Numerical Simulation of Converter Station Fire: A Study focus on the Fire Hazard of Valve Tower

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Abstract. The fire hazard of a valve tower in converter station fires were investigated by using the Fire Dynamics Simulator (FDS). The 2 m², 5 m² and 10 m² transformer oil pool fires with the calculated heat release rate (HRR) of 2.02, 6.23 and 13.78 MW were considered in the simulations, and the smoke propagation process, smoke temperature and visibility were mainly concerned. The results showed that the whole valve tower was immersed in the fire smoke at about 600 s in 2 m² fire condition, and the maximum temperature rise inside the valve hall was about 20 ºC. In the 5 m² fire condition, the smoke layer height descended to the bottom of the valve tower at about 300 s, and the visibility around the valve modules was lower than 5 m at about 450 s. The maximum smoke temperature inside the valve hall was over 60 ºC, and the temperature of smoke around the valve modules ranged from 43 to 52ºC. In the 10 m² fire condition, the valve tower was immersed in the fire smoke at about 210 s, and the visibility around the valve modules was lower than 5 m at about 300 s. The smoke temperature beneath the ceiling of the valve hall was over 100 ºC, and the temperature at the height of valve towers ranged from 65 to 80ºC. It was observed that the larger the fire size was, the higher the fire hazard of the valve tower would be found. In the 5 m² and 10 m² pool fire conditions, the thermal damage to the valve tower was non-negligible. The normal operation of the electrical components in the valve tower might be affected, and the failure of electrical components might be occurred.

1. Introduction

With development of electric power and electric system, the direct current (DC) power transmission technology gets into a new period of vigorous advancement. Compared with the alternating current (AC) power transmission technology, the DC power transmission technology has the advantage of low dissipation and high stability. The convertor station, which is used to exchange the AC and DC, is the core of the DC transmission system. Once there is an electricity interruption, the fire accident may be induced in the convertor station. The fire safety of convertor station is of great significance to the stable operation of power grids. Therefore, the fire hazard of convertor station should be attached great importance to.

In the convertor station, the convertor transformer has high fire risk, and most of the fire accidents inside the convertor were originated from the convertor transformer. Therefore, there were many related studies focused on the convertor transformer fire. Sun et al. [1] established a calculation model for foam
extinguishing system, and applied it to the simulation of 110 kV transformer fire. Lindström et al. [2] investigated the extinguishing capacity of profile plank in transformer pit fire, which is an alternative solution of the conventional fire extinguishment method. By conducting a small-scale experiment, Lin [3] explored the development process and the fire hazard of the transformer pool fire. The numerical simulation of UHV converter transformer fire was conducted by Zhang et al. [4]. The occurrence and development process of the typical transformer fires were discussed in detail. In addition, there were several studies focused the combustion characteristics of the transformer oil and transformer insulating paper board [5-6].

Since the converter transformer is adjacent to the valve hall, the transformer fire may spread to the valve hall once the fire separation failed and pose a threat to the equipment in the valve hall. However, there is rare study has put attentions on this fire condition. In the valve hall, the converter valve towers are hanged on the ceiling. The converter valve tower contained thousands of electrical components, and it is very expensive and of great importance to the converter station. Once there is a fire in the valve hall, it would pose a serious threat to the security of the converter valve towers.

To sum, the converter station fires were investigated by using the numerical simulation in the present study, and the research was mainly focused on the fire hazard of converter valve towers. The smoke propagation process and the fire parameters were mainly discussed.

2. Numerical Method and Simulation Model

The numerical simulations in this study were conducted by using the FDS, which is a field simulation software of fire that developed by National Institute of Standards and Technology. By using this fire simulation software, the smoke spread process and fire parameters of buildings or structures under specific fire condition could be obtained. It has been widely used in many fire related researches [7-9].

The valve hall with the dimensions of 86.0 m (L) × 35.0 m (W) × 2.05 m (L) was built by steel structure, as shown in Figure 1. The height and width of the door were 3.0 m and 5.0 m, respectively. Six valve towers were hanged on the ceiling of the valve hall. The bottom of the lower shielding case of the valve tower was about 11 m above the floor of valve hall. The valve towers were labelled as 1# to 6#, and their locations are shown in Figure 1. Each valve tower had four stacks of valves, which adopted the split-level arrangement. The simulation model of the valve tower is also illustrated in Figure 1.

![Figure 1. Simulation model of the valve hall and valve tower.](image-url)

For simulating the fire condition that originated from the converter transformer and spread into the valve hall after the failure of fire separation, the fire source in the simulation model was set close to the wall of the valve hall towards the converter transformer. The type of fire was set as transformer oil pool fire. Three fire size, including 2 m², 5 m² and 10 m² pool fires were considered in the simulations. The mass loss rate of transformer oil in fire can be established as [10],

\[
\dot{m'} = \dot{m}_u (1 - e^{-4\beta D})
\]
Where \( \dot{m} \) is the mass loss rate of fuel (kg·s\(^{-1}\)·m\(^{-2}\)); \( \dot{m}_\infty \) is the mass burning rate for an infinite diameter pool (kg·s\(^{-1}\)·m\(^{-2}\)), \( k \) is the extinction coefficient (m\(^{-1}\)); \( \beta \) is the mean beam length correction; \( D \) is the effective diameter (m), expressed as,

\[
D = \sqrt{4A/\pi}
\]  

(2)

Where \( A \) is the area of the fuel surface (m\(^2\)). For the transformer oil, the \( \dot{m}_\infty \) is 0.039 kg·s\(^{-1}\)·m\(^{-2}\), and \( k\beta \) is 0.7 m\(^{-1}\). The HRR of the transformer pool fire is,

\[
\dot{Q} = \chi \cdot \Delta H_c \cdot \dot{m}_c \cdot A
\]  

(3)

Where \( \chi \) is the combustion efficiency, and value as 0.83 in the present study; \( \Delta H_c \) is the heat of combustion of fuel, which is 46.4 MJ·kg\(^{-1}\) for the transformer oil. According to equation (1) to (3), the HRR of 2 m\(^2\), 5 m\(^2\) and 10 m\(^2\) transformer oil pool fires are about 2.02, 6.23 and 13.78 MW, respectively.

The size of mesh for the area near the fire source is set as 0.25 m × 0.25 m ×0.25 m. The parameter \( D^*/\delta \) in the three fire conditions are 5.1, 8.0 and 11.0, respectively, which are all in the range of 4~16 and meet the requirement of the mesh resolution [11].

3. Simulation Results and Discussion

3.1. Smoke Propagation

The smoke propagation process in the valve hall of the 2 m\(^2\) pool fire condition is shown in Figure 2. In this fire scenario, the smoke plume rose to the ceiling level at about 10 s. Then the smoke spread horizontally beneath the ceiling. At about 90 s, the smoke reached the side walls, and the upper smoke layer was formed. As the fire developed, the smoke layer gradually thickened. At about 600 s, the smoke layer decreased nearly to the bottom of the valve towers. The six valve towers were all immersed in the fire smoke. The simulation was terminated at 1800 s, at which the height of smoke layer was close to the floor level of the valve hall.

The smoke propagation process in the valve hall of the 5 m\(^2\) and 10 m\(^2\) pool fire conditions are shown in Figure 3 and Figure 4, respectively. The smoke filling process of these two fire scenarios were similar to the 2 m\(^2\) fire scenario. However, the larger the fire size was, the faster the smoke layer height would descend. In the 5 m\(^2\) fire condition, the smoke plume rose to the ceiling level at 7 s, and the smoke reached to the side wall at about 60 s. The smoke enveloped the whole valve tower at about 300 s, and smoke layer height decrease to the floor level at 1200 s. In the 10 m\(^2\) fire condition, the smoke spread horizontally to the side walls at 30 s after the fire. After 210 s, almost the whole valve tower was immersed in the fire smoke, and the smoke layer height decreased to the floor level of the valve hall at about 800 s.
3.2. Gas Temperature

The temperature distributions of the valve hall in the 2 m², 5 m² and 10 m² pool fire conditions were shown in Figure 5. The location of the temperature slice was taken across the centre of the valve tower. Since the fire smoke would accumulate under the ceiling due to the effect of buoyancy, the temperature increased with the height of valve hall. In the 2 m² pool fire condition, the gas temperature around the suspension structure and optic cable was about 30°C, and the gas temperature rise between the top and bottom shield cases of the valve tower became obvious at 270 s. At 1800 s, the smoke temperature around the suspension structure and optic cable was 35 to 40°C, and local area beneath the ceiling exceeded 40°C. The gas temperature of smoke around the valve modules was about 30 to 35°C. It can be found that the temperature rise inside the valve hall was not very significant in the 2 m² fire condition, since the volume of the valve hall was huge. The temperature rise around the valve module in this fire scenario was lower than 20°C.

In the 5 m² pool fire condition, the gas temperature between the top and bottom shield cases began to increase, and the maximum temperature in the area of suspension structure and optic cable was about 50°C at 120 s. At 1800 s, the temperature of fire smoke under the ceiling of valve hall was above 60°C, and the smoke temperature around the valve modules was about 50 °C. In the 10 m² pool fire condition, the rate of temperature rise in the valve hall was faster compared with the 2 m² and 5 m² fire scenarios. At about 90 s, the valve modules were influenced by the fire smoke from the perspective of temperature rise, and the smoke temperature around the suspension structure and optic cable was more than 60°C. At 1800 s, the smoke temperature under the ceiling was more than 100°C. The average smoke temperature around the valve modules was about 70°C. In the 10 m² pool fire condition, the smoke temperature was higher compared with the other two fire conditions with smaller fire size. Although the fire smoke would not affect the structure safety of the valve hall significantly, while it might affect the normal operation of the electrical components in the valve tower and even cause the new fire source due to the failure of electrical components.
Figure 5. Temperature distribution of the valve hall.

For evaluating the thermal hazard of the converter valve towers in detail, the curves of smoke temperature around the valve towers versus time are shown in Figure 6. The heights marked in the figures were measured from the bottom of valve tower. Since the six valve towers were hung at the same height in the valve hall, the temperature measured at the six valve towers were similar. So only the smoke temperature curves derived at 1# and 4# valve towers were illustrated in Figure 6. According to Figure 6, the smoke temperature around the valve tower increased with the height.

In the 2 m² fire condition, the temperature curve showed the obvious increase at about 270 s, and the temperature variation became stable at about 1100 s. At the steady stage, the smoke temperature was ranged from 28°C to 32°C. In the 5 m² fire condition, the obvious temperature rise was found at about 120 s, and the temperature variation was not significant after 700 s. The minimum temperature and maximum temperature were 43°C and 52°C, respectively. In the 10 m² fire condition, the smoke temperature had an obvious rise at about 100 s, the steady stage appeared at about 500 s. The maximum temperature in this fire scenario was about 80°C and the lowest temperature that measured at h=0.5 m was about 65°C.
3.3. Visibility

Since there are usually few staff worked in the valve hall, the effect of reduced visibility on personnel safety evacuation was not significant. However, the reduced visibility would hinder the fire detection and fire extinguishment. The visibility distribution inside the valve hall in 2 m², 5 m² and 10 m² fire conditions is shown in Figure 6.

Figure 6. Temperature of smoke around the valve tower (between the top and bottom shields).
scenarios are shown in Figure 7 to Figure 9. The location of the visibility slice was taken across the centre of the valve tower.

In 2 m² fire condition, the reduced visibility began to influence the height of valve stacks at about 270 s, and the visibility of the upper space showed obvious reduction. At 1800 s, the valve towers were immersed in the dense smoke and the visibility was reduced lower than 5 m. In the 5 m² fire condition, the visibility around the valve modules began to reduce at about 120 s. At 450 s, the visibility around the valve modules was lower than 5 m. At 1500 s, the visibility of the whole valve hall was nearly lower than 5 m. In the 10 m² fire condition, the reduce rate of the visibility inside the valve hall was faster. At 90 s, the valve modules were influenced by the reduced visibility. The visibility around the valve modules was lower than 5 m at about 300 s, and the visibility of the whole valve hall were lower than 5 m at about 1200 s.

Figure 7. Visibility distribution of the valve hall in 2 m² fire condition.

Figure 8. Visibility distribution of the valve hall in 5 m² fire condition.

Figure 9. Visibility distribution of the valve hall in 10 m² fire condition.
4. Conclusion

Numerical simulations of the converter station fires were conducted in the present study by using the FDS, and the discussion was mainly focused on the fire hazard of the converter valve tower. Three fire sizes, including the 2 m², 5 m² and 10 m² transformer oil pool fire, were considered, and the calculation results of HRR were 2.02, 6.23 and 13.78 MW, respectively.

In 2 m² fire condition, the whole valve tower was immersed in the fire smoke at about 600 s, and the visibility around the valve stacks reduced accordingly. In this fire scenario, the maximum temperature rise inside the valve hall was about 20°C. In the 5 m² and 10 m² fire conditions, the valve tower was immersed in the fire smoke at about 300 s and 210 s, respectively. The maximum smoke temperature inside the valve hall was over 60°C, and the temperature of smoke around the valve modules was ranged from 43 to 52°C in the 5 m² fire condition. In 10 m² fire condition, the maximum smoke temperature inside the valve hall was over 100 °C, and the temperature of smoke around the valve modules was ranged from 65 to 80 °C. The smoke temperature in the 5 m² and 10 m² pool fire conditions were relatively high, which might affect the normal operation of the electrical components in the valve tower and even give rise to new fires due to the failure of electrical components.

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