Effect of the Geometry on the Aging of Metalized Polypropylene Film Capacitors

M.H. EL-HUSSEINI*, P. VENET*, G. ROJAT*, M. FATHALLAH**

*CEGELY-UCBL UMR-CNRS 5005
43, Bd du 11 novembre 1918
69621 Villeurbanne Cedex
FRANCE

**CEGELY-INSA UMR-CNRS 5005
20 Avenue Albert Einstein
69621 Villeurbanne Cedex
FRANCE

Abstract—Aging of MPPF capacitors have been studied in this paper with the aim to improve their reliability regarding their design. The statistical approach showed that the failure mode may be represented by two parameter Weibull distribution and the experimental approach proved that long capacitor deteriorates faster than a plate-shaped having the same features.

I. INTRODUCTION

A basic feature of an electrical system is to perform its function as economically as possible and with an acceptable degree of reliability and quality. System reliability depends on the reliability of each single part and component. Conditions of components will directly affect system conditions with respect to adequacy and security. In general, capacitor units play an important role in power system operation due to their relatively large number. It is therefore important to investigate and analyze their failure modes, reliability level, failure causes and mechanisms, not only from the user perspective, but also from the manufacturing point of view.

The Metalized Polypropylene Film (MPPF) capacitors have been produced for more than 40 years and new developments still take place. They are used in the industry due to their cheap production cost and good reliability. Due to their superior performance they have largely replaced the old impregnated paper capacitors for the power electronic applications in low and medium voltage range [1, 2]. The self healing property of MPPF capacitors results in reduction in capacitance and an increase in the Equivalent Series Resistance (ESR) with aging. With a view to establish the service reliability of MPPF capacitors, long-term aging tests have been performed in the author’s laboratory. For the estimation of the lifetime of a component in a relatively short period of time, is faced with fulfilling two opposing requirements: increasing the stress without changing the aging mechanism [2].

As a first step, the results obtained from an accelerated aging test were statistically analyzed with the aim of constructing a mathematical model for general analysis purposes. The collected data is used for evaluating the capacitors failure mode and the failure rate concerning a given and restricted type of MPPF capacitors.

Additional accelerated aging tests with various stress levels have been performed for capacitors of different manufacturing construction shapes. Failure mechanisms and causes of composite dielectric failures are also analyzed in this paper. The approach taken here is to concentrate on certain phenomena about which information is required. Our objective is to make a choice among capacitors having different geometry but similar electrical characteristics. The results are enhanced with optical and scanning electron microscopy of the tested elements.

II. CONSTRUCTION OF MPPF CAPACITORS

MPPF capacitors are made of two polypropylene films coated with zinc or aluminum of few nanometer’s thickness. A margin of non-coated film is left as shown in Fig. 1 to prevent short-circuits. The metalized films are either wound in a rolled cylinder or flattened to form a stocked block construction. In this construction the metalized films are displaced so that one extends out at one end of the roll and the next layer extends out of the other end as shown in Fig. 1.
The displaced layer construction is termed extended metalization and facilitates electrical contact with the electrodes. A hot metal (usually zinc) spray technique, called scooping, is used for making electrical contact to the extended edges of the metalized plastic winding. Some manufacturers reinforce the extended metalization which may result in a better attachment with the sprayed-end.

III. EXPERIMENTAL AND STATISTICAL APPROACH

In this part, a statistical study proved that the failure mode of MPPF capacitors may be represented by two parameters Weibull distribution. The study is performed for a random chosen set of MPPF capacitors.

A. Failure Model

Both manufacturers and users anticipate that a capacitor will have a life cycle similar to that described by Fig. 2. Accelerated life testing has shown that capacitor dielectrics containing paper and/or plastic do have a bathtub curved failure rate. The like cycle has three distinct regions or three failure modes as shown in Fig. 2.

1) Early failures: these occur during first year of energization. This failure region is associated with inherent defects which are usually the result of inconsistencies in the manufacturing process and poor materials.

2) Random failures: are not associated with any specific failure pattern and is not predictable for a large portion of the capacitor life. They are produced by chance or operating conditions such as a failure from switching surges or lightning. This failure mode is usually present at very low percentages.

3) Wear-out failures: this type is the result of dielectric material wear-out due to the effect of temperature and electrical stress and causes a general degradation of the dielectric system. Naturally, the wear-out mode becomes predominant after 20 years of operation for the most common capacitor.

Model elements of actual MPPF capacitors, each 9μF and rated voltage V₀ = 250V were considered for the study. The thickness of the PP film was 4μm. Set of 10 elements were aged at 1.3V₀ under 80°C for total period of 2000 hours.

Selection of properties related to aging and their end point is of fundamental importance to the life estimation of MPPF capacitors. In this study, we consider the reduction in capacitance as the criterion of aging. Even though identically processed elements were aged under similar conditions, the change in capacitance was not the same for all as illustrated in Fig. 3. The need for statistical treatment for analysis of data is evident.

Different mathematical models can be used to simulate different failure modes. Obviously, we are most interested in the random failure mode. One important methodology is to find a probability function that can represent the life time t in the random failure period.

In this study, Five percent of reduction in capacitance have been examined as end point criterion for failure. The analysis is based on the assumption that the time to reach the end point follows a two parameters Weibull distribution.

If element fail according to a Weibull distribution, the probability that any simple element will fail at a particular time t is given by

\[ F(t) = 1 - \exp \left( -\frac{t}{a} \right)^b \]

where a is called the scale parameter, b is called the shape parameter and F is the cumulative distribution function.

The parameters a and b can be estimated from the data.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Component failure rate as a function of life time.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3.png}
\caption{Decrease of capacitance for 10 capacitors aged for 2000 hours.}
\end{figure}
Equation (1) can be written as a linear relationship, as in

\[ Y = bX - A \]  \hspace{1cm} (2)

where \[ Y = \ln \ln \left( \frac{1}{1 - F(t)} \right) \] ; \[ X = \ln t \] and \[ A = b \ln a \].

Fig. 4 shown a remarkable linearity for Weibull life data indicating that they are well represented by an underlying Weibull distribution. From Fig. 4, the distribution parameters a and b can be estimated, then we can hypothesize the theoretical probability function of life time t for different failed capacitors. As an example, the distribution parameters a and b can be estimated as follows: \( b = 25 \) and \( a = \exp(A/b) = 1636 \). Then, the theoretical probability function of lifetime t has the form

\[ F(t) = 1 - \exp \left( -\frac{t^{25}}{1636} \right) \]  \hspace{1cm} (3)

IV. EXPERIMENTAL AND PHYSICAL APPROACH

Component aging is viewed as the sum of all the processes which result in changes over time. For capacitor, aging is often considered as negative, characterized by a degradation of physical properties under service conditions that eventually leads to failure. However, in many cases, initial thermal and voltage treatments of capacitors are performed to stabilize the dielectric system and are considered as an example of desirable aging. In the basic design, the rolls are wound as tightly as possible in order to prevent the formation of air voids.

In this section we examine the effect of the geometry on the aging and the deterioration process of the MPPF capacitors. For this purpose, sets of 5 elements of three series are exposed to an accelerated aging test. The elements are of 10 \( \mu \)F capacitance value and have the same electrical and morphological characteristics as well as a similar initial thermal and voltage treatments.

Table 1 shows the common electrical characteristics and the difference in the geometrical design of the tested capacitors.

Fig. 5 is a general real view of a single element taken from each series. The stress conditions are set to be 400V and 85°C for 2250 hours.

Fig. 6 shows the decrease in capacitance for the average of 5 elements of the three series. We notice an important drop in the capacitance of about 20 %. Fig. 7 shows an increase of the ESR for the 3 series with a tendency to be accentuated at higher frequencies. We notice a higher increase in the ESR for the long tested capacitor. After the aging test, the capacitors were unwound for physical examination of the film.

The profile projector picture of aged films shows clear and permanent marks of evaporation and edge recession due to aging. Fig. 8-a and b shows a scanning electron pictomicrograph of a clearing in the film. We notice small punctured sites in the polypropylene film at the center of the clearing area surrounded by the demetalized region. This clearing phenomenon is common to all MPPF capacitors regardless of the geometry of the element.

![Fig. 4. Weibull probability plot for the life time t.](image-url)

![Fig. 5. A general real view of the tested components.](image-url)
A Self-Healing Mechanism in MPPF Capacitors

Capacitor dielectrics for wound capacitors are thin, ranging from few microns to a few hundred microns. In a large capacitor, this results in a very large surface area. One major drawback of foil electrode capacitors is that the capacitor will fail if any part of the dielectric breaks down. When a foil capacitor suffers a dielectric breakdown, the electrodes become connected through a low impedance connection at the point where the fault occurred. At this point, the part of the capacitor where the fault occurred is normally a short circuit and unable to accept a charge.

This problem does not exist for the self-healing metalized electrode capacitors. With a self clearing electrode, a fault in the dielectric will result in the thin metalized electrode in the immediate area of the fault being vaporized or turned from a metal conductor into a metal oxide insulator.

If a fault should occur in the dielectric as shown in Fig. 9, the current will flow from one end sprayed connection, through one electrode, through the fault, to the opposite electrode and to the opposite end sprayed termination.

The current in the area of the fault will be trying to go through a metal conductor that is so thin that it is optically translucent. The amount of current that can go through this thin electrode is very limited. The electrode in the immediate neighborhood of the fault will be blown away; acting much like a fuse, and the current will be safely interrupted. Once the fault has been cleared, as shown in Fig. 10, the capacitor will continue to function with the only measurable damage being a small loss of capacitance [1].
B. Effect of the Geometry

However, the clearing process depends on the applied voltage, the thickness of the electrodes and the mechanical pressure on the individual capacitor layers. In our study, the applied voltage, the temperature and the electrodes' thickness are similar for the tested elements. However, in a cylindrical roll design, it is difficult to maintain a fixed mechanical pressure. Results showed that clearing energy was strongly dependent upon the applied pressure and it has been noticed that the clearings in the outer turns are typically 2 to 10 times larger than those in the interior [4, 5]. Figure 11 shows photos of a metalized film of a plate-shaped capacitor. Fig. 11a, 11b and 11c show photos of the film from outer layers, middle layers and interior layers respectively. A non tested metalized film is shown in Fig. 11d for comparison. From Fig. 11 one can observe that outer layers undergo more damage compared to the inner layers. In addition to the explanation given above about the role of the mechanical pressure on the clearing process, we made the assumption that the outer layers, due to their relatively low mechanical pressure, are favorable to house air and other gaseous molecules which are a weak dielectric structures and therefore are more favorable for a clearing.

Fig. 11. Photos of an aged film selected from different layers (a, b & c), and a non-aged one for comparison (d).

Clearing phenomena is emphasized with the high temperature of the test. Knowing that the outer surface area of a long capacitor is greater than one of a plate capacitor, it is logical to think that a long capacitor degrades more. This explain, in part, the higher increase in its ESR.

C. Burning-out Process of MPPF Capacitors

In order to establish a clear concept about the end life of the MPPF capacitors, tests were carried out with very high electrical
stresses. Set of 3 series of MPPF capacitors with different geometric shape were stressed with 480V under 85°C. 3 of the 9 tested elements burned-out in a short-circuit process with melting of the polypropylene and expulsion of gas. Fig. 12 shows one of these elements.

On the other hand, it can be said that the expulsion of the gas was strong and the internal pressure that built up inside the roll might have pulled the sprayed-end thus ending the melting process as shown in Fig. 13. More investigation with tested elements is needed in order to understand the effect of the geometry on the burn-out process of MPPF capacitors. However, in the light of earlier studies, one can say that the long capacitor burns out faster than a plate one because of its higher heating under the same electrical stress [6,7].

V. CONCLUSION

Aging of MPPF capacitors have been studied in this paper with the aim to improve their reliability regarding their design. Two approaches were employed: the statistical approach showed that the failure mode may be represented by two parameter Weibull distribution and the experimental approach proved that the long capacitor deteriorates faster than a plate-shaped having the same features. The results are enhanced with optical and scanning electron microscopy of the tested elements. More investigation is needed to find out the role of the geometry on the burning-out processes of the MPPF capacitors even though earlier studies proved that long capacitors undergo more heating under the same electrical stress, and therefore, are prone to the burning-out processes.

REFERENCES
