Study on the transformer insulation design and insulation margin verification under extremely cold conditions

Jianquan Liang*, Wei Suna, Hongda Zhanga, Xuecheng Zhuc, Peng Zhangd and Lin Li, Zhao Leilei

State Grid Heilongjiang Electric Power company Limited, Electric Power Research Institute, Harbin, China

*Corresponding author e-mail: ljq_hit@163.com, a sunwei19850525@163.com, 
bzhanghongda99@163.com, cljq708@163.com, d 275432669@qq.com, 
elilin77@yeah.net, f13813739@qq.com

Abstract. Under extremely cold conditions, the property of insulation materials will change with the decreasing of the temperature. Therefore, the research on the dielectric property of insulation materials under unknown extreme cold conditions and the verification on the insulation margin of the insulation materials shall be conducted to ensure that the insulation margin of key transformer parts can meet operation requirements and to avoid the discharge or breakdown failures. The paper studies the main insulation of transformer winding, the insulation of high-voltage connection and the electric field distribution of high-voltage lead model under ambient temperature and low temperature conditions. In addition, the insulation margin curve of the transformer under different temperature conditions is obtained through breakdown characteristic experiment and simulation experiment.

1. Introduction
The verification of the transformer insulation margin is to evaluate the reliability of transformer insulation design. Based on the analysis, it can be seen that firstly the accuracy of electromagnetic field calculation shall be guaranteed in insulation design process [1], [2]. Over the year, researchers have developed various numerical calculation methods like finite difference method, finite element method, boundary element method, etc. In addition, with the rapid development of computer hardware technology and the gradual completion of electromagnetic field optimization algorithm, the simulation of electromagnetic field has realized a reliable calculation accuracy [3]. By far, the electromagnetic field simulation software can even accurately describe the distribution of time-varying field and multiple physical coupling field of the transformer insulation. However, the precondition to ensure the accuracy of electromagnetic field calculation method of the transformer insulation design is that the input material property parameter shall be accurate [4]. For the insulation design of AC transformer, the electric field distribution is determined by the dielectric constant of oil paper insulation. In the past time, transformer designers or researchers used to take 2.2 as the dielectric constant of transformer oil but the dielectric constant of insulation paper board is usually 4.4, which is the double of the dielectric constant of transformer oil paper. However, the dielectric constant and temperature have certain functional
relationship and the influence degree of the numerical change of the dielectric constant on the electromagnetic field distribution under low temperature still needs to be quantified [5].

Under the extremely cold condition, the property of insulation materials will change with the decrease of the temperature. In order to ensure the transformer can enter into operation status under extremely cold conditions, firstly, the stability of the electric field performance shall be guaranteed, and the insulation margin of key parts shall meet operation conditions and the discharge or breakdown failures shall be avoided. Thus, the study shall be conducted to analyze the dielectric property of insulation materials under unknown extremely cold condition and the insulation margin shall be verified.

2. The experiment study on the influence of the insulation material property change on the electric field distribution under low temperature conditions

Under low temperature conditions, the resistivity, dielectric constant and breakdown characteristics of insulation materials are all changed. The winding and lead wire of the transformer are the parts with electricity and will form different electric field distributions through the separation of transformer oil, oil paper and oil immersed cardboard. To analyze the influence of insulation material property change on the electric distribution under low temperature conditions, hereby the insulation structures of key transformer parts like winding’s main insulation structure and high-voltage lead wire insulation structure are taken as the electric field analysis models to conduct related study. This paper also analyzes the influence of winding’s main insulation structure property under low temperature conditions on the electric field distribution [6].

Assume in the uniform electric field shown in following figure 1:

![Figure 1. The diagram of uniform electric field](image)

The field strength in oil and paper usually meets the following relationship:

\[
\frac{E_{\text{oil}}}{E_{\text{paper}}} = \frac{\varepsilon_{\text{paper}}}{\varepsilon_{\text{oil}}} = \frac{4.4}{2.2} = 2
\]

(1)

The oil field strength is the double of the paper field strength. Thus, oil is the weakest link in transformer insulation design and shall be pay more attention to.

Based on the experiment data of the insulation material property change with the change of the temperature, introduce in the actual dielectric constant to get:

\[
\frac{E_{\text{oil}}}{E_{\text{paper}}} = \frac{\varepsilon_{\text{paper}}}{\varepsilon_{\text{oil}}} = \frac{3.7}{2.17} = 1.705 \quad (20^\circ C)
\]

(2)
Under extremely cold conditions, the field strength of oil is decreased and the field strength of paper is increased. The field strength in the two medias tends to become uniform, which can improve the electric field distribution [7].

The above mentioned relational expression is obtained when the two mediums are equal. However, in actual structure the paper accounts for a smaller proportion than oil in the insulation system. Therefore, the oil field strength is not decreased as much as that shown in above mentioned relational expression [8].

2.1. The influence of low-temperature property of winding main insulation on electric field distribution

1) Electric field distribution under ambient temperature

Under ambient temperature (20 °C) condition, the relative dielectric of oil and paper is 3.7 and the relative dielectric constant of transformer oil is 2.17. The simulation result is as following:

$$\frac{E_{oil}}{E_{paper}} = \frac{\varepsilon_{paper}}{\varepsilon_{oil}} = \frac{3.3}{2.26} = 1.46 \quad (-50^\circ C) \quad (3)$$

Figure 2. Cloud chart of electric field distribution of ambient temperature model

Figure 3. Field strength distribution along power line at ambient temperature
From figure 2, it can be seen that the maximum field strength of the external paper with medium voltage is 9.2kV/mm. From figure 3, it can be seen that insulation margin=occurrence field strength value/allowable field strength value. In this structure, the minimum insulation margin is 1.26.

(2) The electric field distribution at low temperature

Under low temperature condition (-50°C), the relative dielectric of oil and paper is 3.3 and the relative dielectric constant of transformer oil is 2.26. The simulation result is as following:

![Figure 4. Cloud chart of electric field distribution of low temperature model](image1)

![Figure 5. Field strength distribution along power line at low temperature](image2)

From figure 4, it can be seen that the maximum field strength of the external paper with medium voltage is 8.9kV/mm. From figure 5, it can be seen that the minimum insulation margin of this structure under low temperature condition is 1.13.

2.2. The influence of low-temperature insulation property of high-voltage lead wire on electric field distribution

(1) The electric field distribution at ambient temperature

Calculation conditions: Under 20°C and the water content of 0.77%, the dielectric constant of paper is 4.288. The relative dielectric constant of oil is 2.17 and the dielectric constant of oil and paper is 3.7.
Figure 6. Electric field strength and equipotential line of high-voltage lead wire at ambient temperature

Figure 7. The electric field strength distribution at the turn point of the lead wire and along line 1 at ambient temperature

(2) The electric field distribution at low temperature
Calculation condition: Under -50℃ and the water content of 0.77%, the dielectric constant of paper is 4.105. The relative dielectric constant of oil is 2.26 and the dielectric constant of oil and paper is 3.3.
Figure 8. Electric field strength and equipotential line of high-voltage lead wire at low temperature

Figure 9. The electric field strength distribution at the turn point of the lead wire and along line 1 at low temperature

Through the simulation experiment, it can be seen that the breakthrough voltage of insulation oil with the water content of 2.5mg/kg is 71kV/2.5mm at 20°C and is 63kV/2.5mm at -50°C. Thus, the breakthrough voltage at -50°C is 88.7% of that at 20°C.
2.3. The influence of low-temperature property of experimental high-voltage lead wire model on the electric field distribution

(1) The electric field distribution at ambient temperature

In order to verify the electric field property of high-voltage wire structure, the high-voltage lead wire model that can reach low temperature condition in lab test condition is established to realize the simulation and experiment comparison. Then, the model is used to conduct the electric field simulation.

Calculation conditions:
At 20℃, the relative dielectric constant of oil is 2.17 and the relative dielectric constant of oil paper is 3.7.
At -50℃, the relative dielectric constant of oil is 2.26 and the relative dielectric constant of oil paper is 3.3.

![Cloud chart of electric field strength distribution at ambient model temperature and low model temperature](image)

**Figure 10.** The cloud chart of electric field strength distribution at ambient model temperature and low model temperature

It can be seen from the figure that the minimum insulation margin of the model structure is 0.64 at ambient temperature and the maximum field strength is 15.2kV/mm. At low temperature, the minimum insulation margin of the model is 0.58 and the maximum field strength is 15.1kV/mm.
3. The transformer/high-resistant key parts insulation margin verification under extremely cold conditions

Based on the two main insulation structures of the transformer and three simulation model data (as shown in table 1), it can be seen that the insulation margin at low temperature is lower than that at ambient temperature. For instance, the insulation margin at -50°C decreases by 10% compared with that at 20°C. The insulation margin decrease degree of all insulation parts are basically consistent.

| Simulation case         | Minimum insulation margin | Maximum field strengthkV/mm | Insulation margin ratio (low temperature/ambient temperature) |
|-------------------------|---------------------------|-----------------------------|---------------------------------------------------------------|
|                         | Ambient temperature (20°C) | Low temperature (-50°C)     | Ambient temperature (20°C) | Low temperature (-50°C) |
| Main insulation         | 1.26                      | 1.13                        | 9.2                        | 8.9                        | 0.9                        |
| High-voltage lead wire  | 1.34                      | 1.21                        | 7.16                       | 7.04                       | 0.9                        |
| insulation             |                           |                             |                             |                             |                             |
| Experiment model        | 0.64                      | 0.58                        | 15.2                       | 15.1                       | 0.91                       |

Figure 11. The electric field strength distribution at the turn point of the lead wire and along line1 at low temperature

4. Conclusion

With the decrease of the temperature, the relative transformer dielectric constant is slightly increased and the dielectric constant of oil paper decreases with the decrease of temperature. These two tendencies lead to the result that the relative dielectric constant tends to get closer and the insulation structure’s electric field strength tends to become uniform. However, the breakdown voltage of the transformer oil will change with the change of temperature. In the transformer oil and oil paper insulation system, the field strength of transformer oil is higher than that of oil paper, but the voltage-resistance performance of transformer oil is poorer than that of oil paper. Thus, the transformer oil is the weak point of the insulation system. Therefore, under extremely cold condition, the insulation margin of the oil in each transformer insulation structure shall be verified.
In accordance with the breakdown experiment and simulation experiment of transformer oil, it can be seen that the insulation margin curve is similar to para-curve and is not linear. The poorest insulation margin appears when the temperature is close to -10°C rather than under extremely cold condition of -60°C. At -50°C, the transformer insulation margin is close to that at 20°C and when the temperature is lower than -50°C, the insulation margin is increased. It proves that in transformer design, the electric field shall be considered based on the low temperature of -10°C and it is not necessary to take the extremely cold condition into consideration.

Acknowledgments
Project supported by Science and Technology Project of SGCC (Research on key technologies for operating reliability improvement of transmission corridors under extreme climatic conditions).

References
[1] Hugo Rodriguez-Ignacio,Xose M. Lopez-Fernandez,Casimiro Álvarez-Mariño. A methodology for the optimized design of power transformer insulation system[J]. COMPEL - The international journal for computation and mathematics in electrical and electronic engineering,2018,37(3).
[2] Rodriguez-Ignacio Hugo,Lopez-Fernandez Xose M,Álvarez-Mariño Casimiro. A methodology for the optimized design of power transformer insulation system[J]. Compel,2018,37(3).
[3] G. Srelatha,M. Rajkumar,Y. Sudhakar,T.K. Ganguly. Improvements in Internal Insulation Design of Power Transformer using Electric Field Analysis Through Finite Element Method[J]. Power Engineer Journal,2014,16(2).
[4] Fofana,Setayeshmeh A. Low Temperature and Moisture Effects on Oil—Paper Insulation Dielectric Response in Frequency Domain[C]. IEEE Electrical Insulation Conference,Montreal,Q C,Canada,2009:368.
[5] Zhou Yuanxiang,Sun Qinghua,Li Guangfan,et al. Effects of space charge on breakdown and creeping discharge of oil-paper insulation[J]. Transactions of China Electrotechnical Society,2011,26(2):27-33(in Chinese).
[6] Jin Fubao,ZhouYuanxiang,Sha Yanjiao,et al. Effect of preloaded DC voltage on characteristics of partial discharge in oil-paper insulation[J]. High Voltage Engineering,2015,41(3):936-946(in Chinese).
[7] Cavallini A,Chen Xiaolin,Carlo G,et al. Diagnosis of EHV and HV transformer through an innovative partial-discharge-based technique[J]. IEEE Transactions on Power Delivery,2010,25(2):814-824.
[8] Ommen T V. Moisture equilibrium charts for transformer insulation drying practice[J]. IEEE Transactions on Power Apparatus and Systems,1984,103(10):59.