Influence of different oil-paper configurations on the electric field distribution simulation of the internal insulation of converter transformer

Z D Cheng¹, L Cheng¹,³, J H Wang¹ and L Wang²

¹Country State Key Laboratory of Power Equipment & System Security and New Technology, Chongqing University, China
²China Electric Power Research Institute, Haidian Xiaoyingdong Road 15, Beijing, China

E-mail: chengl16@cqu.edu.cn

Abstract. Converter transformer is an important equipment in HVDC system and it is the key to the stable operation of the whole power transmission and distribution system. Unlike the traditional AC transformer, the oil-paper insulation of converter transformer will receive both AC and DC voltage. So the requirement for the structure design of oil-paper insulation system will be more stringent. It is of great engineering significance to study the electric field distribution of converter transformer and to study the influence of different oil-paper insulation configuration on the electric field distribution in the internal insulation of converter transformer. In this paper, first, an oil-paper insulation structure of converter transformer is established and electric field distribution under AC/DC composite voltage is studied. Then change the thickness and layers of pressboard, the distance of oil channel and the oil-paper ratio to get different oil-paper configurations. Use the simulation software to calculate the electric field distribution under the different oil-paper configurations. Finally, the influence of different oil-paper configuration on the electric field distribution of internal insulation structure of converter transformer is analysed which will provides significant reference for the internal insulation design of converter transformer.

1. Introduction
When the society is growing rapidly, the demand for electricity is increasing year by year. In order to meet the requirements of long distance transmission and large capacity, the HVDC transmission system is born, which plays a significantly critical role in energy transmission and distribution system [1]. Converter transformer, as a key role in HVDC system, will have a serious impact on the whole transmission and distribution system in case of failure, bringing incalculable economic losses to social production and life [2]. In addition, it is different from the ordinary ac transformer. During the operation, the valve side winding of converter transformer will receive the combined ac and dc voltages, which has more severe requirements on the insulation system [3]. Oil-paper insulation, which is the main form of insulation structure in converter transformer, will receive the action of composite voltage. The study on the of electric field distribution in oil-paper insulation inside converter transformer under the action of composite voltage will provide important reference for the design of typical insulation structure inside converter transformer [4].

Multi-physics field simulation software is getting more popular as a simulation platform [5]. Based
on the finite element calculation of multiple physical field simulation software, it can be quick, easy for the analysis of multi-physics field distribution in electric equipment, such as transformer. Now researches generally use multi-physics simulation software based on the finite element to calculate and analyze the internal field distribution for converter transformer.

There have been many calculation and analysis of electric field distribution in oil-paper insulation structure of transformer done by researches and equipment manufacturers, including: 1) calculation of electric potential distribution of transformer internal insulation structure [6]; 2) calculation and analysis of characteristics of electric field distribution in internal insulation under the action of dc and ac voltages and compound voltage [7]; 3) study the transient change rule of field-distribution of internal main insulating structure in the case of voltage polarity reversal [8]; 4) calculation and analysis of temperature rise inside transformer under oil flow state [9]. However, the analysis and designing of the oil-paper insulation structure in converter transformer with large capacity and high voltage are still in the stage of calculation and analysis from the empirical formula, and there are few simulations of the influence of different oil-paper configuration on typical insulation structure inside the converter transformer.

To figure out the influence of oil-paper configuration on the field-distribution in insulation structure of the converter transformer, this paper establishes a two-dimensional model of main insulation structure of converter transformer. Including the end winding insulation and main insulation of valve side and line side. Then using the multi-physics simulation software to get the distribution of field distribution. After that, the layers and thickness of pressboard are changed to get different oil-paper configuration. And influence of layers and thickness of pressboard on the electric field distribution inside the internal insulation structure of converter transformer are studied. So that it can provide some references for the design, manufacture, operation and maintenance of converter transformer.

2. Establishment of typical internal insulation structure of converter transformer

Because of the huge size and complex inside construction of converter transformer, it will be very difficult to test the typical insulation structure of large converter transformer [10]. But the multi-physics field simulation software can provide a significant approach to calculate and analysis the field distribution of insulation structure inside converter transformer [11]. In order to calculate the field distribution in insulation structure, this paper first builds the typical inside insulation structure of converter transformer which can be shown in figure 1.

![Figure 1. A typical internal structure of converter transformer.](image1)

![Figure 2. Main insulation and end winding insulation structure of converter transformer.](image2)

In order to facilitate the calculation and minimize the calculation deviation, this paper has appropriately simplified the internal structure of converter transformer. And neglected the influence of
the structure such as lead wire, connector and casing on the distribution of electric field. The internal insulation structure of a typical converter transformer shown in figure 1 is mainly composed of iron core, iron yoke, line side winding, valve side winding, oil-paper insulation and transformer metal wall [12]. Due to the actual distribution of electric field in practical engineering, the insulation material at the end winding is often subjected to higher voltage and temperature, which is the key part to be examined in design and manufacture [13]. The simplified model of typical winding end insulation and main insulation of converter transformer is shown in figure 2.

As shown in figure 2, the AB is the iron yoke and BC is the metal wall of transformer shell. AD is the iron core. The end winding and main insulation of converter transformer are mainly composed of pressboard. And forming angle ring is also made of pressboard. The line side winding and the valve side winding are covered with several layers of paper. Several layers of pressboard and forming angle ring are arranged with certain distance, and finally form a number of insulation oil channels. Thus the whole internal main insulation and end winding insulation model of converter transformer is formed.

3. Simulation of field distribution of internal insulation structure of converter transformer

3.1. Mathematical model for electric field distribution simulation

With the development of computer software technology, there has been more and more simulation software. The Multi-physics simulation software that this paper will use has been widely used in many industry areas and scientific research. It has powerful functions and is widely used by researchers and scholars in various industries [14].

In converter transformer, since the valve windings of converter receives ac and dc composite voltage, this paper selects the current module given in simulation software to conduct transient analysis of field distribution in insulation structure. The transient calculating model of electric field distribution is shown in equations (1) to (3).

\[ \nabla J = Q_{j,v} \]  \hspace{1cm} (1)

\[ J = \sigma E + \frac{\partial D}{\partial t} + J_e \]  \hspace{1cm} (2)

\[ E = -\nabla V \]  \hspace{1cm} (3)

As shown in these equation, J is current density, Q stands for the charge density while E means the field strength. V is potential while the D stands for the electric displacement. By further combining and simplifying the above equations, the partial differential equation of electric field transient distribution can be obtained. If three-dimensional spatial coordinate system is established, the three-dimensional transient electric field equation can be obtained as shown in equation (4) [15].

\[ \left( \gamma + \varepsilon \frac{\partial}{\partial t} \right) \left( \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} \right) = 0 \]  \hspace{1cm} (4)

As shown equation (4), \( \gamma \) is conductivity and \( \varepsilon \) is permittivity. In the setting of boundary conditions, as shown in figure 2, AB section of iron yoke, BC section of converter transformer wall and transformer core section are all grounded, and 0 potential is maintained [16]. The valve side winding receives dc voltage and line side winding receives ac voltage.

3.2. Simulation of electric field distribution under applied composite voltage

When converter transformer is operating in actual condition, the network side windings of converter transformer only receives ac voltage, while the valve side windings receives both of ac and dc voltages. To simulate the field-distribution of converter transformer and the appropriate to simplify the calculation, this paper set up a working condition of the converter transformer: in this situation, the line side winding of converter transformer receives 900 kV ac voltage with 50 Hz, and the valve side
winding of converter transformer receives 1250 kV dc voltage. The electric field distribution of typical insulation structure of converter transformer is shown in figure 3.

![Electric field distribution](image)

**Figure 3.** Electric field distribution under applying ac and dc voltages.

From the result, the electric field closely around the valve side winding mainly is composed by the dc component while the ac electric field is mainly accumulated around the line side winding. The maximum value of electric field strength in pressboard is about 35 kV/mm and about 10 kV/mm in oil.

### 4. Influence of different oil-paper configuration on field-distribution of insulation structure

#### 4.1. The setting of different oil-paper configuration

With the increasing voltage grade of transformer, the configuration of oil-paper insulation structure will also change in the design of transformer. Including the number of pressboard layers, pressboard thickness, oil-paper ratio and so on [17]. The ratio of oil-paper in transformer is complementary to the number and thickness of pressboard. Different thickness and layer of pressboard will result in different oil gap space. That is, different oil-paper configuration change the ratio of oil and paper. Thus forming different oil-paper configuration. Therefore, it is of great engineering significance to study the influence of different oil-paper configuration on field distribution.

In order to simplify the research method, this paper sets 4 different thickness and 4 different numbers of layers of pressboard to form different oil-paper configuration. Then calculate electric field distribution with these different oil-paper insulation configuration under the composite voltages. These 4 different thickness of insulating board refers to the thickness of 3, 4, 5 and 6cm. Number of layers of pressboard that form the Angle ring around the valve side are set as 5, 6, 7, 8. Thus under these settings, there forms different number of oil-paper ratio and oil-paper insulation configuration mode. Next step is to study the influence of different oil-paper configuration on the field distribution under composite voltage.

#### 4.2. The simulation about influence of oil-paper configuration on the electric field distribution

Different oil-paper configurations can be formed by changing the number of layers and thickness of the pressboard. In each oil-paper structure configuration, the field distribution is simulated under the composite voltage. Maximum electric field strength in insulating oil or in insulating paper of each oil-paper configuration are observe and record. Finally the variation rule of field distribution in insulation structure under different oil-paper configuration is obtained.

**4.2.1. Change layers of pressboard.** Change the number of layers of pressboard. The relationship between the field distribution and different number of layers of pressboard in typical insulation
structure of converter transformer under composite voltage are shown in figures 4(a), 4(b), 4(c) and 4(d).

![Figure 4](image)

**Figure 4.** Influence of layers of pressboard on electric field distribution. (a) 5, (b) 6, (c) 7 and (d) 8.

The maximum value of electric field strength in insulating oil and insulating paper are extracted and plotted in figure 5.

![Figure 5](image)

**Figure 5.** Influence of layers of pressboard on the maximum value of electric field strength.

As the number of layers of pressboard increases, the electric field strength in the pressboard decreases significantly, with a drop range up to 10 kV/mm. At the same time, the electric field strength in oil only rises slightly, with a range of about 0.5 kV/mm, and the rise is basically negligible.
4.2.2. Change the thickness of pressboard. Change the thickness of pressboard. The relationship between the field distribution and the thickness of pressboard in the typical structure of converter transformer under composite voltage is obtained, as shown in figures 6(a), 6(b), 6(c) and 6(d).

![Figure 6](image1)

**Figure 6.** Influence of thickness of pressboard on electric field distribution. (a) 3 cm, (b) 4 cm, (c) 5 cm and (d) 6 cm.

The maximum value of electric field strength in oil and paper are extracted and plotted in figure 7.

![Figure 7](image2)

**Figure 7.** Influence of thickness of pressboard on the maximum value of electric field strength.

It can be seen that when the thickness of pressboard increases, the field strength distributed in pressboard will drop substantially, with a drop range of about 20 kV/mm. Due to the distribution characteristics of ac voltage, the proportion of the pressboard increases, and the electric field strength
in oil will rise slightly, but also with a small increase.

4.3. Discussion about the influence of oil-paper configuration on electric field distribution

From the simulation results, it can be seen that when the composite voltage is applied, the field strength in the oil is low that the maximum value of field strength is no more than 12 kV/mm. The minimum electric field strength in pressboard is more than 30 kV/mm, and the maximum value is close to 60 kV/mm. And the region where the maximum field strength exists on the pressboard is located close to the valve side end winding, which belongs to the dc component. The maximum electric field strength in pressboard is much higher than that in oil. And the influence result of different oil-paper configuration on the field distribution of typical insulation structure of converter transformer under composite voltage is shown in table 1.

|                | Electric filed in oil | Electric filed in paper |
|----------------|-----------------------|-------------------------|
| Increase of layers | increase             | decrease                |
| Increase of thickness | increase            | decrease                |

From the simulation results, it can be found out that the increase in the number of layers of pressboard can significantly reduce the electric field strength in paper. However, because of the distribution characteristics of ac voltage [18], the increasing of layers of pressboard increases the proportion of paper in the ratio of oil-paper. It will increase the electric field strength in oil slightly. Increasing of thickness of pressboard and the number of layers of pressboard both have a similar mechanism of action. Increasing of thickness will greatly reduce the concentration of voltage in pressboard while the electric strength in oil will rise slightly.

In conclusion, the change in the number of layers and thickness of pressboard reflects the influence of different oil-paper ratio on the characteristic of electric field distribution. When applying the composite voltage, if the proportion of paper increases, the electric field of dc component in the insulation structure decreases while the electric field of ac component increases slightly. When the proportion of paper decreases, the dc electric field strength in insulation structure increases while the ac electric field strength decreases slightly. Therefore, for a large converter transformers, the proportion of dc and ac components in the voltage waveform must be carefully considered in the designing of internal insulation structure to determine the ratio of oil and paper. When setting the oil-paper configuration, the numbers of layer and thickness of pressboard should be increased appropriately. On the other hand, it can decrease the maximum value of field strength in pressboard, on the other hand, the maximum value of field strength in oil should be well controlled to let it only rise only slightly and far above its critical breakdown field strength. Under this circumstance, the electric field distribution will be in a stable and safe situation.

5. Conclusion

- In converter transformer, when line side winding receives the ac voltage while valve side winding receives composite voltage, electric field strength in pressboard is much higher than that in insulating oil, and the maximum electric field strength in oil is located near the line side while the maximum field strength in paper is located close to the valve side.
- Applying the composite voltage, when the number of layers of pressboard increases, the electric field strength in pressboard decreases. While the electric field in insulating oil slightly increases. When the thickness of pressboard increases, the electric field strength of pressboard decreases, while the electric field strength in insulating oil increases slightly.
- In the actual operating situation, when the proportion of dc component dominants, it should be considered to decrease the ratio of oil-paper appropriately in the designing and manufacturing of converter transformer. But when the proportion of ac component dominants, more ratio of
References

[1] Li Y et al 2008 Transient response characteristics of new HVDC transmission system based on new converter transformer 2008 3rd Int Conf Electric Utility Deregulation and Restructuring and Power Technologies (Nanjing) pp 1873-7

[2] Li Y, Zhang Z, Rehtanz C, Luo L, Rüberg S and Liu F 2011 Study on steady- and transient-state characteristics of a new HVDC transmission system based on an inductive filtering method IEEE Trans. Power Electron. 26 1976-86

[3] Ji L I et al 2006 Study on electric field characteristics at ends of valve-side winding in converter transformer High Voltage Eng. 32 121-4

[4] Wang Y, Wei X, Chen Q, Huang Y and Nie H 2009 Breakdown characteristics of converter transformer insulation under composite AC and DC voltage 2009 IEEE 9th Int Conf the Properties and Applications of Dielectric Materials (Harbin) pp 634-7

[5] Christen T 2015 HVDC insulation boundary conditions for modeling and simulation IEEE Trans. Dielectr. Electr. Insul. 22 35-44

[6] Zhang H, Gong W, Cao L and Huang P 2013 Simulation of distribution of space charge in ±500kV converter transformer in DC tests 2013 Annual Report Conf Electrical Insulation and Dielectric Phenomena (Shenzhen) pp 242-5

[7] Hou S, Tian Y, Fu M and Zhuge X 2015 Influential factor analysis and computation on electric field of converter transformer barrier 2015 IEEE 11th Int Conf the Properties and Applications of Dielectric Materials (ICPADM) (Sydney)

[8] Liu G et al 2012 Analysis of transient electric field and charge density of converter transformer under polarity reversal voltage IEEE Trans. Magn. 48 275-8

[9] Wang Q, Li X and Yin Y 2009 Computer simulation and analysis of electric and temperature fields of HVDC cables 2009 IEEE 9th Int Conf the Properties and Applications of Dielectric Materials (Harbin, China) pp 101-4

[10] Hagiwara M, Pham P V and Akagi H 2008 Calculation of DC magnetic flux deviation in the converter-transformer of a self-commutated BTB system during single-line-to-ground faults IEEE Trans. Power Electron. 23 698-706

[11] Singh A K, Das P and Panda S K 2014 High voltage high frequency resonant DC-DC converter for electric propulsion for micro and nanosatellites 2014 IEEE 36th Int Telecommunications Energy Conference (INTELEC) (Vancouver, BC) pp 1-5

[12] Shuai Y, Han X, Zhang L, Yang C, Hu X and Wu H 2016 Major insulation design consideration of converter transformer 2016 Int Conf Condition Monitoring and Diagnosis (CMD) (Xi'an, China) pp 1004-7

[13] Grant D H and McDermid W 2004 Assessment of thermal aging of HVDC converter transformer insulation Conference Record of the 2004 IEEE International Symposium on Electrical Insulation (Indianapolis, IN, USA) pp 230-2

[14] Liu H, Hao Y P, Fu M L, Wang D B and Yang L 2017 Study on ventilation of indoor substation main transformer room based on COMSOL software 2017 1st Int Conf Electrical Materials and Power Equipment (ICEMPE) (Xi'an, China) pp 296-300

[15] Wu H, Li C, Qi B, Zhao X, Lv J and Zhao L 2012 The electric field distribution in oil-paper insulation under combined AC-DC voltage 2012 IEEE Int. Conf. Condition Monitoring and Diagnosis (Bali, Indonesia) pp 1097-101

[16] Liu G, Li L, Zhao X, Li B and Sun Y 2012 An effective method of solving anisotropic nonlinear periodic electric field in oil-paper insulation under the AC-DC hybrid voltage 2012 Sixth Intl Conf Electromagnetic Field Problems and Applications (Dalian, China) pp 1-4

Acknowledgments

This research work is supported by National Key R & D Program of China (2016YFB0900804).
[17] Cheng J, Peng Z and Liu P 2012 Research on the electric field distribution of multilayer dielectric under AC-DC composite voltage 2012 IEEE 10th Int Conf the Properties and Applications of Dielectric Materials (Bangalore, India) pp 1-4

[18] Qi B, Zhao X, Li C and Wu H 2016 Electric field distribution in oil-pressboard insulation under AC-DC combined voltages IEEE Trans. Dielectr. Electr. Insul. 23 1935-41