Research on Oil Chamber Flow in On-load Tap-changer Switching Process with CFD

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Abstract. The on-load tap-changer is one of the key components of the converter transformer. The arc generated by the oil-extinguishing on-load tap-changer switching process will cause the insulating oil in the diverter switch oil chamber to be thermally expanded and surging. In order to accurately reflect the flow field shape inside the diverter switch oil chamber, the three-dimensional flow simulation software Fluent is used to add the energy generated by the arcing process in the form of User Defined Function. The Realizable k-ε model is selected for a model double. Numerical simulation of the flow of the on-load tap-changer oil chamber. By comparing and analysing the similarities and differences of oil pressure and oil flow in oil chamber under different capacity transition resistance conditions, it can be seen that when the transition resistance is too small, the pressure and flow of the oil chamber will change greatly. The simulation results can provide reference for the selection of the on-load tap-changer transition resistance and the configuration of the oil flow relay.

1. Introduction
Converter transformers are important equipment in High voltage direct current (HVDC) transmission systems. The on-load tap-changer is one of the key components of the converter transformer, which plays a role in compensating for grid voltage changes and optimizing the control angle [1-2]. The on-load tap-changer consists of a diverter switch and a tap selector. The switch is specially responsible for switching the load current, and the action is completed by the fast motor-drive mechanism.

In order to make the transformer output continuous current during the switching process, the two taps must be turned on for a period of time. At the same time, to limit the reflow between the two taps, a series of transition impedances [3-4] is required. The transition resistor is connected in series to the adjacent two taps of the transformer voltage regulating winding, so that the load current can be tapped and converted without interruption, and the circulating current is also limited, thereby avoiding the occurrence of short circuit [5]. Due to the faster switching speed of the on-load tap-changer, the transition resistor has the characteristics of small resistance and large carrying current. Therefore, for the selection of the transition resistance, the breaking capacity is often used as the basis for selection [6-9]. The value is generally proportional to the ratio of the stage voltage to the rated current. The proportional coefficient is the transition resistance coefficient, denoted by $n$. 

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Since the selection of different transition resistances will significantly affect the arc energy during the switching process, which will cause the transformer oil to deteriorate to different degrees. Therefore, exploring the influence of the energy of the arcing process on the transformer oil is essential for improving the operation and maintenance of the equipment [9]. In this paper, a dual-resistance on-load tap-changer is studied, and the physical properties of transformer oil are simulated and analyzed under different transition resistance conditions. The simulation breaks through the limitations of traditional pure mathematical simulation. The computational fluid dynamics method is used to calculate the oil temperature and oil pressure in the arcing process, and the flow characteristics are analyzed to provide a reference for the selection of transition resistance.

2. Research objects and models

2.1. Research object

The switching process of the double-resistance on-load tap-changer is as shown in Figure. 1. The switch is cut off from the main contact A, and the current passes through the A-side auxiliary contact, which is accompanied by the arc during the cutting process, and when the sinusoidal current crosses zero. Extinguished. However, if the transition resistance is not properly selected, the recovery voltage between the breaking contacts will be too high, causing the arc to reignite and the current to continue to conduct. When the switch is operated between the two auxiliary contacts, current passes through the two auxiliary contacts while generating a circulating current. As the swing arm of the switch continues to rotate, the A-side main contact is disengaged, and with the second arcing phenomenon, the current passes through the B-side transition resistor. Finally, the swing arm turns on the B-side contact to complete the entire switching process.

Figure.1 Switching process of double resistance On-Load Tap Changer

Figure 2 shows the actual operation of the dual-resistor swing-arm on-load tap-changer. The upper side of the swing arm is the main contact, and the lower side is the auxiliary contact. The calculation is performed using Ansys Fluent software, and the dynamic mesh technique is applied in the process, and the rotation axis of the swing arm is defined by a custom function (UDF). In the actual calculation process, it is a fluid domain. Due to the large gradient of the fluid domain mesh and the complex topology of the mesh, the local mesh will be stretched or compressed during the calculation process. Therefore, the mesh needs to be reconstructed and strengthened in the calculation process. The convergence of the calculation process.

Figure.2 Movement process of double resistance On-Load Tap Changer
2.2. **Model pre-processing**

One of the most critical factors in performing high quality fluid calculations is the quality of the computational grid. The oil chamber structure of the on-load tap-changer is very complicated. As shown in Figure. 3, there are more large spaces and excessive local irregularities. How to deal with the mesh of the transition part is very important.

In this paper, the ICEM pre-processing software is used to mesh the entire flow field calculation area of the on-load tap-changer. In order to adapt to the complex geometric model of the oil chamber, an unstructured full tetrahedral mesh with strong adaptability to complex boundaries is used [10-11], the grid distortion rate is less than 0.6, and the grid quality meets the requirements of engineering simulation. In order to improve calculation accuracy and reduce workload, the total number of grids used was 22.68 million.

![Figure.3 Oil chamber structure of and integral grid at part of switch](image)

### 3. Mathematical model and boundary conditions

#### 3.1. Turbulence model

The Realizable $k$-$\epsilon$ model is adopted, which is improved on the basis of the standard $k$-$\epsilon$ model. The $k$ equation remains unchanged, mainly improved in the two aspects of the dissipation rate $\epsilon$ equation and the eddy viscosity equation. The corresponding transport equation is:

\[
\frac{\rho}{\partial t} \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + G_k + G_b - \rho \epsilon - Y_u
\]

(1)

\[
\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_i} \right) + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{u'_e}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b
\]

(2)
Among them $C_i = \max \left[ 0.43, \frac{n}{n+5} \right]$, $\eta = \frac{Sk}{\varepsilon}$, $G_k$ indicates the turbulent energy due to the average velocity gradient, $G_b$ is the kinetic energy caused by buoyancy, and $Y_M$ indicates the effect of compressible turbulent pulsation expansion on the total dissipation rate. The turbulent Prandtl number of turbulent energy $k$ and dissipation rate $\varepsilon$ is taken as $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.2$. Other default value constants are $C_1 = 1.44$ and $C_2 = 1.9$.

3.2. Boundary conditions

Under normal operation, the tap changer is placed in a sealed cylindrical cavity formed by an insulating cylinder, and the cavity is filled with transformer oil. Therefore, the calculation area is set to be filled with 25# transformer oil, the oil pressure is 100 kPa, and the oil temperature is set at 40 °C. The corresponding density is 895 kg/m³, the dynamic viscosity is 0.97 kg/(m•s), the thermal conductivity is 0.128 W/(m•K), and the specific pressure specific heat capacity is 1.8 kJ/(kg•K).

Since the arcing process is not transient, it is done by adding a user-defined function when adding a boundary. The energy boundary is added to start the main contact arc energy for the first action of the mechanism action for 1 ms. Because there is a continuous flow in the switch oil compartment, and the inlet boundary condition is the transformer oil flow rate, which is 2.24 kg per minute. The outlet sets the pressure boundary to the standard atmospheric pressure.

4. Numerical simulation results analysis

4.1. The effect of the switching process on the oil flow surge

Figure 4 is a velocity field, a pressure field and a temperature field at a section of 11 mm from the center of the front cylinder after the transition of the unsteady flow field is converged after the transition resistance coefficient $n$ is 0.2. It can be seen from the Figure that before the switch starts switching, the flow in the switch cylinder is gentle, the whole field speed is very low, and the maximum speed is about 0.055 m/s; the oil pressure in the cylinder is basically the same, and the oil pressure on the cylinder wall is about 100.4 kPa; The difference in body temperature is very small, only 0.5 °C.

Figure 5 shows the speed field, pressure field and temperature field at the 11 mm section of the center of the front end of the arcing energy of the main contact with the moving contact and the fast mechanism acting for 13.9 ms. It can be seen from the Figure that the oil flow rate near the moving contact and the fast mechanism increases significantly before the arcing energy of the main contact is started, but the flow in the remaining area is still gentle, the flow rate is very low; the oil pressure on the tube wall does not change much. About 100.6 kPa, the temperature difference across the barrel is not large, only 1.8 °C. It shows that the influence of the switching action on the flow field in the cylinder is mainly concentrated near the moving contact and the fast mechanism.

![Figure 4](image-url) Velocity field, pressure field and temperature field before swing arm movement
When the swing arm running time exceeds 13.6ms, the most intuitive performance is the sudden change of the temperature field due to the addition of arc energy. The temperature field after the arcing process is completed is shown in Figure. 8. It can be seen that the oil temperature near the arcing region can reach up to 1600K. However, since the area is very small, the energy generated by the arc is quickly absorbed by the surrounding transformer oil, which has little effect on the oil temperature of the transformer oil.

4.2. Influence of different transition resistance on oil flow surge

Figure 6 shows the distribution of the pressure distribution at the top of the oil chamber after arcing under different resistance conditions. As can be seen from the Figure, when the transition resistance coefficient is 0.2, the pressure at the top of the oil chamber reaches 160 kPa or more. As the transition resistance increases, the pressure at the top of the oil chamber gradually becomes smaller. When the excess resistivity is 1, the pressure at the top of the oil chamber is reduced by 17.5 percent.

In order to be able to quantitatively characterize changes in oil flow and oil pressure, the calculation results are summarized in Table 1. It can be seen from the table that as the resistance value decreases, the arcing energy and total arcing energy of the transition contact increase, and the oil flow velocity and oil pressure increase. Therefore, the use of a large transition resistance value is advantageous for reducing arcing energy, oil flow velocity, and oil pressure.
Table 1. Experimental flow rate in switching of on-load tap-changer

| Observation Measurement | n=0.2 | n=0.3 | n=0.4 | n=0.5 | n=0.6 | n=0.8 | n=1 |
|-------------------------|-------|-------|-------|-------|-------|-------|-----|
| Velocity /m/s           | 1.11  | 0.81  | 0.74  | 0.67  | 0.64  | 0.62  |     |
| Pressure/kPa             | 161.4 | 44.1  | 40.5  | 35.9  | 34.1  | 33.2  |     |

* Both the main contact and the transition contact are calculated according to the limit of discharge for 10ms.

5. Conclusion

In this paper, based on the Realizable $k$-$ε$ model, the full-channel simulation method for the flow of a double-resistance on-load tap-changer oil chamber is explored. By analyzing the results of unsteady calculations, the following conclusions can be drawn:

1) During the switching process of the on-load tap-changer, the influence of the switching action on the flow field in the cylinder is mainly concentrated near the moving contact and the fast mechanism. However, because of arcing, the temperature of the arcing region rises sharply in a short time, and the energy generated by the arcing process is absorbed by the surrounding transformer oil in a short time, which has little effect on the full field temperature in the oil chamber.

2) Gas is generated during the arcing of the on-load tap-changer, resulting in significant changes in the outlet oil flow and oil pressure. When different transition resistances are selected, the oil pressure and flow rate of the oil chamber will be different. The smaller the transition resistance, the greater the arc energy generated, and the higher the outlet oil flow rate and the pressure at the top of the oil chamber.

3) In the process of selecting the transition resistance of the on-load tap-changer, it is necessary to comprehensively consider the switching capacity to meet the requirements of the recovery voltage. Therefore, the selection of the transition resistance is not as large as possible. In combination with the influence of these two factors, for this type of on-load tap-changer, the oil flow relay is generally suitable for 1.5m/s.

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