Study on Self-Healing and Lifetime Characteristics of Metallized-Film Capacitor Under High Electric Field

Yaohong Chen, Hua Li, Fuchang Lin, Fei Lv, Miao Zhang, Zhiwei Li, and De Liu

Abstract—A high-energy-density capacitor is a key device in power supply source in an electromagnetic-gun system. In order to increase the reliability of the power source equipment, the lifetime of the capacitor must be extended. The increasing of the lifetime is mainly beneficial from the self-healing characteristic of the capacitor. First, this paper verifies the effects of sheet resistance ($R_s > 30 \, \Omega$) and pressure between layers on the self-healing characteristic through experiments. The experimental results show that the self-healing energy is approximately inversely proportional to the square of sheet resistance. When the sheet resistance is reasonable, the self-healing energy can be limited to less than 40 mJ. In addition, the self-healing energy decreases with the increase of the pressure. When the pressure is greater than 200 kPa, the self-healing energy can be limited to less than 10 mJ. Then, the effect of interlayer air on the discharge arc in the self-healing process is analyzed. Meanwhile, this paper presents that the lifetime of the capacitors can be extended through excluding or decreasing the interlayer air. At last, two methods are provided: wrap strengthening and impregnation in vacuum. The experimental results show that the lifetime of the capacitors can be extended up to 1.6 times and 4–5 times through these two methods, respectively.

Index Terms—Lifetime, metallized-film capacitor, pressure, self-healing, sheet resistance.

I. INTRODUCTION

A METALLIZED-FILM capacitor has a characteristic of self-healing, so it can work under relatively high electric field strength condition and enjoy high energy density [1]–[5]. In addition, it also has advantages of high output power, high available energy, and convenient control strategy, as well as low cost. All these features make pulsed-power capacitor as one of the most suitable energy storage elements in pulsed-power system. Moreover, it is widely used in nucleosynthesis, pulse-laser power supply, and electromagnetic-launch systems [6], [7].

Manuscript received January 17, 2012; revised April 17, 2012; accepted May 14, 2012. Date of publication June 20, 2012; date of current version August 7, 2012. This work was supported by the National Natural Science Foundation Youth Fund under Grant 50907028.

Y. Chen, H. Li, F. Lin, Z. Li, and D. Liu are with the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: cyhyhc1314@tom.com; leehua@mail.hust.edu.cn; fclin@mail.hust.edu.cn).

F. Lv is with the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China. He is now with the Shandong Electric Power Corporation, Jinan 250001, China.

M. Zhang is with the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China. He is now with the Bank of China, Wuhan 430074, China.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2012.2200699

II. CAPACITANCE LOSS MECHANISM OF MPPFCs

During the self-healing of a weak spot, there is a small amount of energy dissipation in the capacitor. The energy depends on the applied voltage, the capacitance, the sheet resistance of the electrodes, and the interlayer pressure on the individual capacitor layers. The self-healing energy ($W_s$) in a capacitor can be expressed as follows [8]:

$$W_s = \frac{k U^a C}{R_s^b} f(P) \quad (1)$$

where $k$, $a$, and $b$ are coefficients, $U$ is the operating voltage, $C$ is the capacitance of the tested capacitor, $R_s$ is the sheet resistance (in ohms per square) of the metallized film, and $f(P)$ is a function which relates the interlayer pressure to the self-healing energy. For the special capacitor which is applied under
For the MPPFCs which are applied under high electric field, if the sheet resistance is too small, the energy that flows through the breakdown channel is so large that the capacitor will soon be damaged, as shown in Fig. 1(a). So, if the MPPFCs are applied under high electric field, the sheet resistance is preferably larger than 30 $\Omega/\square$. In this case, the self-healing energy is small, and the self-healing morphology is as shown in Fig. 1(b).

MPPFCs are made up of two polypropylene films coated with zinc or aluminum of thickness of a few nanometers as its electrodes. The metallized films are wound in a rolled cylinder. The statistical capacitance loss of a dry-type MPPFC is shown in Fig. 2. The vertical axis indicates a capacitance loss ratio per unit area, and the horizontal axis represents the corresponding layer number ratio to the whole. As shown in Fig. 2, the capacitance loss ratio decreases with film layers progressing from the outside to the inside. Most of the capacitance loss occurs in the outer layers of the winding, according to the experimental results.

The resistance strain gauge was chosen to measure the interlayer pressure of MPPFCs [10]. When preparing to measure strain, paste the strain gauge to the mandrel along its stress orientation first. In order to obtain the radial pressure correctly, the sensitive gate of the strain gauge should be pasted to the mandrel along the winding direction of the film. The test results of the interlayer pressure in two capacitors are shown in Fig. 3. The vertical axis indicates the interlayer pressure, and the horizontal axis represents the corresponding layer number ratio to the whole. As shown in Fig. 3, the pressure between outer layers is smaller than that between the inner layers. Moreover, the pressure between the outer turns only changes in a small range; for the inner layers, the pressure increases gradually. The pressure brought up by the radial force has a significant effect on the self-healing. With the increasing of the pressure in the inner layers, the capacitance loss becomes less and less. The tendency of capacitance loss is considered to be associated with the interlayer pressure.

By the aforementioned analysis, without considering the differences in the quality of the dielectric films, the main factors affecting the lifetime performance of the MPPFCs can be summarized as two aspects: One is associated with the sheet resistance of the capacitor, and the other is associated with the interlayer pressure [10], both of which have a great impact on the lifetime of the capacitors applied in repeated pulsed discharge application.

### III. Experiment

The test circuit of self-healing in metallized films is shown in Fig. 4. In Fig. 4, $R_s = 1$ M$\Omega$, $C_0 = 0.1 \mu$F, and $C_s$ is the tested capacitor sample, which is made up of two metallized polypropylene films. All tested capacitor samples are selected at the same area (40 cm$^2$). The thickness of the polypropylene film is 7.5 $\mu$m. During the test, the charge rate is 200 V/s, and the tested capacitor is applied to several set pressures. The self-healing current ($i_s$) is measured through monitoring the voltage across the sampling resistance ($R_s$). At the same time, the voltage ($U_s$) across the tested capacitor is measured, so the self-healing process can be characterized by measuring the discharge current ($i_s$) and the voltage ($U_s$) during clearing events. The self-healing energy can be expressed as follows:

$$W_s = \int U_s i_s \, dt.$$  (2)
A. Sheet Resistance and Self-Healing

In order to study the relationship between the sheet resistance and self-healing characteristic, three kinds of metallized films are chosen for the self-healing tests. The sheet resistances of these metallized films are $R_0$, $1.5R_0$, and $2R_0$, respectively. To exclude the influence of other factors, the pressure applied on the tested capacitor is 3.2 kPa, and the operating voltage is 4 kV. The relationship between the sheet resistance and the self-healing energy is shown in Fig. 5. Each batch of data in Fig. 5 has a large divergence. The divergence may be related to the uniformity of deposited electrode. The thickness of deposited electrode is only a few nanometers. It is very difficult to keep the sheet resistance having a very small divergence. In general, the sheet resistance of metallized films is an average value. For example, if the sheet resistance is $R_0$, in fact, the sheet resistance is in the range about $0.75R_0 - 1.25R_0$.

Fig. 5 shows that the self-healing energy is inversely proportional to the square of sheet resistance, as shown in (3). The conclusion is consistent with Heywang and Kammermaier’s results in [11]–[13]. Moreover, they got the results through testing the metallized films with the sheet resistance smaller than 10 $\Omega/\square$. In this paper, all sheet resistances are larger than 30 $\Omega/\square$. As shown in Fig. 5, when the sheet resistance is large enough, the self-healing energy can be limited to less than 40 mJ at 3.2 kPa.

$$W_s \propto 1/R_s^2. \quad (3)$$

Kammermaier and Heywang have shown that the volume of metal evaporated (i.e., the product of the cleared area by the metallization thickness) is proportional to the dissipated energy during the discharge [12]–[14], as shown in

$$W_s \propto V = Sd \quad (4)$$

where $S$ is the clearing area and $d$ is the thickness of the electrode.

Fig. 6 shows the relationship between the clearing area and self-healing energy. It can be seen that, for any kind of sheet resistance, the self-healing energy is proportional to the clearing area.

By the aforementioned analysis, for the MPPFCs with high sheet resistance, the self-healing and clearing area are small, so the lifetime of the MPPFCs can be extended. However, too large sheet resistance means that the equivalent series resistance is large. This will lead to the fact that the heating of the electrode is serious, and the current-carrying capacity and output efficiency are limited [15], [16]. Thus, on the premise of meeting the current-carrying capacity and the heating requirements, the sheet resistance should be as large as possible.

B. Pressure and Self-Healing

For the self-healing of an MPPFC, the clearing area and self-healing energy are large in the outer layers, and the radial pressure between the layers is small, which is less than 1 MPa. In order to study the relationship between the pressure and the self-healing characteristic, some metallized films with sheet resistances $R_s = 1.5R_0$ are chosen for the self-healing tests. The pressure applied on the tested capacitor ranges from 0.5 kPa to 1 MPa. The relationship between the self-healing energy and pressure is shown in Fig. 7. The result indicates that the self-healing energy decreases with the increase of the pressure. When the pressure is 0.514 kPa, the self-healing energy is about 150 mJ; when the pressure is larger than 200 kPa, the self-healing energy can be limited to smaller than 10 mJ. Then, with the increasing of the pressure, the self-healing energy is maintained at a relatively small value.

By the aforementioned analysis, if the interlayer pressure between the outer layers of the MPPFC is much larger than 200 kPa, the self-healing energy will be limited to a small value.
so is the clearing area. However, too large pressure between the layers increases the risk of a short circuit, because the discharge energy is completely absorbed by the dielectric, causing a thermal damage in successive layers [17]. This phenomenon is likely to happen in the conditions of continuously repeated charging and discharging. Particularly in those conditions, the pressure of the interlayer pressure on the outer layers should not be too large; it must be in reasonable range.

C. Interlayer Air and Self-Healing

From the aforementioned results, it can be seen that the self-healing energy of an MPPFC is dependent on the interlayer pressure. The statistical capacitance loss in Fig. 2 has shown that the capacitance loss decreases gradually from the outer layers to the inner layers. It is said that the elastic films add compressive radial force to every wound wrap, and the pressure brought up by the radial force has a significant effect on the self-healing. With the increasing of the pressure in the inner layers, the capacitance loss becomes stabilized. In fact, the relationship between the self-healing energy and the interlayer pressure can be explained through the effect of interlayer air on the discharge arc in the self-healing process [18].

Fig. 8 shows the process of discharge current pulse during clearing events. The interlayer air is ionized under high electric field stress. In Fig. 8(b), the positive charges collide with the metal electrode. If the electric field is high enough, electrons will escape from the surface of the negative metal. Moreover, the ionization energy will be released when the positive charges are neutralized at the negative electrode. If the ionization energy is twice larger than that of the electron work function, it may also cause ionization of the metal electrode with a certain probability, as shown in Fig. 8(b).

After electrical breakdown occurs in the dielectric film, the charges which are produced from the dielectric film flow through the breakdown channel. The positive charges collide with the air molecules; thus, the charges scatter, and the flow zone of the charges expands. At last, the positive charges arrive at the negative electrode, and the self-healing current forms, as shown in Fig. 8(c).

By the aforementioned analysis, it can be found that, because interlayer air supplies initial charged particles, the clearing area increases. Moreover, the thicker the air layer is, the more significantly the clearing area increases. For the outer layers, the tension of the film is not strong enough, and there is a large number of air molecules; thus, the capacitance loss of outer layers is serious. For the inner layers, as the tension increases, a part of air is excluded from the capacitor, so the capacitance loss of inner layers is relatively small. For most of the inner layers, when the interlayer pressure reaches a certain value, the films stick tightly together with each other. So, the effect of air can be neglected, and the capacitance loss is minimal and tends to be stable. The aforementioned analysis is consistent with the results in Fig. 2.

IV. METHODS OF EXTENDING LIFETIME

For the MPPFCs applied under high electric field, on the premise of meeting the current-carrying capacity and the heating requirements, the sheet resistance should be as large as possible. In addition, the interlayer pressure and interlayer air affect the process of self-healing and increase the clearing area. As shown in Fig. 2, most of the capacitance loss occurs in the outer layers of the winding. Moreover, the result in Fig. 7 shows that, if the pressure is larger than 200 kPa, the self-healing energy can be limited to smaller than 10 mJ. Thus, two methods are provided to increase the lifetime of the MPPFCs: wrap strengthening and impregnation in vacuum.

A. Wrap Strengthening

Fig. 9 shows the schematic diagram of wrap strengthening technology. The aim of wrap strengthening is to increase the interlayer pressure of MPPFCs. Generally, it is needed to insert another polypropylene film without metallization to strengthen the tension at the end of the winding of an MPPFC. To improve the winding process, heat sealing is carried out on the joint when the polypropylene film is inserted; thus, the winding tension is strengthened, and the interlayer air between the outer layers can be excluded from the capacitor. The experimental result shows that the lifetime of the capacitors can be increased up to 1.6 times, as shown in Fig. 10.
show that the lifetime of the capacitors can be increased up to several times longer. The experimental results suggest that the lifetimes of the MPPFCs with full impregnation increases.

Through this technology, the lifetime of the MPPFCs can be increased up to several times longer. The experimental results suggest that the lifetimes of the MPPFCs with full impregnation increases.

B. Impregnation in Vacuum

Through oil impregnation test, it is revealed that full impregnation can be achieved in vacuum for the MPPFCs with low compression coefficient. For the capacitors with full impregnation, the interlayer air is filled with the impregnant. So, the effect of the interlayer air on self-healing is weakened. In addition, the dielectric strength of the impregnant increases. For the capacitors with full impregnation.

The interlayer pressure. When the pressure is larger than 3.2 kPa, the self-healing energy can be limited to less than 40 mJ. However, if the sheet resistance is large enough, the self-healing energy can be limited to less than 10 mJ.

4) The self-healing energy is dependent on the interlayer pressure and due to the fact that the discharge arc is dependent on the interlayer air in the self-healing process.

5) Through methods of wrap strengthening and impregnation in vacuum, the lifetime of the MPPFCs can be increased up to 1.6 times and 4–5 times, respectively.

V. CONCLUSION

The self-healing and lifetime characteristics of MPPFC with high sheet resistance under high electric field have been studied in this paper. From the research mentioned earlier, we achieve the following conclusions.

1) The capacitance loss ratio of MPPFCs decreases with film layers progressing from the outside to the inside. Most of the capacitance loss occurs in the outer layers of the winding.

2) The self-healing energy of metallized films is approximately inversely proportional to the square of sheet resistance. The clearing area is proportional to the self-healing energy. If the sheet resistance is large enough, the self-healing energy can be limited to less than 40 mJ at 3.2 kPa.

3) The self-healing decreases with the increase of the interlayer pressure. When the pressure is larger than 200 kPa, the self-healing energy can be limited to less than 10 mJ.

4) The self-healing energy is dependent on the interlayer pressure and due to the fact that the discharge arc is dependent on the interlayer air in the self-healing process.

REFERENCES


Yaohong Chen was born in Huanggang, China, in 1985. He is currently working toward the Ph.D. degree at Huazhong University of Science and Technology, Wuhan, China.
He has been working on pulsed-power technology and high-voltage engineering.

Hua Li was born in Hubei Province, China, in 1979. She received the Ph.D. degree in electrical and electronic engineering from Huazhong University of Science and Technology (HUST), Wuhan, China, in 2007.
She is currently an Associate Professor with the College of Electrical and Electronic Engineering, HUST. She has been working on pulsed-power technology and high-voltage engineering.

Fuchang Lin was born in Zhejiang Province, China, in 1969. He received the Ph.D. degree in electrical and electronic engineering from Huazhong University of Science and Technology (HUST), Wuhan, China, in 1996.
He is currently a Professor with the College of Electrical and Electronic Engineering, HUST. He has been working on pulsed-power technology and high-voltage engineering.

Fei Lv, photograph and biography not available at the time of publication.

Miao Zhang, photograph and biography not available at the time of publication.

Zhiwei Li, photograph and biography not available at the time of publication.

De Liu, photograph and biography not available at the time of publication.
学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。

图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：
图书馆首页  文献云下载  图书馆入口  外文数据库大全  疑难文献辅助工具