Electric Field Simulation of Surge Capacitors with Typical Defects

Chenmeng Zhang¹*, Yuxiang Mao², Shijun Xie¹, Yu Zhang¹
¹State Grid Sichuan Electric Power Research Institute, Chengdu 610072, China
²School of Electrical Engineering and Electronic Information, Xihua University, Chengdu 610039, China

*Corresponding author e-mail: zhangchenmeng@126.com

Abstract. The electric field of power capacitors with different typical defects in DC working condition and impulse oscillation working condition is studied in this paper. According to the type and location of defects and considering the influence of space charge, two-dimensional models of surge capacitors with different typical defects are simulated based on ANSYS. The distribution of the electric field inside the capacitor is analyzed, and the concentration of electric field and its influence on the insulation performance are obtained. The results show that the type of defects, the location of defects and the space charge all affect the electric field distribution inside the capacitor in varying degrees. Especially the electric field distortion in the local area such as sharp corners and burrs is relatively larger, which increases the probability of partial discharge inside the surge capacitor.

1. Introduction

Power capacitors are usually impregnated paper, impregnated film and mixed insulation between the two structures. For surge capacitors installed between neutral bus and the ground, full film insulation structure is adopted. In a full film capacitor, the dielectric loss is greatly reduced; the possibility of thermal breakdown is reduced, while the possibility of electrical breakdown is even more pronounced. The reasons of breakdown are: (1) uneven surface of DC charging medium (film and oil) interface charge; (2) the oscillation between the capacitor and the loop inductance as well as the reverse voltage peak value; (3) edge effect of the insulation. In the electric field simulation, all three aspects above are reflected by the conductivity γ and the dielectric constant ε⁽¹⁾.

Capacitor due to: (1) burring process is not sufficient; (2) capacitor impregnation degree is not enough; (3) non-uniform insulation material; (4) bad welding technology and other manufacturing problems caused by insulation defects, will greatly reduce the capacitor life expectancy⁽²⁾. For surge capacitors, the partial discharge usually happens at the defect of the film, the corners of the film, and oil bubbles and other electric field distortion area. As the applied voltage increases, the electric weak point of the film will be the first breakdown point, the partial discharge will happen in the surge capacitor. Practice has proved that under the action of a high electric field, the main reason to shorten the insulation life is partial discharge.

In this paper, according to the study of the insulation defects of the power capacitors⁽³⁻⁵⁾, four kinds of typical defects that affect the insulation properties of the capacitor were simulated, namely the internal defects, the contact defects, the overlap defects and the oil defects. The effect of defect location and the space charge to the electric field is also studied.
2. Simulation model

The normal operating mode of the surge capacitor is DC voltage, but will be affected by the impulse voltage in the converter station or the remote fault. Due to the effect of the inductance and resistance of the discharging circuit, the impulse voltage will be damped oscillation and peak inverse voltage. This process lasts only a few milliseconds, defining this process as the oscillation voltage. If the capacitor is connected to the high-voltage rectifier at the outlet and the rectifying element is operated in reverse voltage, the peak inverse voltage is limited to about 20% U. Consider the voltage limiting effect of arrester operating in parallel with the surge capacitor, the reverse voltage considered to be 20% U. Based on the principle of superposition, the impulse voltage sustained by the surge capacitor in the oscillation region is decomposed into the coupling of the constant current field influenced only by the electrical conductivity γ and the calculation result of the quasi-electrostatic field influenced only by the dielectric constant ε. Such as equation (1):

\[
\begin{align*}
\vec{J} &= \gamma \vec{E} \\
\nabla \cdot \vec{D} &= \rho_v \\
\vec{E} &= -\nabla V
\end{align*}
\]

In equation, J is the current density in A/m², E is the electric field strength in V/m, γ is the conductivity in S/m, D is the electric displacement vector in C/m, ρ_v is the body charge density, V is the potential in V. Under the peak inverse voltage 20%, the superimposed electric field strength E is obtained by superposing constant current field strength E₁ and quasi-static field strength E₂, as equation (2):

\[
E = E_1 - 1.2E_2
\]

At the same time, considering the influence of the space charge in the defect, the body charge is added within the defect by defining the body charge density. The electric field boundary conditions are Dirichlet conditions, as equation (3):

\[
\vec{n} \cdot \vec{E} = 0
\]

The surge capacitor, rated at 12kV and 0.6 μF, consists of 6 cores (2 rows and 3 columns) with a dielectric layer consisting of 2 layers of 15 μm thick polypropylene film (PP film) overlaid, vacuum dried and immersed. The purified benzyl toluene is the impregnant. Polypropylene film have relative dielectric constant of 2.2, the conductivity is 10e-17, Impregnation benzyl toluene relative permittivity is 2.61, conductivity is 10e-12. Since the thickness of the insulating layer is small relative to its length, the cross-section of the capacitor dielectric layer can be thought of as being axially symmetrical so as to establish its two-dimensional model, as shown in Fig.1. The model consists of a film, an oil medium, aluminum foil with a thickness of 6 μm on the upper and lower layers as a boundary, a 400 μm long film as a medium, a lower electrode potential of 0 and a voltage applied to the upper electrode. The simulation results of the non-defect surge capacitor model are shown in Fig.1.

![Non-defect surge capacitor electric field distribution.](image)
3. Simulation results of typical defects

3.1. Internal defects
Regardless of the space charge inside the defect, when the internal defect with a length, width and height of 10μm * 10μm * 15μm is located in the polypropylene film close to the low voltage electrode and the capacitor is loaded with the rated voltage 6000V in the normal working area, the electric field distribution of the impulse capacitor is shown in Fig.2.

In the non-defect area, the electric field is evenly distributed. The electric field intensity is slightly larger than the rated working field strength of 0.2kV/μm, and the electric field distribution in the defect area changes. The electric field strength of the air gap defects on the contact surface of the two layers change to the direction of high potential direction and low potential direction. It can be observed from Fig.2. (a) that the internal field strength at the air gap defect interface exceeds the rated working field strength of 0.2kV/μm, and the corner point distortion is the most serious with the maximum field strength value reaching more than 4 times. The distortions of the electric field is affected by the quality of the finite element meshes, especially in the local areas such as corner points. Therefore, the range of the electric field intensity is narrowed down to reflect the range of the electric field intensity. The local electric field distribution is shown in Fig.2. (b). The field strength of the polypropylene film at the interface of the air gap defect is obviously less than the rated working field strength of 0.2kV/μm. The reason for the change in the electric field strength at the interface between different media is that the conductivity of the polypropylene film (10e-17S/m) is much larger than the air conductivity.

Regardless of the space charge in the defect, under the applied voltage of 6000V and the peak voltage of 20% Un, the electric field intensity distribution of the air gap defect capacitor core cross section is shown in Fig.3. The results show that the maximum field strength of the discharge zone is still located at the defect corner of the polypropylene film contact surface and its air gap defects, the maximum field strength is about 1.22 kV/μm, the local effective field strength is about 0.9 kV/μm, which is 1 ~ 1.4 times of the field strength of DC gap defects.

The breakdown strength of benzyl toluene impregnant is above 24 V/μm, considering the impulse coefficient of 2.5\(^6\), the breakdown field strength of benzyl toluene impregnant is 0.06 kV/μm, obviously 10μm internal air gap defects under the discharge area field strength greatly exceeded the breakdown strength, which will cause the impulse of capacitors in the impulse of oscillation partial discharge.

(a) Local electric field distribution.  (b) Local effective electric field distribution.

Figure 2. Distribution of air gap defects in the capacitor of normal working area.
Considering the space charge in the defect, the body charge density of the internal defect with the size of 10μm * 10μm * 15μm is 3333C/m³ when the capacitor is in the impulse oscillation region, that is, the charge is 5pC. Surge capacitor air gap defect electric field distribution is shown in Fig.4. The electric field strength of the defect under the air gap defect is relatively high, decreasing towards the defect center.

3.2. Contact defects

Normal working area and oscillation area aluminum foil electrode burr field strength distributions are shown in Fig.5 (a) and Fig.5 (b) below. The glitch spikes form a pin-plate electrode with the film to increase the local electric field strength. The maximum electric field in the simulation model can reach about 0.27 kV/μm and 1.18 kV/μm, respectively, which exceed the breakdown field strength of benzyl toluene impregnation liquid of 0.06 kV/μm, which seriously damages the electrical insulation properties of capacitors.

Figure 3. Distribution of electric field of air gap defects in the capacitor of shock oscillation area.

Figure 4. The impulse of oscillation region Capacitor internal air gap defects by the space charge of the electric field.

Figure 5. Aluminum foil electrode burrs on the electric field.
Under the condition of a peak inverse voltage of 20%U at the oscillation region, the maximum local field strength at the non-end region reaches about 0.1 kV/μm, as shown in Fig. 6 (a). The breakdown field strength exceeds the impregnating agent which is 0.06 kV/μm. When the lead oxide defect region is located at the end of the aluminum foil electrode, the maximum local field strength can reach about 0.98 kV/μm as shown in Fig. 6 (b).

Figure 6. Lead oxide defects on the electric field.

3.3. Overlapping defects
The upper polypropylene film is folded, irrespective of whether the folded and extended portions are squeezed, to obtain the electric field distribution as shown in Fig. 7. Although the strength of the electric field is reduced due to thickening of the media, the electric field strength at the corner is slightly greater than the electric field strength of the flat polypropylene film portion, far greater than the electric field strength in the overlap portion.

Figure 7. Overlapping defect electric field distribution.

3.4. Oil defects
A bubble of 10 μm in diameter was arranged 80 μm from the side of the polypropylene film. As shown in Fig. 8 (a), the electric field distribution of capacitor in shock oscillation region is very small, which has little effect on the whole electric field distribution and narrows the display range of electric field intensity. As shown in Fig. 8 (b). The maximum field strength of about 31V/μm, less than the impregnation field breakdown strength of 0.06 kV/μm.
4. Conclusion

1) The existence of space charge affects the electric field distribution inside the defect of Surge capacitor and increases the electric field strength inside the defect so that the partial discharge is easier to occur and harms the insulation performance of the capacitor.

2) Under the condition of the foil electrode burr, the maximum electric field strength of the capacitor in the normal working area and the oscillation area is far greater than the breakdown strength of the impregnating oil, which brings harm to the insulation. However, under the condition of copper lead oxide defect, the maximum electric field strength of the capacitor is only slightly larger than the breakdown strength of the impregnant in the oscillation region. The damage of foil electrode burr is more serious than the copper lead oxide defect.

3) Film folding on the one hand increased the thickness of the medium will reduce the field strength, on the other hand increased the corner point, an increase of electric field distortion.

4) No matter the bubbles or blisters existed in the oil, when they are not in direct contact with the electrode or the medium, the internal field strength is less than the breakdown field strength of the impregnating agent, and the impulse on the overall electric field distribution is very small.

Acknowledgments
This work was financially supported by the SGCC project 521999160013.

References
[1] Dandan Zhang, Zonggan Yao. Edge Electric Field Calculation and Analysis of Pulsed Capacitor during Discharge[J]. High Voltage Technology, 1995(4):14-16.
[2] Xueqin Zhang. Study on Insulation Failure Mechanism and Testing Technology of High Voltage Storage Capacitor[D]. Southwest Jiaotong University, 2007.
[3] Wen Shu. Signal Analysis of DC Partial Discharge in High Voltage Storage Capacitor Based on Delta (t) Method[D]. Southwest Jiaotong University, 2006.
[4] Xueqin Zhang, Guangning Wu, Xiaohua Li, et al. Effect of Typical Defects on Electric Field Distribution in High Voltage Storage Capacitors[J]. Journal of Southwest Jiaotong University, 2008, 43 (1): 14-18.
[5] Wen Shu, Guangning Wu, Xueqin Zhang. Research on Defect Type Identification of High Voltage Storage Capacitors [C]/ National Engineering Dielectric Conference. 2005.
[6] Dandan Zhang, Zongqian Yao. Electric Field Calculation and Breakdown Analysis of a Simplified Model of Impulse Capacitor [J]. Power Capacitor and Reactive Power Compensation, 1995 (2): 1-9.