Fire and blast resistance analysis of the firestop system of valve hall in UHVDC converter station

Bo Zhong\textsuperscript{1}\textsuperscript{*}, Chang-Zheng Zhao\textsuperscript{1}, Ze-Jiang Zhang\textsuperscript{1}, Ya-Qiang Jiang\textsuperscript{1}, Jia-Qing Zhang\textsuperscript{2}, Xiao-Sheng Liu\textsuperscript{3}, Hao Huang\textsuperscript{1}

\textsuperscript{1} Sichuan Fire Research Institute of Ministry of Emergency Management, Chengdu, Sichuan, 610036, China
\textsuperscript{2} State Grid Anhui Electric Power Research Institute, Hefei, 230022, China
\textsuperscript{3} Global Energy Interconnection Research Institute Co., Ltd, Beijing, 102211, China
\textsuperscript{*}Corresponding author’s e-mail: zhongbo@scfri.cn

Abstract. The ultra-high voltage direct current (UHVDC) converter station is the core of the UHVDC project to realize the mutual conversion of alternating current (AC) and direct current (DC). Its operational reliability directly affects the safety of personnel and equipment and the stable operation of the grid. The firestop system is key part of the protective system in converter station, and it faces the threat of fire and explosion of converter transformer. In this paper, in order to analyze the shortcomings of the existing firestop system of valve halls, numerical models for fire and blast resistance analysis of typical firestop system are established. For a typical UHVDC converter station, the temperature distribution under hydrocarbon heating curve and dynamic response under different blast loads are analyzed by using the established numerical model. And the results show that the existing firestop system has good heat insulation performance, while the blast resistance cannot meet the demand.

1. Introduction
The UHVDC converter station is the core to realize mutual AC/DC conversion in UHVDC projects. Its operational reliability is directly related to the safety of personnel and equipment and the grid stability. There is more than 100 tons of insulating oil in the tank of a converter transformer. Once the fault arc causes fire or explosion, the firestop system of the valve hall would be destroyed, and the fire would spread to the inside, leading to immeasurable economic loss and serious social impact. In recent years, fire accidents caused by explosion of converter transformer occur from time to time. For example, on April 7, 2018, an explosion occurred at the ±800kV Tianshan Converter Station in Hami, Xinjiang, resulting in the destruction of a high-end valve hall and six converter transformers, which is a heavy economic loss.

In order to ensure that the converter transformer can be moved conveniently, it is arranged adjacent to the valve hall, as shown in Figure 1. They are separated by a firestop system made of PAROC plates (a lightweight rock wool sandwich panel: 0.5mm deagussing stainless steel plate + 150mm rock wool + 0.6mm deagussing stainless steel plate). This structure does not take into account the effect of explosion. Once the converter transformer explodes and catches fire, the firestop system may be directly damaged, losing its fire proofing function completely, leaving the fire spread to the valve hall. This will cause incalculable economic losses and affect the operation of the national economy. Therefore, it is necessary to conduct in-depth research on the protection performance of the firestop...
system of the valve hall of the converter station so as to improve the system design, deliver better fire control performance, and avoid the damage to the internal facilities of the valve hall caused by fire or explosion after the failure of the converter transformer. It is of great significance not only to the safe and stable operation of the national power system, but also to the sound development of the national economy and the national defense security.

Figure 1. Scheme of the firestop system in a typical valve hall

2. Analytical methods

2.1. Evaluation method of fire proofing performance of the firestop system
The most reliable way to evaluate the fire proofing performance of the firestop system in the valve hall of the converter station is to build a test model based on the actual use of the system in the project, and obtain the fire endurance value of the system by testing it on the combustion furnace. However, the fire endurance test is costly in terms of time and money. Therefore, before the test, it is necessary to calculate the temperature field distribution of the system using numerical simulation method, understand the fire proofing performance of the system and optimize its structure based on the numerical evaluation results. In this way, a preliminary plan of the system can be obtained, which shall go through fire endurance test to verify its reliability.

This paper conducts numerical stimulation of the temperature field during the heat transfer process using the thermal analysis module in the general finite element software LS-DYNA [1]. A numerical model is established based on part of the system. The typical heat transfer boundary conditions are shown in Figure 2. After setting the boundary conditions, material parameters and solving control parameters, the temperature field of the system can be calculated.

Figure 2. Heat transfer boundary conditions

2.2. Evaluation method of blast resistant performance of the firestop system
After the 9/11 incident in the United States, lots of researchers have carried out a large number of experimental and numerical simulation studies on the dynamic response and failure process of engineering structures under blast loads, and they have established relatively mature evaluation method of the blast resistant performance[2, 3]. The firestop system of valve hall of the converter
station may suffer from the load effect caused by fire and blast, which is the result of the arc fault of the converter transformer. Therefore, it is necessary to evaluate the blast resistant performance of the currently used firestop structure, understand its risks, strengthen the blast resistance of the system, and deliver blast resistant design of the firestop system of the new converter station.

To evaluate the blast resistant performance of the widely used PAROC plate blocking system, it is feasible to build a finite element numerical model of the system according to the actual situation. The steel plate layer and the core material of rock wool of the sandwich panel adopt shell element and solid element, respectively. And the two share the same node. This paper establishes a numerical model of the blocking system in LS-DYNA, and analyzes its dynamic response or damage process under blast loading.

3. Case studies

3.1. Project overview

Xiluodu left bank-Jinhua, Zhejiang ±800 kV UHV DC project was once China's DC project with the highest voltage grade and largest amount of transmission power. The project starts from Shuanglong Converter Station in Yibin, Sichuan Province in the west and travels 1,700 kilometers eastwards to Jinhua Converter Station in Zhejiang Province, passing through Sichuan, Guizhou, Hunan, Jiangxi, and Zhejiang provinces. The firestop system of the valve hall in Shuanglong Station is shown in Figure 3. The entrance is 5.0m wide and 4.35m high, and it is made of the monolayer 150mm-thick PAROC plate.

![Figure 3. Scheme of firestop system for valve hall of ShuangLong Converter Station](image)

3.2. Evaluation of fire proofing performance

The numerical simulation method in Section 1.1 evaluates the fire proofing performance of the blocking system, which only takes into consideration the fire proofing and heat insulation performance of the PAROC plate, but not the heat transfer in the panel joint and the penetration area. Since the stainless steel plates at both ends of the PAROC plate are only 0.5 mm and 0.6 mm thick, the thermal analysis can ignore the effect of the stainless steel plate, and heat transfer analysis can take a standard block as the sample, as shown in Figure 4.

![Figure 4. Scheme of standard block of PAROC plate](image)
For the rock wool, its thermal conductivity is $k=0.048 \text{ W/mK}$, the specific heat capacity is $c=750 \text{ J/kgK}$, the density is $\rho=180 \text{ kg/m}^3$, and the convective heat transfer coefficient is $h=15 \text{ W/m}^2\text{K}$. The general FE software LS-DYNA is adopt to simulate the $1\text{m} \times 1\text{m} \times 0.15\text{m}$ standard block. In heat conduction, the thermal conductivity and the specific heat capacity are set using the keyword *MAT_THERMAL_ISOTROPIC; in heat convection, the convective heat transfer coefficient is set using the keyword *BOUNDARY_CONVECTION_SET; in heat radiation, the radiative heat transfer coefficient is set using the keyword *BOUNDARY_RADIATION_SET.

The hydrocarbon heating curve shown in Figure 5 is applied to the bottom of the plate. Adiabatic boundary conditions are set around the plate, and convection and radiation boundary conditions are set at the bottom and the top of the plate. Considering that the thermal conductivity of rock wool will inevitably change with the increase of temperature, Global Energy Internet Research Institute has determined the relationship between the thermal conductivity of the core material of rock wool in PAROC plate and the temperature through experiments, as shown in Table 1. By taking the thermal conductivity value of the rock wool in Table 1 as the input parameter of the keyword of the thermal analysis material (*MAT_THERMAL_ISOTROPIC_TD), we can calculate the heating curve of the exposed surface, the middle part and the unexposed surface of the plate, as shown in Figure 6. As can be seen from Figure 6, the temperature of the unexposed surface after 4h influence of hydrocarbon heating curve is about 140 °C, which is less than 180 °C, indicating that the fire proofing and heat insulation performance of the 150 mm thick PAROC board can meet the requirements.

![Figure 5. ISO834 and Hydrocarbon fire curves](image)

| Temperature (°C) | Thermal conductivity (W/mK) |
|-----------------|-----------------------------|
| 300             | 0.039                       |
| 500             | 0.057                       |
| 800             | 0.134                       |
| 1000            | 0.197                       |
Figure 6. Comparison on heating curves of exposed, middle and unexposed surfaces

It is worth noting that Figure 7 shows the calculation results of the heating curve of the unexposed surface when the thermal conductivity of the rock wool is taken as the constant value and the thermal conductivity changes with temperature. It can be seen from the figure that when the thermal conductivity coefficient of the rock wool is set to be a fixed value of 0.048 W/mK, the temperature of the unexposed surface after 4h effect of carbon-hydrogen heating curve is only about 60 °C, which is greatly deviated from the result of 140 °C, which is calculated when the change of thermal conductivity is taken into consideration. Therefore, whether or not the change of thermal performance parameter of the blocking material with temperature is taken into consideration in the thermal analysis of the blocking system has a great influence on the accuracy of the calculation result.

Figure 7. Influence of thermal conductivity on heating curve of unexposed surface

3.3. Evaluation of blast resistant performance

According to the evaluation method of blast resistant performance of the blocking system in Section 1.2, since the firestop system of the valve hall of Shuanglong Station is composed of a single layer of 150mm thick PAROC plate, it is necessary to establish a numerical model of the blocking system according to the actual situation. The stainless steel of the surface layer and the core material of rock wool of the PAROC plate adopt shell element and solid element, respectively, and the above two share the same node. In addition, the cohesion failure of the two is not taken into consideration. For the convenience of modeling and analysis, the height of the entrance is adjusted from 4.35m to 4m in numerical calculation. Four 1m-wide PAROC plates are used for assembly, while rigid material is used in the outer frame. The joint is defined by contact failure algorithm. The final numerical analysis model of the blocking system is shown in Figure 8.
The explosion caused by the arc fault of the converter transformer usually occurs at the side of the grid. Based on the size of the transformer, the vertical distance between the explosion source and the center of the blocking system is assumed to be 5m. 1kg, 5kg and 10kg equivalent TNT is set at the explosion source, with the peak values of reflection overpressure of 71kPa, 227kPa and 414kPa, respectively. The calculated displacement time history curves of the center of the blocking structure is shown in Figure 9. The maximum deformation delivered by the above equivalent TNT is 19.5mm, 74mm and 111.6mm, respectively. Based on the technical manual of PAROC plate, with no other reliable information, it is feasible to take L/100 as the deformation limit. Therefore, when the deformation of any point of the blocking structure exceeds 50 mm, the deformation of the blocking structure can be considered to be failed. It can be seen that under the effect of 5kg and 10kg equivalent TNT, the blocking structure fails. Figure 10 shows the simulation results of the failure of the blocking structure under the effect of 50kg equivalent TNT. It can be seen that the joint part between the PAROC plates, that between the PAROC plate and the frame, and the PAROC plate itself may be destroyed by explosion.
4. Conclusions
This paper analyzes the fire proofing and blast resistant performance of the firestop system of the existing UHV converter station using the numerical simulation method. The result shows that the current blocking system made of 150mm PAROC plate can meet the fire proofing requirements when fire is the only factor taken into consideration, but it delivers poor blast resistant performance. Under the action of 5kg equivalent TNT at the distance of 5m, the blocking system fails, losing its fire proofing function. Therefore, in the renovation or construction project of the firestop system in the valve hall of the converter station, emphasis should be given to strengthening the blast resistant performance.

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