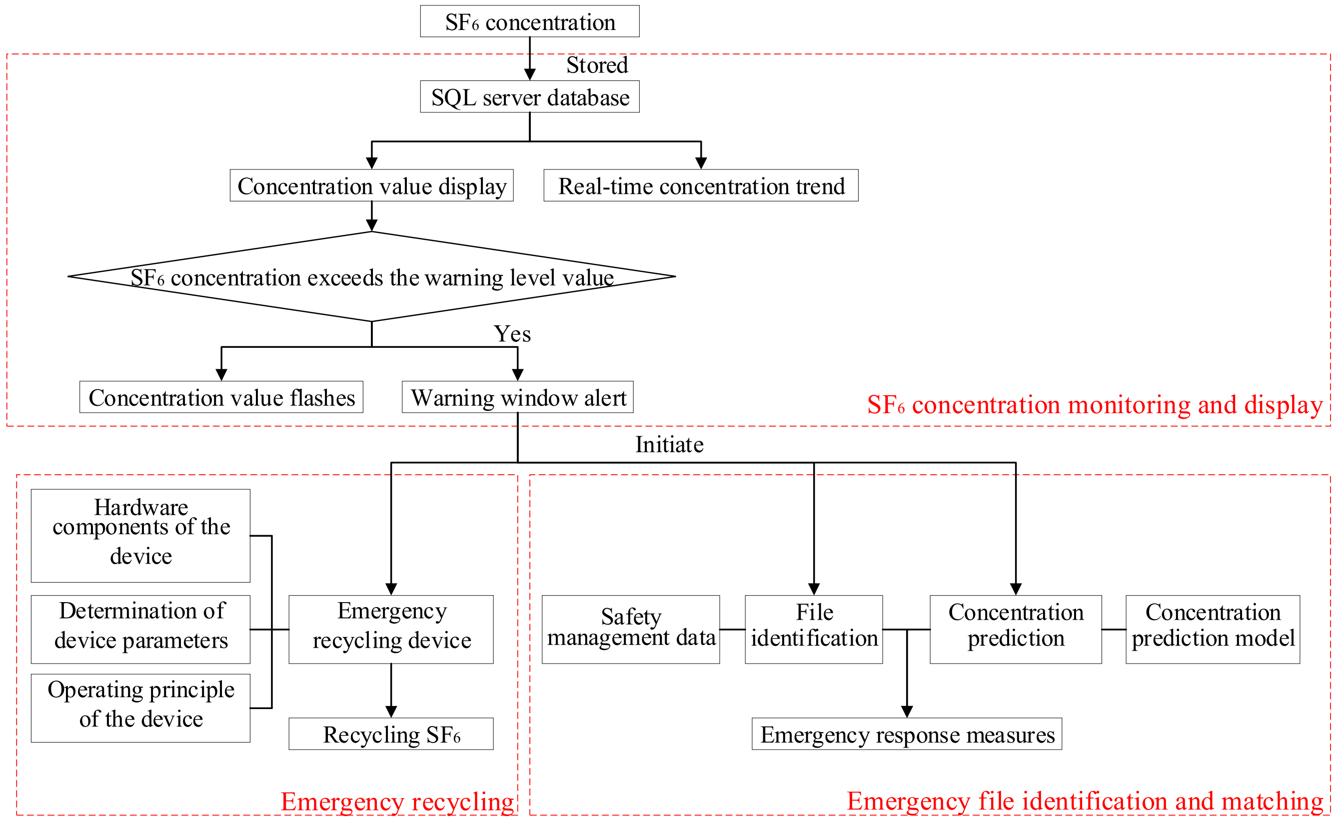
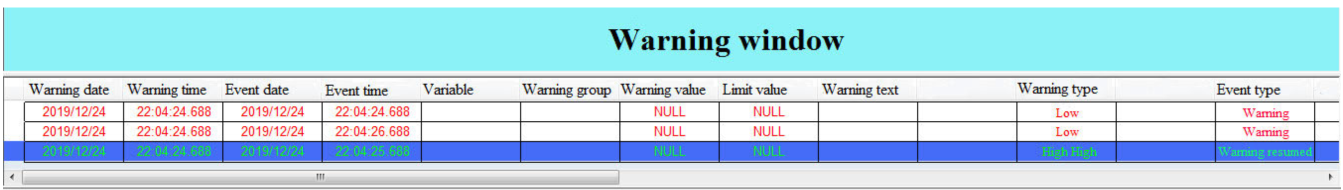


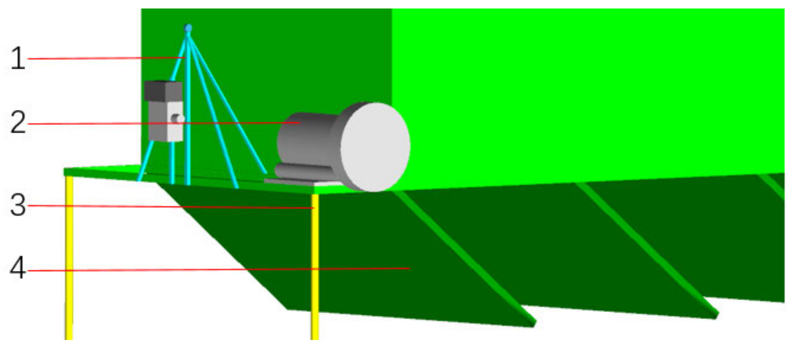
FIGURE 3. Operating principle of the early-warning and emergency response system.



Warning window

Warning date	Warning time	Event date	Event time	Variable	Warning group	Warning value	Limit value	Warning text		Warning type		Event type
2019/12/24	22:04:24.688	2019/12/24	22:04:24.688			NULL	NULL			Low		Warning
2019/12/24	22:04:24.688	2019/12/24	22:04:26.688			NULL	NULL			Low		Warning
2019/12/24	22:04:24.688	2019/12/24	22:04:25.688			NULL	NULL			High High		Warning resumed

FIGURE 4. Warning window.



1 Mechanical transmission unit 2 Suction pump 3 Mechanical frame 4 Active shutters

FIGURE 5. External view of the emergency recycling device.

the mechanical transmission unit, suction pump, mechanical frame, active shutters, and PLC control system, as shown in Figure 5. The mechanical transmission unit is used to pull up or shut down the active shutter to switch between the closed or open modes at the bottom of the device. The mechanical frame serves supporting and fixation functions, which are fixed via anchor bolts.

② *Determination of Parameters of the Emergency Recycling Device:* The following parameters should be determined for the emergency recycling device: the suction pump model and the duration of recycling. Method to determine the suction pump model: recycling of indoor SF_6 in substation's main transformer chamber under different suction pressures is simulated to determine the time needed for maintaining the SF_6 concentration within the main transformer chamber steadily below 1000ppm. Then, the suction pressure of the pump is determined by taking into account the pump cost and the time required to stabilize SF_6 concentrations. Based on the pump's suction pressure and the gas flow area at the suction opening (the suction opening diameter is set as 0.3 meters, while the gas flow area at the suction opening is calculated using the formula for the area of a circle), the Bernoulli's equation is used to determine the capacity of the suction pump. Finally, the pump's model is determined based on the suction pressure and capacity of the pump. Method to determine recycling duration: With a pre-determined suction pressure, recycling of indoor SF_6 in substation's main transformer chamber under different leakage locations and leakage diameters is simulated. The simulation results are used to determine the time needed for keeping SF_6 concentration stably below 1000ppm (that is, the recycling duration). Leakage locations are grouped, and the corresponding leakage orifice diameters and recycling durations are separately regressed, deriving three groups of regression equations. The recycling duration can then be obtained using the regression equations with known leakage orifice diameter and leakage location.

③ *Operating Principle of Emergency Recycling Device:* When the SF_6 concentration detected by a sensor exceeds the alert value, the warning window will issue a warning, and then the emergency recycling device starts immediately. At the point, the device's PLC control system sends a signal to initiate the mechanical transmission unit, which pulls up the shutter to a horizontal position, switching the shutters at the bottom of the device to the closed mode from the open mode; the suction pump starts to recycle SF_6 gas. When maintenance work is completed, and the SF_6 concentration detected by sensors reaches 0, the warning information will be removed. At this point, the emergency recycling device will be immediately shut down, and the device's PLC control system will send a signal to restart the mechanical transmission unit, which drops the shutters to a vertical position, switching the shutters at the bottom of the device to the open mode from the closed mode. The pump shuts down and stops recycling SF_6. The recycling duration is calculated using the fitting equation stated above.

c: EMERGENCY FILE IDENTIFICATION AND MATCHING

The emergency file identification and the matching module comprises of the safety management data and the prediction model of SF_6 concentration in substations. The module is constructed in the following steps.

① *Preparation of Safety Management Data:* The process safety data are divided into the following 15 categories: equipment knowledge, risk analysis, risk quantification, equipment integrity, human factor, change management, operating rules, training, emergency response, review, accident investigation, standards and specifications, contractor management, safety operation licensing process and control system [20]. Based on data categorization, the analytical results of leakage risks relating to equipment in substation's main transformer chamber are matched item by item to derive safety management data.

② *File Identification Function:* Up receiving the warning information, the on-duty personnel will immediately dispatch maintenance personnel to rapidly identify, consult and obtain accident cases, response measures, emergency plans, standards and specifications and other relevant files based on warning information displayed on the warning window and safety management data.

③ *Concentration Prediction Function:* The prediction model of SF_6 concentration in substations predicts the concentration distribution of SF_6 in sensitive areas of the main transformer chamber, providing a reference for the formulation of emergency response measures.

2) APPLICATION OF THE EARLY-WARNING AND EMERGENCY RESPONSE SYSTEM FOR SF_6 LEAKAGE IN SUBSTATION

The application process of each module pertaining to the early-warning and emergency response system for SF_6 leakage in substations is shown as follows.

a: SF_6 CONCENTRATION MONITORING AND DISPLAY

As shown in Figure 6, when SF_6 leakage occurs in the main transformer chamber, all monitoring display panels show an SF_6 concentration value higher than 0. The changes in SF_6 concentrations detected by each sensor in the main transformer chamber can be known from real-time trend curve. The SF_6 concentration values of monitoring point 8 and monitoring point 27 are higher than the alert value, as shown in the monitoring display panel, at this point, the warning window initiates a warning, which shows the date, time and other information of the warning about sensors at point 8 and point 27. The concentration values of sensors alerted in the monitoring display panel constantly flash a red light. In this scenario, working personnel at the spot will immediately evacuate, and ascertain that the leakage location is at location 1 based on the location of the sensor that trigger the earliest warning, as shown in Figure 2.

b: EMERGENCY RECYCLING

After the warning signal is sent by the warning window, the emergency recycling module immediately starts to recycle SF_6 gas leaked in the main transformer chamber to keep its concentration below 1000ppm and avoid the occurrence of personnel injury or death. After the SF_6leakage stops and the recycling of leaked indoor gas has been completed over some time, the concentration value of SF_6 displayed on the monitoring panel will drop to 0. At this point, the warning window will stop alert and shut down the emergency recycling module.

c: EMERGENCY FILE IDENTIFICATION AND MATCHING

Upon receiving the warning information, the on-duty personnel immediately dispatch maintenance personnel to predict

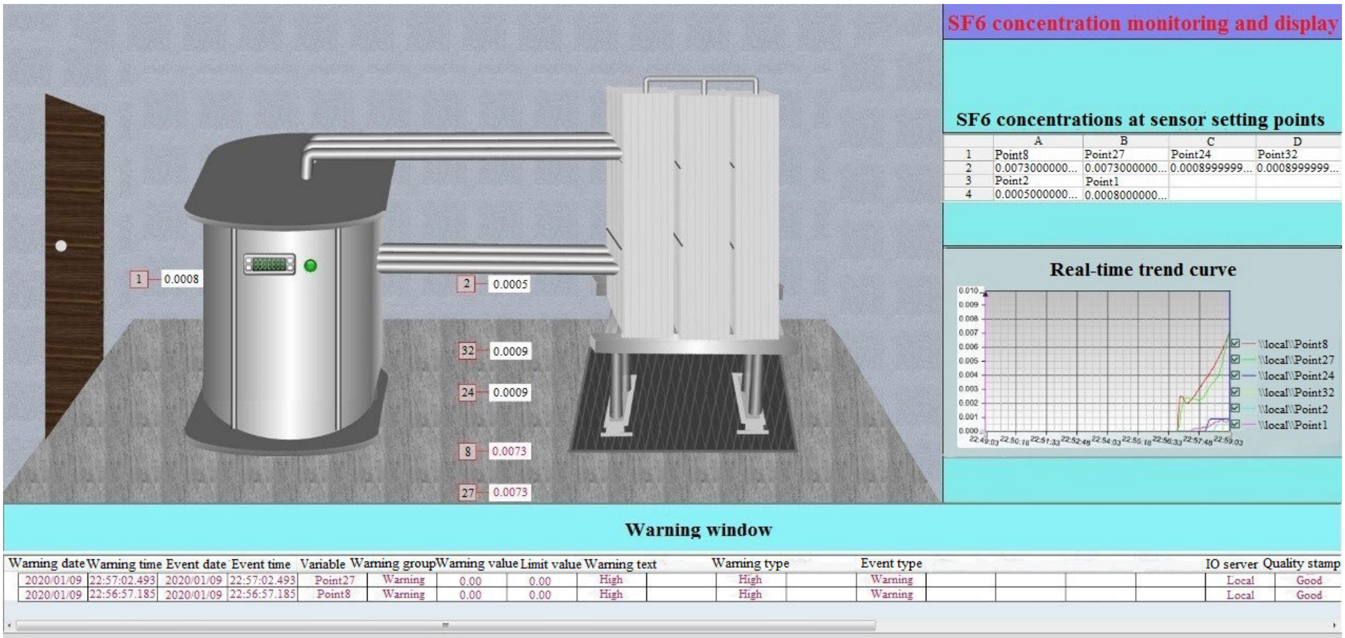


FIGURE 6. The interface of the SF_6 concentration monitoring and display module.

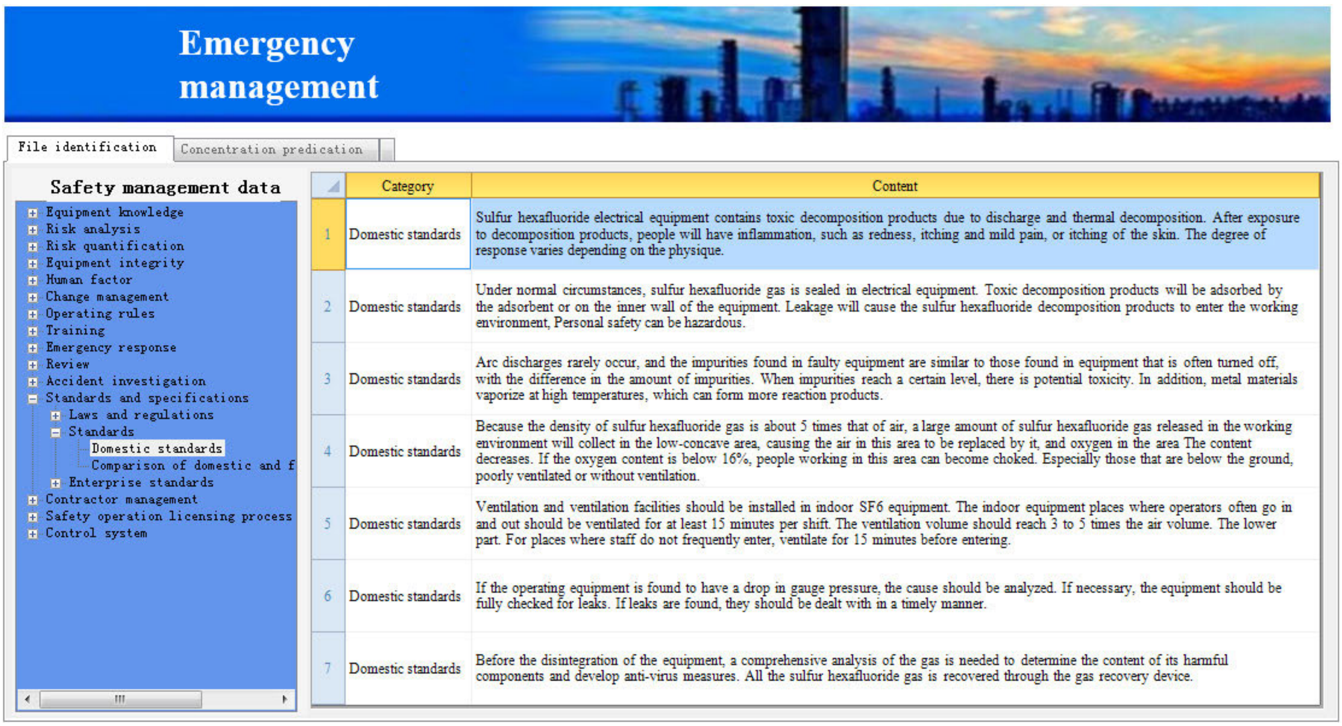


FIGURE 7. The interface of file identification.

the concentration distribution of SF_6 leakages in sensitive areas of the main transformer chamber using the module's concentration prediction function. Utilizing keyword search provided by the file identification function, the maintenance personnel can immediately identify the required technical files from safety management data for emergency responses (take the Domestic Standards in the category option, for instate, the results are shown in Figure 7). Further, the concentration distribution of SF_6 leakage in sensitive areas of the main transformer chamber will be referenced for rapidly developing emergency response measures, so that maintenance can be completed and consequences of the leakage accidents can be minimized as quickly as possible.

IV. CONCLUSION

In this paper, a detailed study of the method to construct an early-warning and emergency response system for SF_6 leakage in substations is presented. First, the SF_6 sensor setting points are determined based on the CFD numerical simulation to ensure that SF_6 leakage can be detected immediately after the occurrence. Next, a prediction model of diffusion concentration of SF_6 in substations is established based on simulated data of sensor setting points. Then, an early-warning and emergency response system for SF_6 leakage in substations is constructed based on the concentration prediction model in combination with safety management data. Finally, a case study of leakage in a substation is presented to describe the method to construct the early-warning and emergency response system for leakage and its application. The study provides assistance for early-warning of SF_6 leakage accidents and the implementation of emergency responses in similar substations and is of great significance for early-warning and response to public safety accidents involving hazardous and harmful substances. The sulfur hexafluoride leakage diffusion and recycling experiments should be conducted. The recycling system should be established. When the monitoring sensors detecting the leakage, the recycling system will be started the recycling system to recycle the SF_6. The research will enhance the intrinsic safety of the plants.

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