Summary of Research on Causes and Aging Mechanisms of Insulation Defects of Power Capacitors

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Abstract. As an important operation equipment in the power system, power capacitors mainly play the role of reactive power compensation, AC/DC filtering and so on. This paper describes the structure and insulation materials of power capacitors and analyses its typical defects. The research status of insulation aging mechanism of power capacitors, including electrical aging, thermal aging, space charge aging, etc., is summarized. Then, recommendations of the research direction of insulation aging mechanism are provided, and some suggestions on the production process of power capacitors are given.

1. Introduction

With the development of power systems, capacitors ("capacitors" used herein are all referred to as "power capacitors") are widely applied. In the AC system, capacitors are mainly used for reactive power compensation, and have both a filtering function in series with inductors [1]; in the DC transmission system, it is one of the main devices of DC field filter for filtering harmonics [2]; in electrical equipment, it is often used as pulse or energy storage capacitors, of which the former is commonly used to generate pulse power or impulse voltage [3], and the latter, also known as super-capacitors, is used to store electric field energy [4]. Therefore the safe operation of capacitors is directly related to the reliability of power systems. However, in recent years, capacitor failures caused by insulation aging have frequently occurred [5, 6], which has been given widespread concern by scholars in the world.

Capacitors are typically housed in enclosures and designed to be maintenance-free. It consists of electrodes, dielectrics, impregnating solution, discharge resistance, bushing and shell, of which electrodes are generally 6 μm self-heating annealed aluminum foil and separated by dielectrics and impregnating agents, and then wound into a multi-winding structure. The electrical connection wire is welded on the electrode to be a terminal, which constitutes a capacitor unit. Several units are connected in series and parallel to form the capacitor body. Dielectrics are used to isolate electrodes in capacitors. Its materials usually need to have high insulation strength, dielectric constant and low dielectric loss. Early capacitor dielectric materials used insulating paper, and currently used membrane (polypropylene film)-paper (insulation paper) structure, and even some capacitors adopt full-film dielectric. Since polypropylene film was used in capacitors in 1960s, it has been widely used because of its low loss and...
high dielectric constant. The thickness of polypropylene film is only about 10 μm, which greatly reduces
the capacitor volume per unit capacity.

In the production process, capacitors will inevitably produce some defects, such as mixing impurities,
lead sheet welding burrs, etc. [7]. During the long-term operation, capacitor defects will gradually grow,
resulting in aging of capacitor insulation medium, dielectric breakdown, capacitor explosion and other
accidents. This paper firstly analyzed the typical types of defects of capacitors and their causes. On this
basis, the possible causes of capacitor aging were analyzed and the existing research results of capacitor
insulation aging mechanism was sorted out. Then, the improvement measures for improving capacitor
insulation life and the research direction of insulation aging mechanism were obtained.

2. Causes of Typical Defects in Capacitors

Due to the limitation of current production technology, capacitors will have small defects in the
production process. The existence of these defects has little effect on the external characteristics of
capacitors, nor does it affect the factory test of capacitors. However, these defects will become internal
hidden dangers in the long-term operation process, with the development and expansion of the defects,
they may eventually lead to more serious consequences. Therefore, it is necessary to analyze the types
and causes of the defects that may occur in the production process of capacitors. The typical defects of
capacitors include overlapping defects, internal defects, oil defects and contact defects.

2.1. Overlapping defects

Capacitors are made up of many capacitor units, a single unit is made of aluminum foil and film
dielectrics by winding. The unreasonable production process of dielectrics and capacitor units will lead
to overlapping defects. From the point of view of medium production, the defect of medium production
process will lead to the uneven thickness of dielectric film; from the point of view of capacitor unit
production, when the parallelism of each axis of winding machine tool is poor, the position of winding
arm is inappropriate, or when the setting of winding pressure is unreasonable, the pressure of each axis
of machine tool is inconsistent, or the vibration of machine tool occurs in the production process, all of
these will form insulation folds in capacitor units, resulting in overlapping defects.

2.2. Internal defects

Internal defect is the most common and unavoidable defect in capacitor production. The main reason is
that the tensile force of polypropylene film is not uniform in the production process, so that there are
minor defects on the film or air gap between the film due to the wrinkle of the film.

2.3. Oil quality defects

In the production process of capacitors, vacuum impregnation is needed to make the impregnating agent
fully impregnated into the capacitor unit. There are three main reasons for oil defect. First, impregnating
vacuum cleaning treatment is not enough, which easily leads to impregnating agent itself mixed with
impurities; Second, the impregnation process is not high vacuum or impregnation time did not meet the
requirements, resulting in the impregnation agent containing bubbles; Third, insulation aging occurs in
the process of use, partial discharge leads to the decomposition of insulating medium and the generation
of gas, which leads to deterioration of the insulation performance of impregnating agent.

2.4. Contact defects

Capacitors are made up of many capacitor units, each capacitor unit electrode is connected with other
units through the lead sheet and generally require the lead strip to be flat and burr-free. At present,
capacitor unit electrodes are mostly aluminum foil or metallized film. The contact area between
capacitor unit electrodes and lead wire is very small. When the current is too high, it is easy to cause the
contact burning. Contact defects of capacitors are mainly caused by burrs on the edge of lead sheets or
oxidation of lead sheets and electrodes, resulting in poor contact.
3. Study on Aging Mechanism of Capacitor Insulation

3.1. Electrical aging
Due to the limitation of production technology, small defects will occur in the production process of capacitors. Under the action of electric field during the operation of capacitors, partial discharge may occur in these small defects. Reference [8] studied the distribution of electric field in capacitors with various typical defects. The finite element simulation shows that the electric field in capacitors will produce electric field distortion at the defects, and the local electric field strength will be enhanced, which will lead to more serious partial discharge. In addition, there are two main mechanisms of partial discharge damage to insulation: one is the chemical aging caused by partial discharge, such as the decomposition of impregnating agent, the decomposition of macro-molecule polymers, and the other is the bombardment of dielectric by charged particles produced by partial discharge [9]. The gradual development of partial discharge in micro-defects will lead to the gradual expansion of defects or more insulation defects, which will lead to the early insulation failure of capacitors.

In 1983, V. Krishnan, an Indian scholar, showed that the severity of partial discharge was closely related to the aging degree of polypropylene dielectrics and with the development of partial discharge, the insulation strength of polypropylene dielectrics decreased gradually, the conductivity of dielectrics around the discharge site changed accordingly [10]. Particle impact and precipitation of decomposition products caused by partial discharge can also change the surface morphology of insulating media [11]. The research team of Professor Wu Guangning of Southwest Jiaotong University in China carried out accelerated electrical aging test on pulse capacitors. During the test, the capacitors were detected by partial discharge, and the relationship curves between the parameters of partial discharge (maximum discharge, average discharge and discharge repetition rate) and the aging degree were obtained. The surface micro-morphology of capacitors in different aging stages was studied by electron microscopy. Through observation and analysis, it is pointed out that the main cause of capacitor failure is the local insulation defect in the edge area of the electrode [12]. Reference [13] builds an aging test platform for pulse capacitors, designs a testing system based on DC partial discharge, and obtains the statistical characteristics of partial discharge in different aging stages. The characteristics of partial discharge under different typical defects are different, which can be used as a basis for judging the type of partial discharge. Reference [14] analyzed the partial discharge in air gap, surface and corona discharge models under DC, compared the discharge pulse waveforms of the three models with different stages of DC voltage application, and analyzed the difference of partial discharge characteristics in different stages of DC voltage application from the perspective of discharge mechanism. Meanwhile, French scholar R. Hammal discussed the characteristics of AC partial discharge in capacitors with different typical defects, and analyzed the partial discharge patterns under different typical defects [15]. He also pointed out that the development of partial discharge can be divided into two stages: one is the small amplitude negative polarity discharge in liquid phase; the other is the discharge in bubbles with both positive and negative polarity.

3.2. Thermal aging
Under the action of heat, the ageing process of dielectrics will accelerate, and the thermal ageing may lead to the thermal melting of dielectrics and the decrease of dielectrics quality macroscopically; from a microscopic point of view, the molecular weight of the polymer will decrease, and the crystal structure will change, resulting in the decrease of the degree of crosslinking. When partial discharge occurs in dielectrics, the energy released by the discharge will lead to the increase of local temperature, thus accelerating the thermal aging of dielectrics.

When capacitor insulation medium is in high temperature environment, its mechanical properties and volume will change with temperature. For metallized film capacitors, due to the different thermal expansion coefficients of dielectrics and metal films, stress will occur during thermal aging, which will affect the structure of metallized film. Even when the temperature returns to normal, the stress caused
by different thermal expansion coefficients still exists and may lead to defects in the medium, thus increasing the dielectric loss.

There are many models for judging the thermal aging rate of medium. Because capacitor is an energy storage element, its breakdown process is equivalent to a chemical reaction. According to Arrhenius rule [16], the aging rate can be expressed by formula (1):

\[ v = v_c \exp \left( -\frac{E}{kT} \right) \]  

(1)

Among them, \( v_c \) is Arrhenius coefficient, \( k \) is Planck constant, \( E \) is activation energy, \( T \) is absolute temperature.

In reference [17], another model for evaluating the aging state of capacitors is proposed, which combines the effects of electrical aging and thermal aging:

\[ \tau_s = \tau_R \cdot F \cdot 2^{\frac{T_R - T_A}{T_A}} \]  

(2)

Among them, \( \tau_s \) is the service life of the equipment, \( F \) is the electrical aging factor, \( TR \) is the environmental temperature, and \( TA \) is the rated environmental temperature of the equipment.

3.3. Space charge

Insulating materials can be divided into many units with the same structure from the microscopic point of view. Each unit should be electrically neutral. However, in some cases, the positive and negative charges in the cell cannot cancel each other out, and the remaining charges are called space charges [18]. Under the action of electric field, there are three main sources of space charge:

1) Thermal ionization of impurities means that certain catalysts and antioxidants will be added in the production process of insulating media, and these additives will become impurities [19]. Then, the thermal ionization of impurity molecule will produce positive and negative charges, which will move towards heteropolar electrodes under the action of electric field. During the movement, some charges will be trapped by traps in the medium, forming space charges.

2) Interfacial polarization means that there are many interfaces in the dielectric. Interfacial polarization will lead to the accumulation of charges at the interface, and then space charge will be formed.

3) Charge injection is due to Schottky effect and Pull-Frank effect. When the electric field intensity reaches a certain value, the charge will be injected into the insulating medium from the electrode, thus forming space charge [20].

Under different electric field intensities, the proportions of the above three methods for generating space charge are also different. Ionization of impurities dominates when the field strength is low, and charge injection dominates when the field strength is high [21]. Reference [22] shows that not only charge injection but also space charge detachment has a direct impact on dielectric breakdown.

During the operation of capacitors, space charge will exist on the surface and inside of dielectrics. The accumulation of space charge will lead to the distortion of the internal space electric field, which may rise to 8-10 times of the external electric field [23]. With the aging of capacitors, the performance of insulating media decreases gradually, and the number of traps also increases gradually. The traps caused by molecular relaxation will intensify, so the phenomenon of space charge trapping and trapping in capacitors becomes more frequent. In addition, reference [23] points out that the trapping and detachment of space charge will produce energetic particles and rays, which will lead to the decomposition of polymers and the formation of micro-holes in the medium. Therefore, the existence of space charge is one of the main reasons for aging and breakdown of polymer insulation.
3.4. Other causes of aging
In addition to the above three main aging reasons, recent studies have shown that there are other factors leading to aging of capacitors. Among them, reference [25] has studied the effect of the absence of antioxidants on the thermal stability of power capacitors using recycled insulating oil. The results show that the absence of antioxidants in recycled oil is the main factor causing abnormal increase of capacitor loss and thermal instability. In reference [26], the influence of mechanical stress on partial discharge characteristics of capacitor dielectrics was studied. The results show that the effect of mechanical stress can lead to the increase of micro pore in polypropylene film dielectrics and the breakage of molecular chains. The electric field in dielectrics is seriously distorted, which leads to the deterioration of DC partial discharge performance. In reference [27], the changes of equivalent impedance (ESR) of metal oxide film capacitors with different geometric shapes (long, short and disc) before and after aging were studied. The results show that the longer the shape of capacitors, the faster the aging speed.

4. Analysis and expectation
Firstly, this paper analyses several typical defects that may occur in the production process of power capacitors, and analyses various factors that will lead to insulation aging of capacitors in the operation process. Through the analysis of this paper, the following suggestions can be made for the insulation design in the future capacitor production process:

1. From the point of view of reducing partial discharge, the production process control of dielectric film should be strengthened, and the insulation film should be as uniform and defect-free as possible; In the process of winding capacitor units, the technological level should be improved to reduce the wrinkles caused by the uneven force on the membrane; In the impregnation process of capacitor unit, the purity, impregnation time and vacuum of impregnating agent should be guaranteed, and the impurities and bubbles in impregnating agent should be reduced.

2. From the point of view of enhancing heat dissipation of capacitors, impregnating agents with good thermal conductivity should be selected for capacitors, which can quickly transmit heat generated during operation to the outer shell to avoid local overheating of units and thermal breakdown.

3. In order to reduce the influence of space charge, capacitors should choose metal electrodes with high escape work as far as possible to reduce the number of charges entering the medium from the electrodes.

4. From the point of view of mechanical structure, the edge of the electrode should be wrapped to ensure that there is no metal wire drawing at the edge of the electrode and to reduce the defect of the edge of the electrode of the capacitor; the core of the capacitor should avoid excessive stretching of the medium and excessive loosening of the medium material to ensure the electrical strength of the medium.

From the analysis in this paper, it can be seen that the current analysis of the aging mechanism of capacitor insulation only focuses on the single aging factor. But the aging of capacitor insulation is the result of multi-aging factors. In the aging process, various aging factors interact with each other and promote each other, leading to insulation aging and breakdown together. At present, the aging test environment of capacitor insulation often can’t reflect the actual working conditions of insulating medium, and the data obtained are also far from the actual operation data. Therefore, in the next step, it is necessary to further study the aging mechanism of capacitor insulation under the combined action of various aging factors.

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