Research on Resistance Characteristics of the Self-circulating Evaporative Cooling System for Traction Transformer

Jing Yan\textsuperscript{1*}, Bin Xiong\textsuperscript{1}, Zhiwei Wen\textsuperscript{1} and Ding Liu\textsuperscript{1,2}

\textsuperscript{1}The New Power Equipment Technology Research Department, The Institute of Electrical Engineering of Chinese Academy of Sciences, Beijing, 100190, China
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing, 100049, China
\textsuperscript{*}jingyan@mail.iee.ac.cn

Abstract. Compared with the tradition cooling technology, the evaporative cooling technology has the advantage of energy-saving, safety and reliability. So a self-circulating evaporative cooling structure was proposed. The narrow flow channels were designed between disk-type windings. The evaporative coolant flows in the narrow flow channels and takes away the heat loss through phase transition. In this paper the resistance characteristics of the system were studied through experiment based on the 900kVA transformer prototype.

1. Introduction

With the rapid development of high-speed railway, higher demand was proposed on lightweight and safety for the traction transformer, which is the core equipment of traction drive system.

Usually the oil was chosen for traction transformer. The high voltage winding and low voltage winding are immersed in oil. As an important part for oil-immersed transformer, the transformer oil has relatively better insulation characteristic and heat-dissipating characteristic.

However, for the oil-immersed traction transformer, there is a risk of flammable explosion. Moreover, due to the cooling effect of oil, the oil-immersed traction transformer usually has large weight and volume. So in order to realize the lightweight and to further ensure the safety of the transformer, a new cooling system was prosed here.

The evaporative cooling technology uses the latent of coolant to take away heat loss. And the coolant chosen for evaporative cooling technology has good performance of high insulation and non-burning, which can ensure the safety of transformer. Moreover, self-circulating evaporative cooling system can keep running without external pump. It has the advantage of energy-saving and high efficiency.

In this paper, the high voltage and low voltage winding are both immersed in the liquid evaporative coolant. And the coolant flows in the narrow flow channels may absorb the heat loss. Then the temperature may rise. When the temperature reaches the saturated boiling point, the liquid coolant may change to gas. Then due to the density difference between liquid coolant and gas coolant, the two-phase coolant may rise along the tube into the condenser. In condenser, the two-phase coolant may change to liquid again through the heat exchange with the secondary coolant which is air. The liquid coolant will flow back to the transformer along tubes. Thus a self-circulating system was formed.

2. Circulation mechanism

The traction transformer is installed at the bottom of the carriage. As is shown in fig.1, the high and low voltage windings are designed as the horizontal disk-type structure here.
Aiming to provide flow passages for evaporative coolant, the axial flow channels are set between the high and low voltage windings using the struts. It is shown in fig.2.

Moreover, the flow passages in the vertical direction are formed between the disk-type windings using struts. An insulating support cylinder is arranged between the low voltage winding and the iron core, and flow passages are formed between the insulating support cylinder and the low voltage winding. Then the evaporative coolant can flow in the axial and radial directions. The heat loss in traction transformer can be taken away by coolant through phase transition.

3. Experiment
According with the scheme shown above, a 900kVA prototype was produced. Then the resistance characteristics of the system was studied through experiments.

As is shown in fig.3, the air condenser is installed at the height of three meters. Before experiments, the evaporative coolant should be poured into the system. Then the windings and iron core of traction transformer are both immersed in coolant.

The two-phase evaporative coolant flow out from traction transformer may flow into condenser along connect tubes. And then make a heat exchange with air and change to liquid coolant again. The liquid coolant may flow back into the traction transformer along connect tube.
The operation condition of experiment system can be changed by adjusting the exhaust valve which is installed on air condenser.

In the experimental study, the pressure was measured by pressure sensor at the inlet of condenser, the inlet and outlet of transformer. The temperature was measured the distributed optical fiber temperature sensor at ten test point on the windings. And the flow rate was measured by metal tube rotameter before the fluid coolant flow back into transformer. In experiments the real-time value of them was recorded.

4. Results and analysis
The temperature results was shown in fig.4. The results show the temperature is low and the temperature distribution is uniform. The cooling effect of the system designed for the 900kVA prototype was verified. The saturated boiling point of evaporative coolant chosen for system here is $110^\circ$C.

In this paper, the experiment results were got when the system has one outlet and two inlets for coolant. Here $P_1$ denotes the pressure at the inlet for coolant. $P_2$ denotes the pressure at the outlet of transformer for coolant and $P_3$ denotes the pressure at the inlet of condenser for coolant. Then the experiment results were shown as follow.
As is shown above, when the system has two outlets for coolant, the system has uniform distribution characteristics. The pressure condition of the two up-tubes is similar. Compared with results when the system has one outlet, the pressure condition in traction transformer is lower.

For self-circulation, the operation characteristic depends the balance between the circulating driving force and flow resistance. For the system here, the driving force is provided by the density difference between two-phase coolant in up-tubes and liquid coolant in down-tube, so it can be described as follow. Here consider the up-tubes are heat insulation, so the void fraction in up-tubes is regarded as constant.

\[ \Delta P_{drive} = \rho_{in} \cdot gL_{down} - \rho_{out} \cdot gL_{up} \]  

(1)

\[ \rho_{out} = \alpha \cdot \rho_g + (1 - \alpha) \cdot \rho_l \]  

(2)

\[ \alpha = \frac{1}{1 + \frac{\rho_g}{\rho_l} \frac{1 - x_e}{x_e}} \]  

(3)

\[ x_e = \frac{Q'}{(GA) \cdot R} \]  

(4)

The temperature of liquid coolant flow back into traction transformer is lower than the saturated boiling point under the local pressure. So the liquid coolant may utilize specific heat to absorb a part of the heat loss until the temperature reaches the saturated boiling point. And the other part of heat loss can be used
to calculated the gas quality at the exit of traction transformer. The gas quality at the exit can be got as follow according with above formulas. The calculated results are shown in fig.8.

![Fig. 8. The calculated results of the gas quality at exit](image)

![Fig. 9. The pressure drop in traction transformer](image)

And the flow resistance includes the pressure drop along the up-tubes and the pressure drop in traction transformer. The experiment results of them are shown in fig.9. The change of the pressure drop in traction transformer is small with the increase of heat load. And the results of one outlets and two outlets are similar.

The pressure drop of coolant in up-tubes includes the friction, gravitation and acceleration pressure drop. Here the homogeneous model was chosen to calculate the pressure drop.

\[
\Delta P = \Delta P_f + \Delta P_a + \Delta P_g
\]

\[
\Delta P_f = \frac{2 f_{tp} G^2}{D} \nu_{tp} \cdot L_{up}
\]

\[
\nu_{tp} = \nu_e \cdot \frac{\nu_g + (1 - \nu_e) \cdot \nu_l}{\nu_e}
\]

\[
f_{tp} = \begin{cases} 
16 / \text{Re}_{tp} & \text{Re}<2000 \\
0.079 \left( \frac{\text{Re}_{tp}}{1600} \right)^{0.25} & \text{Re} \geq 2000 
\end{cases}
\]

\[
\Delta P_a = G^2 \left( \frac{1}{\rho_g} - \frac{1}{\rho_l} \right) x_e
\]
\[ \Delta P_g = \rho_{up} \cdot gL_{up} \] (10)

With the increase of heat load, the gas quality of coolant at the exit may rise. And with the increase of gas quality, \( \Delta P_g \) may decrease, \( \Delta P_f \) and \( \Delta P_a \) may increase. Then when the heat load is small, the change rate of \( \Delta P_g \) is faster, so with the increase of heat load, the total pressure drop in up-tubes may decrease. And with the increase of heat load, the void fraction is approaching to 1 and the change rate of \( \Delta P_f \) and \( \Delta P_a \) may faster than \( \Delta P_g \). So as is shown in fig.10, the pressure drop decreases trend slowly.

When the system of traction transformer has two outlets, the resistance characteristics is uniform for the two flow passages. And when the system has only one outlet, the pressure drop is larger at the same flow rate.

In the design of self-circulating system for traction transformer, the resistance characteristics play an important role. When the system has one outlets, it is easier to gather for two-phase flow and form a stable flow. The experiment results have shown that the fluctuation amplitude of flow rate is much smaller and the fluctuation period is shorter. However, the flow resistance is larger. It means the ultimate heat transfer capacity is smaller. It needs to be considered comprehensively in the design. So the work in this paper may provide a valuable basis for system design and operation in future.

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References
[1] Chen Tingkuan, Two-phase and heat transfer, Xi’an: Xi’an Jiaotong University Press. 2004.
[2] Cai J, Study on the Friction Resistant in the Hollow Stator Bar of Evaporative Cooling Generator, dissertation for the doctor degree of Chinese academy of sciences. 2005.06.
[3] Guo Chaohong, Yu Shunzhou, Cai Jing, et al. Research on two-phase flow frictional pressure drop in the evaporative generator[J]. Proceedings of the CSEE, 2006, 26(19): 139-144.
[4] Ruan L, Gu G, Tian X. Numerical simulation for circulating systems and experimental comparison of the closed-loop, self-circulating evaporative cooling of hydro-generators. Electrical Engineering, 2004, 86(3):127-134.
[5] S. Wongwises, M. Pipathattakul. Flow pattern, pressure drop and void fraction of two-phase gas-liquid flow in an inclined narrow annular channel, Experimental Thermal and Fluid Science 30,2006: 345 -354.
[6] Yan Jing. Study on the Two-phase Flow Frictional Pressure Drop and Instability of the Evaporative Inner Cooling System for Wind Power Generator, dissertation for the doctor degree of Chinese academy of sciences. 2013.06.