Lifetime investigation and prediction of metallized polypropylene film capacitors

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Abstract

Metalized polypropylene film capacitors (MPPFCs) possess characteristics of high reliabilities and high energy densities, so they are widely used in the pulse power systems. MPPFC prototypes with high voltage and large capacitance are composed of a number of cylindrical MPPFC elements connecting in series or in parallel. The experimental data show that the lifetime of MPPFC prototypes is far shorter than that of MPPFC elements under the same voltage stress.

This paper analyses operational factors that affect influence the lifetime of MPPFCs, and predicts the lifetime under various operational factors based on the experimental results. The relationship between MPPFC elements and MPPFC prototypes in terms of lifetime is presented with a reliability analysis of the Weibull distribution, and is validated through experiments. Finally this paper presents a lifetime prediction model. The results suggest that the predicted data could match well with experimental results.

This paper is devoted more to the lifetime analysis under various operational factors and less to theoretical physical analysis.

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1. Introduction

Metallized polypropylene film capacitors (MPPFCs) are made up of two polypropylene films coated with several tens of nanometers thick zinc or aluminium as electrodes [1–4], and possess characteristics of high reliabilities and high energy storage density (<3 kJ/L) for their self-healing capability and high breakdown strength (~700 V/μm at capacitor level) [2,3]. Thus they are widely used in pulse power systems. The self-healings result in the decrease of the metallized electrode area and hence a decline in capacitance. The MPPFC could be designed to age gracefully with a predictable lifetime. The definition of the lifetime of MPPFCs applied in pulsed systems is the number of shots at which the capacitance decreases by 5% below its initial value [4–6]. The lifetime is extremely sensitive to operational factors such as the voltage, current reversal, temperature, pulse repetition rate and so on [7–9]. Actually MPPFCs should be optimized to provide the designer with a well-defined level of reliability through the designed lifetime [10]. Such demand facilitates the researches of the lifetime characteristics of MPPFCs.

The MPPFC prototype applied in high-energy pulsed power systems is composed of a number of cylindrical MPPFC elements connecting in series or in parallel, and the typical construction is shown in Fig. 1. The elements are encapsulated with plastic or metal carapace. The series structure can achieve the output of the high voltage and the parallel structure can guarantee the large capacitance, thus the total stored energy of a MPPFC prototype can reach multikilojoule [1]. The number of the elements may reach several hundreds according to the specific parameter requirement from the customer. The lifetime characteristics are usually achieved by accelerating test of elements in order to save the expense and time [6]. But experimental data show that the lifetime of the prototype is half shorter than that of MPPEC element even under the same voltage across elements and other operational conditions. Thus it must be taken into considerations that there is a significant difference between the elements and prototypes. Therefore, there is an urgent demand of establishing the lifetime prediction model by using the accelerated experiment data.

Present researches on the lifetime concentrate on analyzing the data of the capacitance loss based on relevant probability and mathematical statistics models [6,8,11,12]. Accelerated tests are widely adopted to shorten test time [13,14]. This paper analyses the operational factors that influence the lifetime and presents the prediction model. And a prediction formula for elements and prototypes is put forward.

2. Lifetime characteristics of MPPFC

The MPPFCs do not fail short-circuit, but tend to lose capacitance. When a dielectric fault breakdown occurs, the high
current density around the breakdown site will immediately vaporize the metallization. Once the fault has been cleared, the capacitor will continue to function well with only a measurable small loss of capacitance [15–17]. Since every self-healing will only result in a small demetallized area, the capacitance loss in pulse shots is an accumulative result of the demetallized area. During the self-healing of a weak spot, there is a loss of energy in the capacitor. The energy called self-healing energy (\(W_s\)) in a capacitor can be expressed as follows [3,17,18],

\[ W_s \propto V^n C^q t^r \]  

where \(n, q\) are coefficients, \(V\) is the operating voltage, \(C\) is the capacitance of the tested capacitor, and \(t\) is the thickness of the metallized electrode. The self-healing energy determines the sizes of the vaporized area in the metallized electrodes. This graceful aging of MPPFCs can provide the designer with a well-defined lifetime. The increasing of the lifetime can be benefited from the improvement of the self-healing capability. Smaller self-healing energy guarantees smaller vaporized area, less capacitance loss and a longer lifetime [18].

2.1. Operational factors influencing the lifetime

There have been many studies on operational factors affecting the aging process in MPPFCs and the two dominating effects in regard to operational factors are thermal stress and the electric field [19]. Some simple lifetime prediction guidelines have been used by manufacturers to predict actual lifetime based on the already known operational factors: voltage or electric field, reversal, stressed area, and frequency [8]. The fact that the lifetime of the prototype is shorter than that of an element gives the designer some insight into the influence of element number (\(N\)) on the lifetime. Combined with the empirically derived lifetime prediction equations, the lifetime (\(L\)) under a given set of operational factors can be predicted as

\[ L/L_0 = f(U, T, N) \]  

where \(U\) is the applied voltage across the MPPFC element; \(T\) is the temperature; \(N\) is the number of elements; \(L_0\) is the lifetime of MPPFC at the referenced operational factors (\(U_0, T_0, N_0\)), and \(L\) is the lifetime at actual operational factors (\(U, T, N\)); \(f\) is a function to represent the influence of operational factors.

On the assumptions that the voltage, temperature and number of elements are independent variables and their impact of the on lifetime are independent events, Eq. (2) can be written as follows

\[ L/L_0 = k_0 k_1 k_2 \]  

where \(k_0, k_1, k_2\) are the lifetime acceleration factors influenced by the voltage, temperature and number of elements. It is important to point out that the above assumptions are an empirical hypothesis and is hard to prove by mathematically deduction.

The acceleration factors can be written as [8,13,20]

\[ k_0 = (U/U_0)^{-x} \]  

\[ k_1 = 2^{-((T-T_0)/\beta)} \]

where \(x\) and \(\beta\) are accelerating coefficients empirically derived based on numerous experimental data, and \(T_0 = 20^\circ\text{C}\). The effect of the higher voltage on lifetime mainly includes a higher probability of electrical breakdowns and greater self-healing energy. A typical value of \(x\) is 7.5 and it means that the lifetime decreases to half with every rise of the operating voltage by 10% [9,10]. For \(\beta = 8^\circ\text{C}\), the lifetime almost decreases to half with every rise of temperature by \(8^\circ\text{C}\) [7]. The increasing of temperature may accelerate the chemical processes of self-healings and lead to the weakening of the electric endurance [20]. Maybe other forms of functions are better to reflect the acceleration factors.

To the authors knowledge there have been no researches in the literature about the influence of the element number in series-parallel connection on the lifetime.

2.2. Reliability analysis based on Weibull distribution

During the lifetime test, it is a time-consuming work to get enough experimental lifetime data to characterize the performance of MPPFCs, so it is necessary to analyse the limited experimental data in effective ways. For some inertial confinement fusion devices, the capacitor acceptance test and lifetime analysis are based on the Weibull distribution [22,23]. Previous work has been done to analyze the Weibull distribution in the lifetime. The probability distribution function \(F(t)\) can be expressed as follows:

\[ F(t) = 1 - \exp[-(t/\eta)^m] \]

where \(m(>0)\) is the shape parameter, \(\eta(>0)\) is the scale parameter, and \(t\) is the number of shots. \(F(t)\) stands for the probability of the lifetime shorter than \(t\). The value \(\eta\) is the characteristic lifetime with a reliability of 63.2%.

By applying the maximum likelihood estimation, parameters \(m\) and \(\eta\) could be solved with reference to previous paper [6]. The lifetime expectancy (\(ET\)) of the MPPFC element is

\[ ET = \eta \Gamma(1 + 1/m) \]

where \(\Gamma\) is the Gamma function [6]. For prototypes, parallel connections mean larger capacitance and larger self-healing energy, so the capacitance loss increases according to Eq. (1). Moreover larger film areas cause the decrease of the average breakdown strength of the film [24]. Series connections give rise to the voltage-sharing issue. In the manufacturing process, all the elements in the prototype have almost the same capacitance. If one of many series-connected

\[ \text{A MPPFC element} \quad \text{Electrical schematic diagram} \quad \text{MPPFC prototype} \]

Fig. 1. The construction diagram of a MPPFC prototype.
elements in a high-voltage MPPFC loses significant capacitance due to random self-healings, a larger share of the applied voltage will appear across that element, which will tend to accelerate degradation of that element and lead to capacitance loss. As mentioned before, the lifetime is extremely sensitive to the voltage. Thus this positive feedback undoubtedly shortens the lifetime of the prototype.

The above issue can be ascribed to the reliability reduction phenomenon in prototypes. The lifetime of each element can be viewed as independent random events and they obey the same Weibull distribution. According to the probability multiplication formula, the probability distribution function of MPPFC prototype \( F_p(t) \) is

\[
F_p(t) = 1 - \left(1 - F_1\right)^N = 1 - \left(\exp\left[-(t/\eta)^m\right]\right)^N
\]

Let \( F_p(t) \) have a standard form of the Weibull distribution, \( F_p(t) \) can be expressed as

\[
F_p(t) = 1 - \exp\left[-N(t/\eta)^m\right] = 1 - \exp\left[-(t/\eta_p)^m\right]
\]

where \( \eta_p = N^{-1/m}\eta \). And the lifetime expectancy of prototype \( ET_p \) be calculated as

\[
ET_p = \eta_p \Gamma\left(1 + 1/m\right) = N^{-1/m}ET
\]

The result shows that the lifetime expectancy of the prototype would get a multiple of \( N^{-1/m} \) compared to the element under the same reliability. Fig. 2 gives the trends of the relative lifetime changing with the number of elements. It demonstrates that the lifetime expectancy would decrease dramatically with the increasing of \( N \) and the decreasing of \( m \). The number of elements in the prototype can reach several hundreds, thus the lifetime of the prototype may drop to less than half of the element. Therefore the acceleration factor \( k_N \) in Eq. (3) can be written as

\[
k_N = N^{-1/m}
\]

The reliability function and the probability density function of the prototype is shown in Fig. 3. It is assumed that the scale parameter \( \eta \) is 1, which means that MPPFC has a relative lifetime of 1 with a reliability of 63.2%. Fig. 3 demonstrates that the distributions tend to be more concentrated and MPPFCs have higher reliability with the increasing of the shape parameter. Besides, the lifetime of the prototype decreases but it becomes more concentrated with the increase of the number \( N \). The lifetime of the prototype enjoys relatively less dispersion than elements.

3. Lifetime experiments and results

3.1. Experiment setup for the lifetime test

Experiments are designed to investigate the lifetime of the MPPFC elements under different voltages. The lifetime test circuit for MPPFCs is shown in Fig. 4. The MPPFC is charged to the pre-set voltage through a constant current power supply (CCPS) and then discharged to the load (inductor \( L_f \)) through a thyristor \( K \) and a diode for free-wheeling current. While in prototypes, the output power of CCPS is 12 kW and \( K \) is a thyristor paralleled with a diode used for free-wheeling current. In order to guarantee a standard current form. The discharge current waveform is viewed as the unified test standard to characterize the lifetime of different MPPFCs. And the current has a reversal ratio of 10% and an oscillation period of 1000 \( \mu s \). For two elements in parallel (90 \( l \)) in the test, the output power of CCPS is 14.25 kW and \( K \) is a thyristor paralleled with a diode used for free-wheeling current. The typical waveforms of voltage and discharge current in test of element-1 are shown in Fig. 5. For other MPPFCs, \( R_f \) and \( L_f \) has a linear proportion by inversion with the capacitance in order to guarantee a standard current form.
The MPPFC elements and prototypes involved in experiments are shown in Table 1. All the elements in test have the same structure and are placed in a temperature chamber of 20°C. The structures of prototypes are shown in Table 2 and the capacitance and rated voltage are different. The voltage across the element in prototype-A, prototype-B and prototype-C is 3.125 kV, 4.167 kV and 6.0 kV respectively.

3.2. Lifetime of MPPFC elements

The Weibull distribution parameters of MPPFC elements are calculated in reference [6] and are shown in Table 3. In the table, the relative standard deviation is calculated from the statistical data of 20 samples and it represents the dispersion degree of the lifetime. The experimental results of elements and the fitting curves in terms of applied voltage according to Eq. (4) are shown in Fig. 6. As the applied voltage across the element increases, the shape parameter $m$ decreases, thus the lifetime drastically decreases and becomes relatively more dispersed. The dispersions can be ascribed to the inherent dispersion of the random capacitance loss during self-healings.

In Fig. 6, the fitted value of accelerating coefficient $a$ range from 7 to 12. However, the fitted curves could not really reflect the lifetime changing with the voltage. The actual fitted $a$ between two voltages in Table 3 may implicate that the accelerating coefficient increases significantly with higher voltage due to the nonlinear degradation mechanism in dielectric films [21]. It can be seen in Fig. 6 that Eq. (4) does not reflect the real trend, and a new fitting function is put forward as follows

$$k_U = (U/U_0)^{-AU}$$

(12)

where $A$ is a coefficient. The fitting curves of the lifetime in terms of applied voltage based on Eq. (12) are shown in Fig. 7. The results show that the fitting curve with $A = 0.00019/V$, gives a graceful fitting and matches well with experimental results.

3.3. Lifetime of MPPFC prototypes

For MPPFC prototypes in experiments, the capacitance loss changing with the number of shots is shown in Fig. 8. The temperature is the average value during the test. The lifetimes of prototype-A, prototype-B, prototype-C are 62700, 23200 and 554 shots respectively. The voltage across the element in prototype-C is the same with element-3#. The lifetime of prototype-C is 554 shots while the average lifetime of element-3# is 1340 shots. This phenomenon indicates that the lifetime of the prototype is far shorter than that of the element under the same voltage in the elements.

It takes a great expense and time to acquire the lifetime of the MPPFCs operating under low voltage. For example, as one minute is needed for a single shot, the test time for prototype-A is about 62700 min, which equals 85 days without interruptions during the daytime. In this sense, the lifetime prediction is of great significance to shorten the test time.

4. Discussion and prediction model

The lifetime prediction model can be presented based on different operational factors. The lifetime ($L$) under a given set of operational factors can be predicted by the formula

$$L/L_0 = \left( \frac{U}{U_0} \right)^{-AU} \left( \frac{N}{N_0} \right)^{-1/m} \cdot 2^{-\left(T - T_0\right)/f}$$

(13)
where $L_0$ is average experimental lifetime of MPPFC elements applied under voltage $U_0$; $m$ is the shape parameter of elements; $N$ is the number of elements in a prototype and $N_0$ is equal to 1 for the MPPFC element. This prediction model suggests that the lifetime of MPPFC can be predicted based on experimental results of elements. The larger number of samples in experiments guarantees a higher accuracy in predictions.

Table 4 lists the predicted lifetimes of prototypes based on different elements. The values of $k_U$, $k_T$, and $k_N$ are calculated respectively by Eqs. 12, 5, and 11. And $\beta$ is viewed as $8^\circ C$ in predictions [7]. The deviation in Table 4 is defined as the relative deviation (%) of prediction from experiment. The positive value means that the predicted lifetime is longer than that of the experiment. As shown in Table 4, for predictions based on the element-3#, the deviations of prototypes A and B are $-38.74\%$ and $-38.90\%$ respectively. It also can be seen in Table 4 that deviations of prototype C based on the element-1# and element-2# from experiments are $31.93\%$ and $55.13\%$ respectively and these deviations may be large. In fact, the accelerating degradation phenomenon exists in test of MPPFC element-3# and prototype C in which the element is applied under relatively high voltage. This undoubtedly shortens the lifetime. So the predictions of MPPFC prototype A and B based on element-3# are shorter than experiments, and the prediction of prototype C is longer than the experiment.

Moreover, the experimental lifetimes have certain dispersion even under the same conditions. As shown in Table 3, the relative standard deviations of element-1#, 2# and 3# in experiments are $10.10\%$, $15.59\%$ and $17.11\%$. These deviations can be ascribed to the inherent dispersion of the random capacitance loss resulted from self-healings in every shot. For the other predictions in Table 4, deviations range between $1.71\%$ and $22.7\%$ and these predictions are within the acceptable limit ($\pm30\%$) in the design.

Besides, the prediction model is more suitable for prediction of MPPFCs applied under relatively low voltage (lower than 5.7 kV) based on experimental results of elements applied under relatively low voltage.

For the user, the lifetime characteristics of a designed prototype applied under different voltages are of great importance. By Eq. (13), the predicted lifetime of the prototype in reference to element-1# can be obtained. If $U_0 = 5.4$ kV, Fig. 9 gives the lifetime prediction of the prototype with different voltages across the element based on element-1#. It can be seen in Fig. 9 that the predictions are consistent with the experiments and the predicted lifetime of MPPFC prototype C is longer than prototype A and prototype B. This can be caused by the fact that the number of

<table>
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<th>Referred element</th>
<th>Prediction of prototype</th>
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<td></td>
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<tr>
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elements in prototype C is relatively small and the small number weakens the impact on decreasing the lifetime.

For MPPFC prototypes, only lifetimes of elements should be acquired to give an overall evaluation of prototypes. The prediction method is indispensable for offering a guidance in MPPFC design, especially for the designed MPPFC with long lifetime.

5. Conclusions

This paper analyses the lifetime characteristics of MPPFC elements and prototypes. The following conclusions are achieved.

(1) The lifetime of MPPFCs is sensitive to operational factors such as voltage, temperature, the number of elements in the prototype and so on. The reliability analysis based on the Weibull distribution indicates that the lifetime of the prototype would decrease drastically with the increasing number of elements.

(2) A lifetime prediction model base on the accelerating test of elements is established. Empirically derived prediction formula is presented to predict the lifetime of MPPFCs under different operational factors. This prediction model is more suitable for prediction of MPPFC element or prototype applied under relatively low voltages.

Acknowledgement

This work was supported by the open Foundation of National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming and Guangzhou, China).

References
