Currently, the world's first ±1,100 kV HVDC transmission project is under construction in China

Winding design based on the hot spot temperature rise of a ±1,100 kV HVDC converter transformer

ABSTRACT

This paper briefly introduces the world's first ±1,100 kV HVDC transmission project, focusing on the winding design of a converter transformer that was constructed for the project, based on the hot spot temperature rise. The winding temperature rise was first measured during the initial design of the transformer. Then the design of the oil channel was improved and the conductors arrangement was optimized. By changing the oil flow in the line winding and the distribution of eddy-current losses at the winding end, design margin for winding hot spot temperature rise was ensured. Finally, an advanced fibre-optic temperature measurement technology was used to measure the hot spot temperature rise, ensuring the operating life of the converter transformer.

KEYWORDS

±1,100 kV HVDC, converter transformer, hot spot, temperature rise

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A converter transformer is an important piece of equipment in an HVDC transmission system, and its heating and cooling is a very complicated process

1. Introduction

In recent years, China has made great efforts to develop and construct ultra-high voltage (UHV) AC/DC transmission projects. Especially for DC transmission projects, China has continuously been in the forefront of world's power transmission and transformation technologies. As transmission voltage and transmission distances are becoming higher and higher, the power transmission capacity is reaching new records repeatedly. Currently, the world's first ±1,100 kV HVDC transmission project is under construction, which runs from Changji in Xinjiang province in the west to Guquan in Anhui province in the east, with 3,283.94 km in length, ±1,100 kV rated voltage and 12 GW DC transmission capacity, becoming the least expensive, the most economical and most efficient power transmission in the world. It is a technology-leading and innovative project. The project is scheduled to be completed and put into operation in December 2018.

The DC transmission project adopts a bipolar DC system, which consists of two complete monopoles, with each complete monopole consisting of two 12-pulse converter units in series. Compared to another transmission project operated in China, which is the largest transmission project in the world with ±800 kV/10 GW, the transmission voltage of Changji-Guquan ±1,100 kV HVDC project has been increased by 37.5 % while transmission capacity has been increased by 20 %. The matching converter transformer adopted the single-phase double-windings type and with capacity of 607.5 MVA, it posed great challenges on designing and manufacturing. How to control the leakage magnetic and winding hot spot temperature rise after the capacity increase was the key question for the technology to resolve [1].

A converter transformer is an important piece of equipment in an HVDC transmission system, and its heating and cooling is a very complicated process. Therefore, it is very difficult to obtain

Table 1. Main technical characteristics

Product model	ZZDFPZ-607500/750-550
Rated capacity	607.5 MVA
Rated voltage	(775/√3+(+25/-5) · 0.86 %) / (236.2/√3) kV
Rated frequency	50 Hz
Short-circuit impedance	20 %
Insulation level	
Line side	LI 1950, CW 2100, SI 1550, AC900 - LI185 AC 95 kV
Valve side	LI 1350, CW 1485, SI 1250, AC 676 (1h) – DC 914 DC PR 655 kV*
No-load loss	229 kW
Load loss	1690 kW
Cooling type	ODAF
Temperature rise limit at rated capacity	
Top oil temperature rise	≤45 K
Winding average temperature rise	≤53 K
Winding hot temperature rise	≤66 K
Tank, core and structural component temperature rise	≤73 K

* DC 914 is the applied DC voltage withstand test (Clause 10.4.4 in IEC 61378-2); DC PR 655 is the DC polarity reverse test voltage [2].

This converter transformer adopts oil-directed air-forced (ODAF) cooling type, with six groups of 525 kW oil-air coolers

the accurate value of the temperature rise of the winding hot spot in its actual operating conditions because of many influencing factors, such as the boundary conditions by the metal structure, the size and distribution of leakage flux, losses to be dissipated, heat convection transfer coefficient, oil flow distribution, and other important factors. In recent years, with the progress of transformer manufacturing technology and the commercial software applications in transformer design process, domestic and foreign experts and scholars have conducted research on winding hot spot temperature rise and achieved certain progress. Our company has a simulation software similar to VEI, Infolytica, IES, Tsinghua SOLOS, ANSYS, Pro-E, and has been equipped with 12 HP-Z800 series high performance analysis workstations, the database and software simulation platform. The quantitative analysis and calculation capabilities of electric, magnetic, thermal, power, etc. for various transformers and reactors which do not exceed 100 kV have been set up.

2. Product technical parameters

Compared to the converter transformer's temperature index requirements of other DC transmission projects, the winding average temperature and hot spot temperature rise of this convert transformer are all decreased by 2 K because of the altitude above 1,000 m.

3. Oil channel structure in active part

This converter transformer adopts oil-directed air-forced (ODAF) cooling type, with six groups of 525 kW oil-air coolers. The cooled oil reaches the lower part of each limb through the common oil guide pad. The amount and speed of

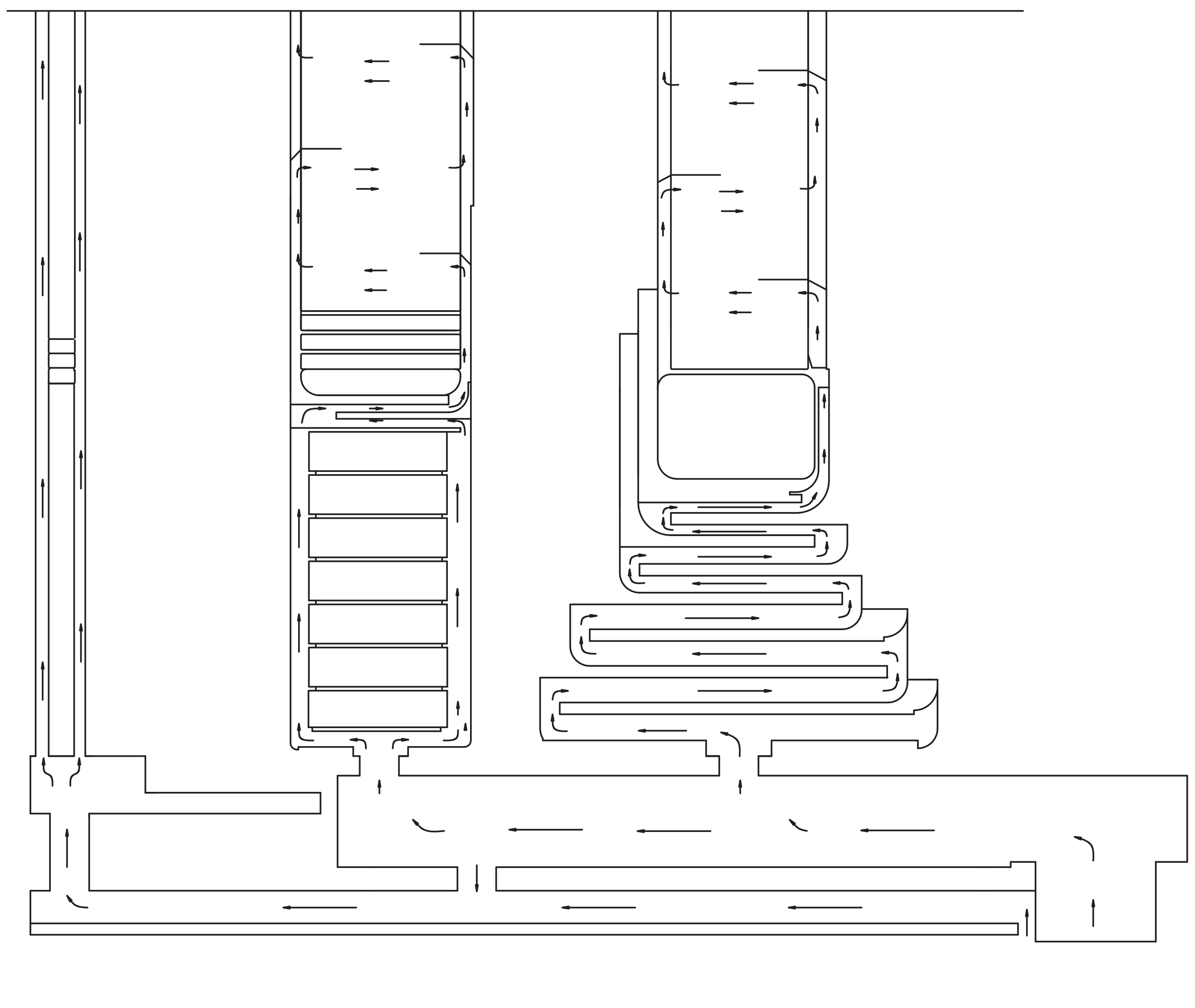

Figure 1. Oil flow structure diagram

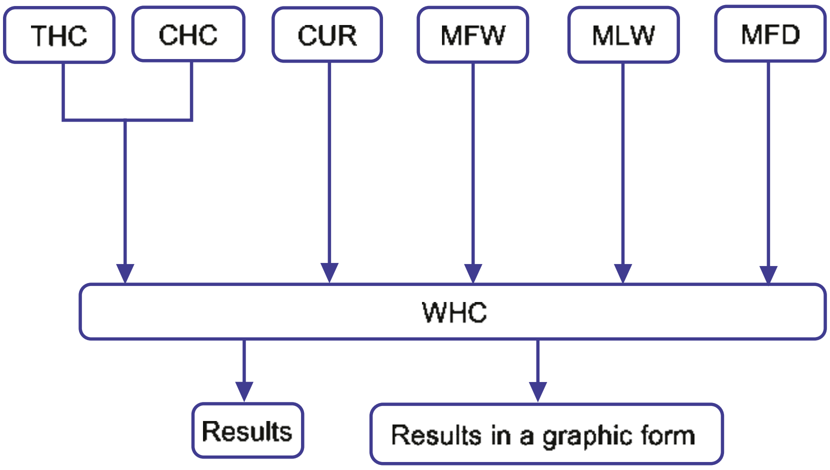

Figure 2. Flow diagram of winding temperature rise calculation

oil distribution in windings is adjusted by controlling size and quantity of the oil ducts at the end of line and valve windings.

The winding arrangement in active part is: core, regulating winding, line winding and valve winding, and the internal oil flow diagram is shown in Figure 1. The regulating winding insulation level is low – this arrangement is more economical and reliable, so the regulating winding is closer to the core. It can be seen that most of transformer oil is directed into the line and valve windings, while some of the oil is diverted to regulating winding through the lower oil duct. Line and valve windings are equipped with oil guiding washers for better control of winding cooling and oil flow.

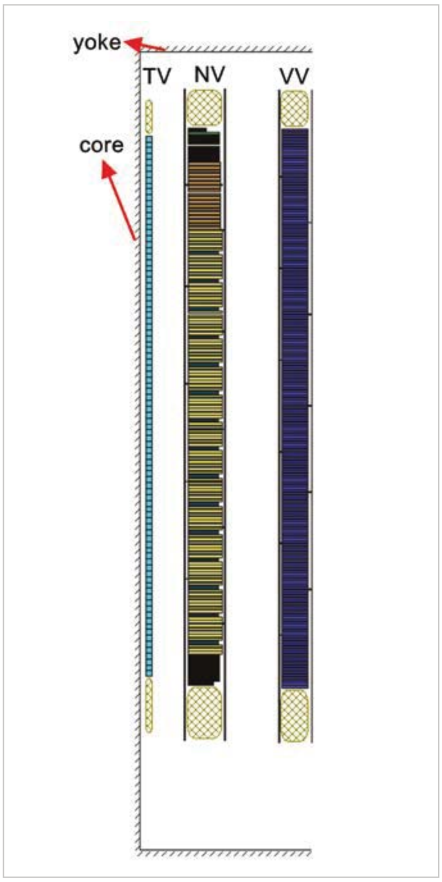

Figure 3. Schematic diagram of the winding arrangement

4. TranCalc software introductions

TranCalc software (the integrated software) has been introduced by the U.S. company SOFTTEAM. TranCalc software includes many modules, such as WHC (winding heat calculation), CHC (cooling system heat calculation), etc. Before calculating the winding temperature rise using WHC module the THC (hydraulic calculation) module needs to be applied to perform resistance calculation and determine the oil flow distribution of each winding. Then, the oil temperature is calculated using the CHC module, the current in winding is calculated by the CUR (current distribution in the windings) module, the magnetic field distribution in winding is calculated by the MFW (winding magnetic fields) module, and finally the main loss and eddy-current loss of windings is calculated by the MLW (windings main and eddy losses) module, Fig. 2.

The winding arrangement is shown in Figure 3. Figure 4 shows circuit connection diagram under the minimum tapping (due to higher current, and therefore thermal constraint), after entering the winding and core parameters in TranCalc. VWI is the current source which can be used to calculate the current flowing automatically through each electrical branch after running the CUR module.

5. Calculation and improvement of the temperature rise

5.1 Calculation results of the temperature rise of initial design

Through the calculation by the fluid resistance module (THC), the oil flow distribution of line and valve windings are obtained. The calculation result of the winding temperature rise after inputting flow is shown in Table 2.

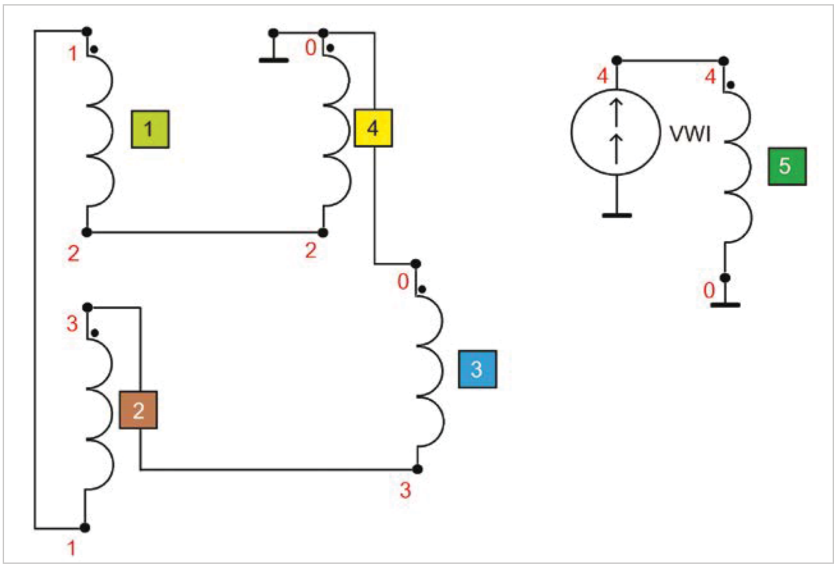

Figure 4. The circuit connection diagram under the minimum tapping

Table 2. Calculation result of the temperature rise of initial design [K]

Name of the winding	Number of the hottest coil	Type of coil	Average winding temperature rise over ambient temperature [K]	Hottest spot temperature rise over ambient temperature [K]
LW (line winding)	9	E (see Fig. 8b)	36.9	64.9
VW (valve winding)	1	/	34.3	50.6

The design of the oil channel was improved and the conductors arrangement was optimized

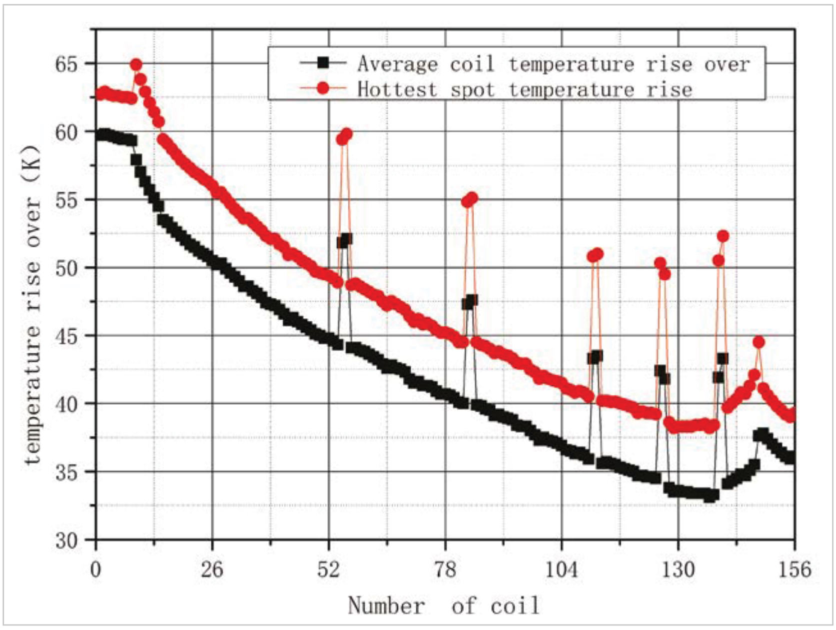

Figure 5. Average temperature rise of the line winding for each disc and the hottest spot temperature rise

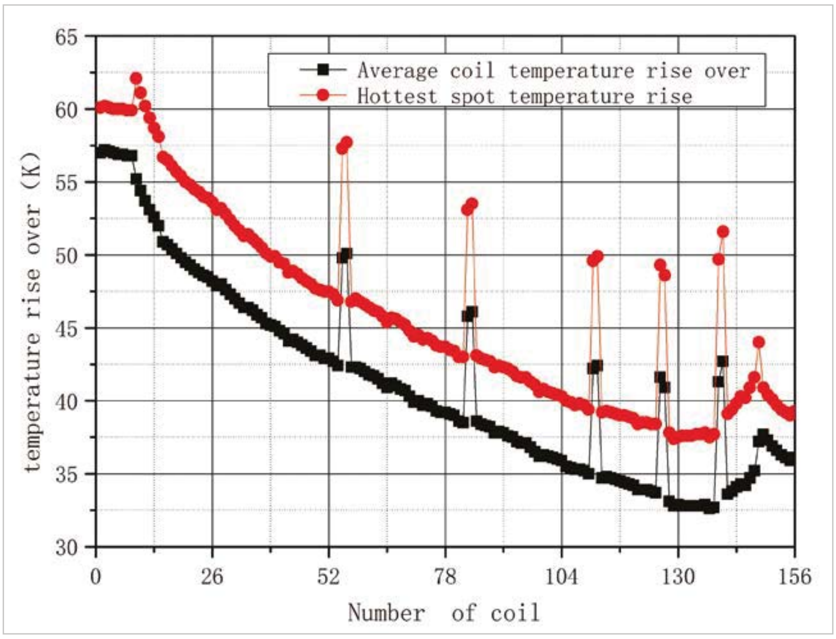

Figure 6. Schematic diagram of each disc (coil) temperature rise in the line winding after changing the oil intake

As shown in Table 2, the hottest spot temperature rise of the line winding appears in the ninth disc, which is 64.9 K, has only 1.1 K difference from the agreement value of 66 K. The hottest spot temperature rise of the valve winding is 50.6 K, which has 15.4 K difference from the agreement value, has enough design allowance to meet the requirements. Therefore, the emphasis is on doing the analysis of the line winding temperature rise. The average temperature rise of the line winding for each disc and the hottest spot temperature rise are shown in Figure 5.

It can be seen from Figure 5 that several singularities of the temperature rise have occurred, which were found in the position of oil guide barriers after checking. While the existence of the oil guide barriers reduces the average temperature rise of the winding, the hottest spot temperature rise on the upper and lower discs of the oil guide barriers is increased, which is in accordance with the theory.

Our company usually has 5 K design margin from the agreement value of the hottest spot to ensure that the measured value does not exceed the agreement. According to the calculation results of the hottest spot temperature rise in line winding, it is necessary to take measures to reduce the hottest spot temperature rise.

5.2 Improvement of design by adjusting the oil flow in line winding

One of the most important reasons for the high temperature rise of the hottest spot is an insufficient oil flow into the coil. Therefore, the first improvement of design was to increase the oil flow into line and valve windings by reducing the oil spill. In the initial design, 20 % of bypass flow was intended for cooling the core and regulating the winding and maintaining their temperature rise within the limits. According to the manufacturing experience of converter transformers, the oil flow can be

Table 3. Calculation results of the winding temperature rise after changing the oil intake of the line winding compared to the first design (K)

Name of the winding	Number of the hottest coil	Type of coil	Average winding temperature rise over ambient temperature [K]	Hottest spot temperature rise over ambient temperature [K]
LW (line winding)	9	E	36.7	62.1
VW (valve winding)	1	/	34.5	49.1

Table 4. Calculation results of the winding temperature rise after allocating the ratio of the oil intake to the line and valve windings compared to the initial design (K)

Name of the winding	Number of the hottest coil	Type of coil	Average winding temperature rise over ambient temperature [K]	Hottest spot temperature rise over ambient temperature [K]
LW (line winding)	9	E	36.6	60.0
VW (valve winding)	1	/	34.4	50.7

reduced to 10 % and the number of the initial drain oil ducts can be reduced by half. The calculation results of the line and valve windings after changing the oil intake of the line winding are shown in Table 3 while the calculation result for each disc in the line winding is shown in Figure 6.

By changing the oil flow in the line winding and the distribution of eddy-current losses at the winding end, design margin for winding hot spot temperature rise was ensured

It can be seen from Table 3 and Figure 6 that the hottest spot position of the line winding still appears in the ninth disc after increasing the line winding oil intake. The maximum value is reduced by 2.8 K (64.9 - 62.1), but that is still higher than 60 K.

The second improvement of design included allocating the ratio of the oil intake to the line and valve windings, increasing the internal oil flow resistance of the valve winding by increasing the oil guide barrier in this winding, and then increasing the oil flow amount of the line winding. The calculation result is shown in Table 4 and Figure 7.

After allocating the ratio of the oil intake to the line and valve windings, the hottest spot temperature rise of the line winding was 60 K, which meets the design requirements. The slightly higher temperature rise of the valve winding will not affect the conclusion that the temperature rise test of the valve winding can meet the agreement value.

Through repeated trial calculations, it was also found that the hottest spot temperature rise cannot be reduced rapidly only by an unrestricted increase of the line winding oil intake, as the decrease of the hottest spot temperature rise is getting slower and slower. Therefore, further increase of the line winding oil intake has no real effect as the demand is already satisfied.

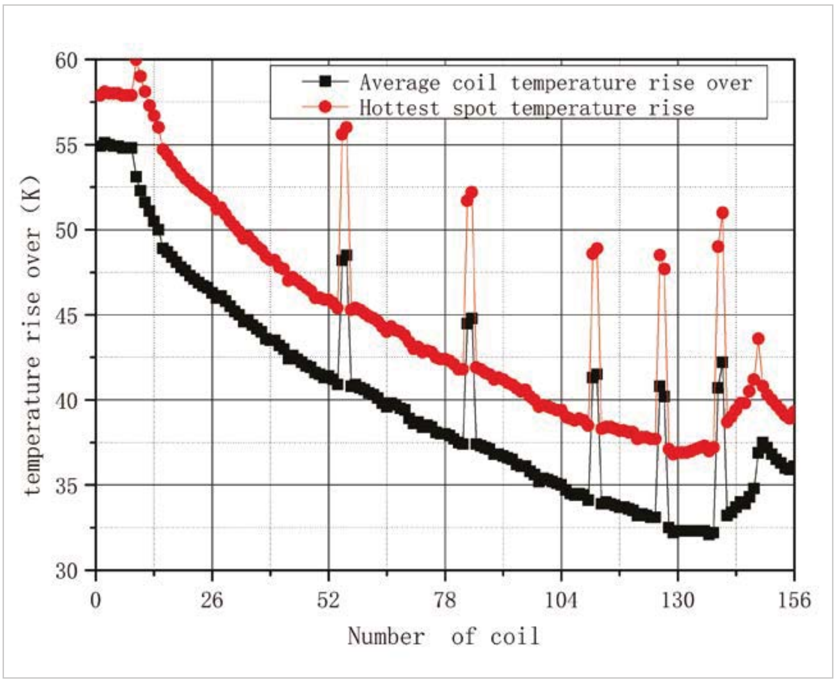

Figure 7. Schematic diagram of the temperature rise of each disc (coil) in the line winding after allocating the ratio of the oil intake to the line and valve windings

An advanced fibre-optic temperature measurement technology was used to measure the hot spot temperature rise, ensuring the operating life of the converter transformer

5.3 The improvement of design by changing the hottest spot size and position and adjusting the arrangement of conductor specifications

After adjusting the oil flow of the line winding, the hottest spot temperature rise of the line winding is slightly reduced, but the position of the hottest spot is still in the ninth disc. The winding resistance losses and eddy losses can be calculated by the MLW module. Using this module, it can be found that the radial eddy losses of the ninth disc are larger compared to the eddy losses of the previous eight discs, which is related to the conductor specification used in the ninth disc. Considering the influence of bending magnetic lines on the winding end, the first eight discs adopt the axial combined conductor as shown in Figure 8(a), which reduces the radial eddy current loss. However, the larger radial combined conductor used for the ninth disc, Fig. 8(b), results in a larger eddy current loss of this disc. The eddy current loss distribution of the first ten discs is shown in Table 5.

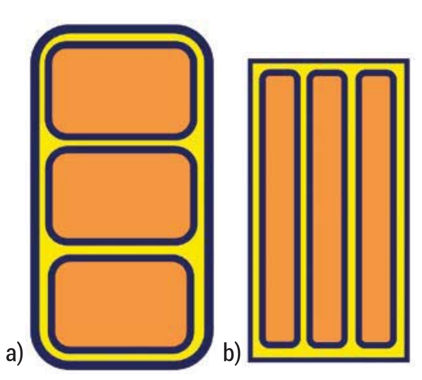

Figure 8. Conductor specification:
(a) G&F disc specification – axial combined conductor;
(b) E disc specification – radial combined conductor

The leakage magnetic field distribution of a large-capacity converter transformer is very complicated, and the magnetic field lines on the winding end are bent, Fig. 9. Since the leakage magnetic field strength is different along with the height or radial direction of the winding, the radial leakage flux is becoming more and more important to the eddy current loss caused by a large-capacity converter transformer.

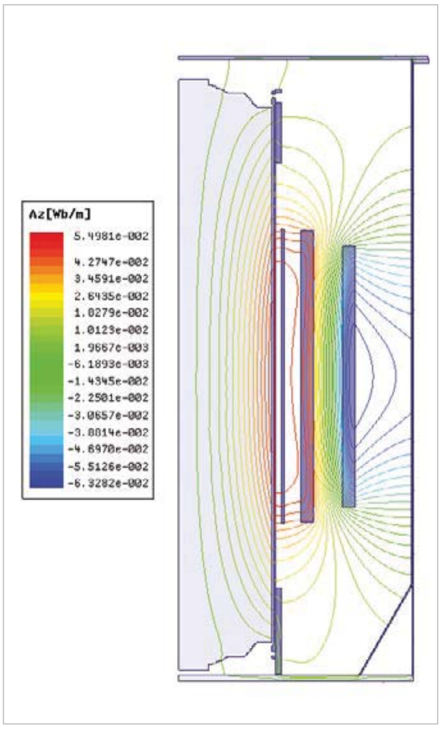

Figure 9. Schematic diagram of the transformer leakage flux distribution

The equation (1) shows that the radial leakage flux increases the eddy current loss:

$$K_w\% = 3.12 \cdot B_r^2 \left(\frac{b_1}{J_q}\right)^2 \quad [\%] \qquad (1)$$

Table 5. The eddy current loss distribution of the first ten discs at the head end of line winding

Number of disc	Type of disc	Axial eddy current loss [W]	Radial eddy current loss [W]	Sum of eddy current losses [W]
1	G	187.0	194.5	381.5
2	F	375.5	287.3	662.8
3	F	429.6	240.2	669.8
4	F	477.5	206.0	683.5
5	F	523.3	181.1	704.4
6	F	564.1	158.4	722.5
7	F	601.6	140.9	742.5
8	F	638.1	127.7	765.8
9	**E**	**62.6**	**1000.4**	**1063.1**
10	E	65.5	880.2	945.7

By comparing software calculated values and winding temperature rise measured values, the accuracy of software calculation result is indicated, and the quality of the product can be fully guaranteed

where:
K_w% is eddy current loss percentage of the main loss caused by magnetic leakage;
b_1 is the size of a single bare conductor that is perpendicular to the leakage field direction, generally referring to the thickness of a single bare conductor (mm);
J_q is conductor current density (A / mm^2); and
B_r is maximum radial leakage flux density (T).

The winding end adopts a three-axis composite conductor where the width b of the conductor is replaced by three equal b_1, which will greatly reduce the eddy current loss. According to equation (1), the first eight discs of the winding end used the three-axis composite conductor [3].

However, according to the data in Table 2, it can be seen that the radial eddy current loss of the ninth disc is obviously larger than that of the eighth, and the total eddy current loss of the ninth disc is larger than that of the eighth, while that of the tenth disc is smaller than that of the ninth, resulting in the higher hot spot temperature rise.

The improvement is changing the conductor specification of the ninth and tenth discs to that shown in Figure 9(a) to further reduce the eddy current loss of these two discs. From the 11th disc upwards the conductor specification will not be changed because the eddy current loss of the 11th disc is close to the eighth. The eddy current loss distribution of first ten discs after the improvement is shown in Table 6.

Compared with Table 5, the total eddy current losses of the ninth and tenth discs shown in Table 6 are reduced in varying degrees. In this case, the calculated temperature rise of the winding is shown in Table 7.

As can be seen from Table 7, hot spots appear in the seventh disc with the axial combined conductor after the above changes, the hot spot temperature decreases by 2.3 K (60.0-57.7), and an overall decrease of 7.2 K (64.9-57.7) is achieved after all the improvements done. By doing this the temperature rise increase margin caused by other factors is fully satisfied.

6. Installation of the fibre-optic temperature sensor

In order to verify the effectiveness of the improvement, the fibre-optic temperature sensor was installed in the spacers of the line and valve windings to monitor the winding hot spot temperature. According to the hot spot positions predicated by the software, the fibre-optic temperature sensor is installed between the seventh and eighth disc of the line winding, respectively, as well as between the 1st and 2nd disc of that valve winding.

During the installation, first the slot should be made in the block – the size and shape of the slot should be exactly the same as that of the sensor probe. The sensor probe should be put inside of the groove, and the probe and the block fixed by a small amount of a special transformer PVA (polyvinyl alcohol) glue. The probe should then be covered by another block, forming a block with a fibre-optic winding temperature sensor.

The advantage of this arrangement is that it is convenient and easy to use, and does not require large amounts of glue

Table 6. The eddy current loss distribution of the first ten discs

Number of disc	Type of disc	Axial eddy current loss [W]	Radial eddy current loss [W]	Sum of eddy current losses [W]
1	G	184.7	191.0	375.7
2	F	370.9	281.3	652.2
3	F	424.3	233.9	658.2
4	F	471.3	199.4	670.7
5	F	516.0	174.0	690.0
6	F	555.3	150.8	706.1
7	F	590.7	132.6	723.3
8	F	623.7	118.6	742.3
9	**F**	**651.6**	**107.5**	**759.1**
10	F	682.0	100.1	782.1

Table 7. Calculation results of the winding temperature rise after adjusting the arrangement of the conductor specifications

Name of the winding	Number of the hottest coil	Type of coil	Average winding temperature rise over ambient temperature [K]	Hottest spot temperature rise over ambient temperature [K]
LW (line winding)	7	F	36.6	57.7
VW (valve winding)	1	V	34.3	50.8

that can cause air bubbles to accumulate, which can affect the functionality of transformer. In the actual use, the oil inlet in the block is positioned to the left to allow slot fixing so that the transformer oil can be in a direct contact with the sensor. Compared with the traditional block package type arrangement where the sensor probe cannot be in a direct contact with the transformer oil, it makes a certain deviation between the temperature measured by the sensor and the real temperature.

This pad single point winding temperature sensor can be arranged in any position of the winding oil channel. In the actual use, just take out the normal pad and replace it.

7. Temperature rise test results

During the temperature rise test, the oil temperature should be obtained after applying the total loss [4]. By comparing the calculation and the temperature rise test values, one can verify the effectiveness of the temperature rise calculation software, and also prove that the above design improvement can reduce the hot spot temperature rise after implementation.

Comparing the test result and the fibre-optic temperature measurement, the deviation percentage is within 6 %, which caters for the engineering application needs. At the same time, because of the adequate design allowance, this optimization design can guarantee the safety and reliability of the converter transformer.

Conclusion

This paper described hot spot temperature rise tests that have been carried out on the converter transformer for a ±1,100 kV HVDC transmission project. Using the most advanced technology, these tests confirmed the hot spot temperature rise values of converter transformer are in accordance with applicable standard.

Though the introduction of cooling structure system in active part of +1100 kV HVDC converter transformer, the initial design scheme still could not satisfy the

Table 8. Comparison of temperature rise test between calculated and measured values

Item	Name of winding	Average winding temperature rise over ambient temperature [K]	Hottest spot temperature rise over ambient temperature [K]
Calculated value by software	LW	36.6	57.7
	VW	34.4	50.8
Test value	LW	38.7	59.7
	VW	33.3	51.1
Deviation percentage [%]	LW	5.4	3.4
	VW	3.4	0.6

design requirements of the customer and the applicable standards, an optimization of design was carried out using TranCalc software.

The oil flow structure was partially improved, and the oil flow in the line winding was increased by adjusting the flow distribution in the winding, reducing the winding hot temperature rise.

By using the radial eddy current loss calculation formula, this paper describes how the winding conductor arrangement of the winding end can be optimized by reducing the eddy current loss of the hottest disc and reduce the hot spot temperature rise.

Using the TranCalc software to calculate the windings temperature rise and hot spot temperature rise after adopting the above mentioned improvement, the effectiveness of the improvement was verified by the fibre-optic temperature measurement data.

Through the comparison between the calculation and test data values of winding temperature rise, the accuracy of software calculation result is indicated, and the quality of the product can be fully guaranteed.

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