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Dissipation Factor as a Degradation Indicator for Electrolytic Capacitors

Moein Ghadrdan, *Student Member, IEEE,* Saeed Peyghami, *Member, IEEE,* Hossein Mokhtari, *Senior Member, IEEE,* Huai Wang, *Senior Member, IEEE,* and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—Capacitors are one of the most critical components in power electronic converters, yet they are notoriously susceptible to failure. Avoiding unforeseen outages caused by capacitor failures is one of the most effective approaches to increase system availability. Therefore, a variety of methods have been proposed to monitor a capacitor health condition based on different degradation indicators. This paper proposes a new approach based on the accurate measurement of an electrolytic capacitor dissipation factor to detect its end-of-life. Since the dissipation factor is affected by both the capacitor resistance and capacitance simultaneously, it can provide more information about the health condition of the capacitor. To employ the dissipation factor as an aging indicator, beyond its accurate measurement, it must be possible to establish an end-of-life criterion and investigate the effect of other environmental factors. Therefore, increasing the frequency of the dissipation factor measurement has been suggested as a solution to minimize the effect of the angle measurement error, for which an optimal frequency range has been calculated. In the following, several electrolytic capacitors are subjected to a laboratory study to investigate the effects of capacitor aging, temperature, and measurement frequency on the dissipation factor. According to the obtained results, changes in the capacitor resistance dominate the dissipation factor, thereby, enabling the same end-of-life criterion to be applied for monitoring a capacitor condition.**

***Index Terms*—Condition monitoring, dissipation factor, electrolytic capacitor, end-of-life criteria, loss angle, predictive maintenance.**

Nomenclature

δ	Loss angle (rad)
φ	Capacitor impedance angle (rad)
X_c	Capacitor reactance (mΩ)
ω	Angular frequency (rad/s)
ESR	Capacitor Equivalent Series Resistance (mΩ)
C	Capacitor capacitance (mF)
ESL	Capacitor Equivalent Series Inductance (μH)
ESR_0	Capacitor ESR initial value (mΩ)
C_0	Capacitor capacitance initial value (mF)
DF_0	Capacitor initial DF
v_c	Capacitor voltage (V)
i_c	Capacitor current (A)
V_e	Electrolyte volume
V_{e0}	Electrolyte initial volume
θ_e	Expected angle measurement error (rad)

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I. Introduction

Widespread use of power electronic converters in a variety of applications, from modern power generation and transmission systems to electrical transportation and home appliances, has resulted in a growing focus on improving the reliability of this equipment [1]-[3]. Fault detection and condition monitoring systems are the most effective ways to improve a converter availability during its operational phase. Fault detection systems output can be used as an indicator for the converter intelligent control to improve its performance in the event of a failure [4]. However, condition monitoring systems can be used to determine the optimal timing for predictive maintenance as illustrated in Fig. 1. It is possible to schedule converter maintenance in two ways. Corrective maintenance is performed after a failure has occurred while preventive maintenance takes place prior to the failure to prevent it. preventive maintenance can also be scheduled periodically or predictably. Periodic maintenance can be set at regular time intervals or based on the system service life. However, to carry out predictive maintenance, a condition monitoring system is needed to evaluate the system actual health status. The converter downtime can be minimized with such systems, increasing its availability.

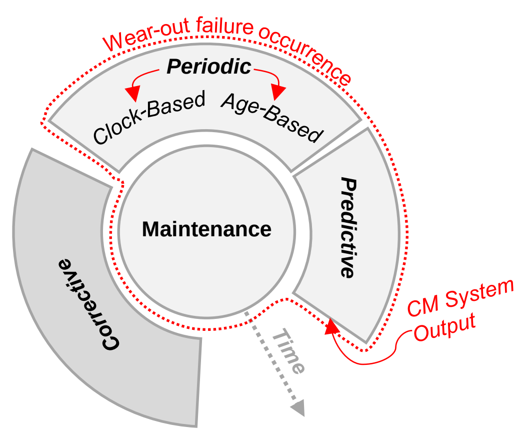

Fig. 1. Different types of maintenance possibilities in components and systems.

Condition monitoring involves continuously observing components degradation indicators to determine a component approximate remaining useful life (RUL). Capacitors and semiconductors are the most vulnerable components in a power electronic converter [5]-[8]. Therefore, condition monitoring systems are often aimed at detecting the end of useful life (EUL) of these components. Semiconductor health condition monitoring methods have been well reviewed in [9], and [10]. References [11], and [12] also offer in-depth reviews of previously presented methods for monitoring a capacitor health condition.

Capacitor failures can be categorized as catastrophic or wear-out. Catastrophic failures occur as the result of a single-event overstress, while wear-out failures are caused by gradual degradation of the capacitor [13]. A condition monitoring system is used to identify the capacitor EUL to prevent wear-out failures by optimally scheduling preventing maintenance. The predominant mechanism of wear-out failures varies depending on the type of capacitor. Electrolyte evaporation is the predominant cause of aging in small-size Aluminum Electrolytic Capacitors (AL-Caps). In contrast, electrolyte evaporation is less common in large-size capacitors due to their lower equivalent series resistance (ESR) and larger heat dissipation surface. For large AL-Caps, electrochemical reactions in the oxide layer play a key role in aging [14]. Any of the mechanisms listed above can result in changes to a set of indicators called capacitor degradation or lifetime indicators. Continuously measuring these indicators allows monitoring of a capacitor condition.

In the last three decades, a variety of degradation indicators have been introduced to monitor the condition of AL-Caps. These indicators can be classified into two categories of electrical and non-electrical. Fig. 2 depicts an overview of the various indicators currently being used [11]-[12].

The methods proposed for capacitor monitoring based on the indicators in Fig. 2 can also be classified into online and offline groups. It is not necessary to dismantle the capacitor in online methods, and the lifetime indicator can be measured while the converter is running normally. However, offline methods require the disassembling of the capacitor and interrupting the converter normal operation before the lifetime indicator can be measured. Non-electrical indicators are commonly measured offline. Of course, online methods can also be carried out using temperature or pressure sensors embedded in the capacitor [15]-[16].

Methods based on measuring electrical indicators have been more popular because they are able to monitor the capacitor condition online without requiring additional hardware. On the other hand, the end-of-life criteria for capacitors are mainly introduced based on electrical indicators of capacitance and ESR [11]-[12]. As a result, if non-electrical indicators are used, it is necessary to establish a relationship between them and electrical indicators. This relationship will probably not be similar for capacitors with different specifications, which complicates the use of non-electrical indicators. Briefly, capacitor condition monitoring methods based on non-electrical indicators usually require the use of expensive measuring equipment. Furthermore, no uniform criteria for the end-of-life exist in non-electrical methods.

Capacitance is the most common electrical indicator for observing the condition of different types of capacitors. For AL-Caps, measuring the ESR along with the capacitance is even more common due to the relatively high ESR of the AL-Caps compared to that of films and ceramic capacitors [11]. On the other hand, there are criteria for determining the AL-Caps end-of-useful life based on the capacitance and ESR, and the effect of temperature on these indicators has been thoroughly studied. These have led to the preference of using the capacitance and ESR over the other electrical indicators shown in Fig. 2. It may be difficult to measure the dissipation factor (DF), impedance, or voltage ripple, or determine the degradation level of a capacitor based on them [12]. Especially in the case of the DF, which is an important indicator used by electrolytic capacitor manufacturers in accelerated degradation testing, an effective online method to obtain the DF values at a satisfactory accuracy level has not yet been developed. The effect of the temperature on this indicator has not been adequately explored either.

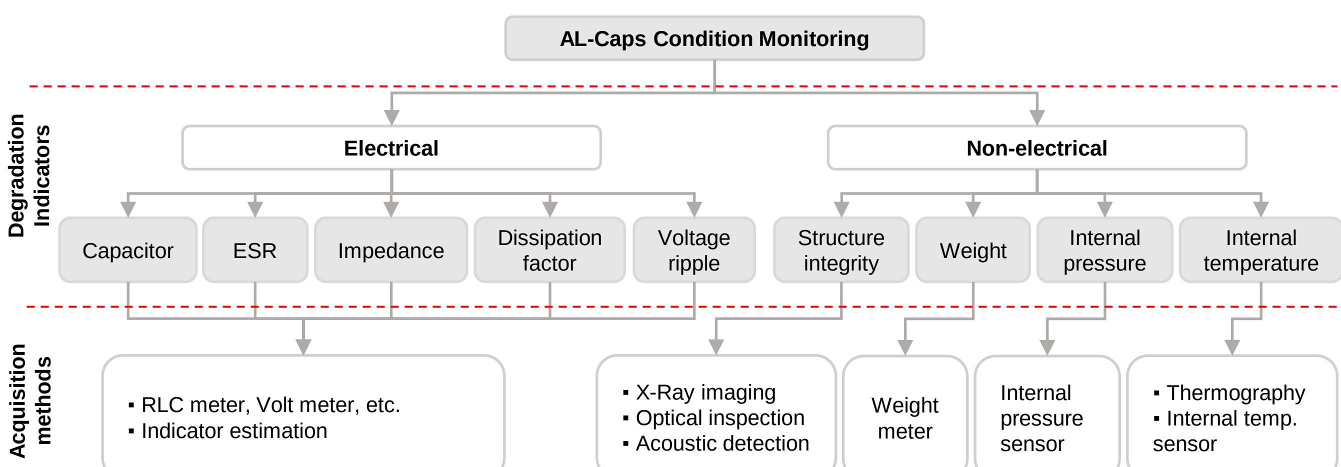

Fig. 2. Aluminum electrolytic capacitors degradation indicators and acquisition methods.

Using other electrical indicators, such as the DF, may be advantageous, and it may even make the capacitor monitoring easier. The DF equals the tangent of the loss angle, which is the complement of the capacitor impedance angle. It is therefore possible to determine the capacitor condition by measuring its impedance angle. The capacitor impedance angle can be found by measuring the time difference between its voltage and current components at a specific frequency. Time measurements have usually shown to be more accurate because timers have been developed further than equipment for measuring electrical parameters.

Accordingly, various studies have been conducted for monitoring the condition of a capacitor by measuring its time constants. In [17], while the converter is turned off, the DC-link capacitor is paralleled with two different resistors using two MOSFETs. The capacitance and ESR are then estimated by measuring the capacitor time constants when it is discharging into the resistors. Additional hardware and the necessity of monitoring during the converter shutdown process are the shortcomings of the proposed method. The reported accuracy of the capacitance and ESR measurement is about 2.5%, which is quite acceptable for monitoring electrolytic capacitors.

Similarly, [18] proposes a method to monitor the condition of DC-link capacitors in multi-module converters (MMC). Using this method, the sub-modules are bypassed one by one, and the capacitance of each cell is estimated by measuring the time constant when the capacitor is discharging into the bleeding resistor. However, the method used in this study can only be used to monitor the capacitors in MMC converters.

Some preliminary studies have examined the possibility to use the DF to monitor electrolytic capacitors [19]-[20]. However, since the DF is normally calculated indirectly based on the capacitor value and ESR, recent studies have not used this indicator to monitor the capacitor health condition. Obviously, if the capacitance and ESR are measured, the capacitor condition can be monitored based on them, which eliminates the need for DF.

An alternative method of estimating the DF based on measuring the capacitor impedance angle can be proposed, as previously explained. Measuring the phase difference between the capacitor current and voltage components at a specific frequency can provide the impedance angle, which subsequently yields the DF. This method of monitoring is problematic due to the sharp change in the DF ratio at low frequencies such as grid frequency. With a high-quality capacitor, the loss angle is almost zero at low frequencies, and the impedance angle is nearly 90 degrees. For these angles, even the smallest angle measurement error will significantly alter the angles tangent ratio, making it practically impossible to monitor the condition by the impedance angle measurement. To solve this problem, this paper suggests increasing the measurement frequency in order to increase the loss angle. Therefore, the effect of the possible angle measurement error on the error of the proposed monitoring system will decrease significantly as the loss angle increases. Of course, for each capacitor, an optimal frequency range is conceivable, in which the error of measuring the DF will be minimal.

To make a decision based on the proposed method, it is necessary to review the capacitor end-of-life criteria based on the DF. In some previous studies, the range of possible changes of the DF over the life of the capacitor has been presented based on the manufacturers' information [14], [19]. However, since different studies have provided different ranges of change, laboratory studies are needed to find the most reliable criteria.

Although a method of acquiring the DF in an AC/DC/AC converter is recently presented in [21], this paper takes a mathematical approach to explain the principle of monitoring the capacitor condition using the DF. Moreover, the necessary considerations for the application of this indicator are described in detail. Given that the proposed method focuses on measuring the DF at relatively high frequencies, it is necessary to fully evaluate the effect of frequency on the DF. On the other hand, the effect of temperature must also be investigated. Accordingly, the main contributions of this article can be summarized:

- monitoring the condition of the electrolytic capacitors based on the DF,
- measurement of the DF based on capacitor impedance angle at high frequencies,
- finding an optimal frequency range for the DF measurement in order to minimize the overall error of the proposed approach,
- investigating the change of the DF of an electrolytic capacitor over its lifetime, and
- analyzing the effect of the frequency and temperature on the electrolytic capacitor DF.

The paper continues as follows. Section II presents a complete analysis of how to use the DF to monitor the electrolytic capacitor condition. In this section, the optimal frequency range for monitoring the condition of the capacitor is determined. In section III, the laboratory data are presented to determine a criterion for the capacitor end-of-life based on the DF, and the effects of the temperature and frequency on the DF are investigated. Finally, section IV concludes the paper.

II. Dissipation Factor as a Degradation Indicator

The DF refers to the ratio of the energy dissipated in the ESR to the energy stored in a capacitor. Since film capacitors have a very low ESR, the DF can usually be estimated for electrolytic capacitors. A practical capacitor can be modeled as a set of an ideal capacitor, an ESR, and a series inductor (ESL). A power electronic converter operating frequency is designed for capacitors to operate in the capacitive region. Therefore, the ESL effect can often be ignored and the simplified equivalent circuit of the capacitor can be considered as a combination of an ideal capacitor and an ESR, as illustrated in Fig. 3. Three components make up the AL-Caps ESR; i.e.:

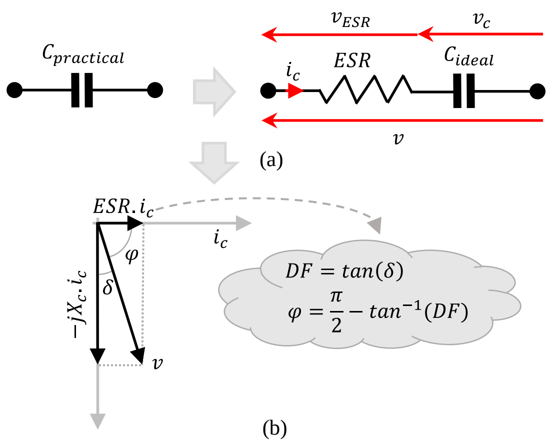

Fig. 3. Capacitor (a) electrical equivalent circuit, and (b) V/I phasor diagram.

$$ESR = R_o + R_e + R_d, \tag{1}$$

When 'R_o' refers to the ohmic resistance of the aluminum plates and terminals. 'R_e' is the resistance of the electrolyte, which decreases with the increasing number and mobility of carriers, and 'R_d' represents the dielectric frequency-dependent losses that occur if the capacitor is exposed to a variable field [22]. As the capacitor ages and the electrolyte gradually evaporates, the number of carriers decreases resulting in an increase in the electrolyte resistance and a decrease in the capacitor capacitance. Increasing the temperature also increases the mobility of the carriers and lowers the electrolyte resistance. Thus, it is clear that the capacitor ESR and capacitance change with temperature and frequency, and these should be taken into account when measuring the degradation indicators.

The DF, based on definition, is equal to the tangent of the angle between the capacitor impedance vector and the negative reactive axis as shown in Fig. 3. This angle is called the loss angle (δ), which is the complement of the capacitor impedance angle (φ). Therefore, by measuring the capacitor impedance angle, the DF can also be calculated. The relationship between the DF and the capacitor ESR and capacitance is as follows.

$$DF = \frac{Energy\ Dissipated/cycle}{Energe\ stored/cycle} = \frac{ESR.i_c{}^2}{X_c.i_c{}^2} = ESR.C\omega \tag{2}$$

The DF can also be calculated based on the capacitor impedance angle as:

$$DF = tan(\delta) = tan\left(\frac{\pi}{2} - \varphi\right) = \frac{1}{tan(\varphi)} \tag{3}$$

Defining an appropriate benchmark for determining the AL-Caps EUL based on the DF is essential for monitoring the capacitor condition. The health index of the capacitor can be defined as the ratio of the DF at any given time to its initial value, i.e.:

$$\frac{DF}{DF_0} = \frac{ESR.C.\omega}{ESR_0.C_0.\omega} = \frac{ESR}{ESR_0} \times \frac{C}{C_0} \tag{4}$$

Alternatively, this relationship can be rewritten based on the capacitor impedance angle.

$$\frac{DF}{DF_0} = \frac{tan(\delta)}{tan(\delta_0)} = \frac{tan\left(\frac{\pi}{2} - \varphi\right)}{tan\left(\frac{\pi}{2} - \varphi_0\right)} = \frac{tan(\varphi_0)}{tan(\varphi)} \tag{5}$$

Equations (4) and (5) point out that there are two possible approaches to find the DF. In the first approach, it is necessary to measure both the capacitance and ESR of the capacitor to calculate the DF. However, it is quite clear that if the capacitance and ESR are available, they can be used to determine the health condition of the capacitor. In the second method, the DF is calculated by measuring the capacitor impedance angle, which, as previously described, may offer an advantage over other monitoring techniques. Therefore, the proposed method in this paper involves monitoring the condition of an electrolytic capacitor based on (5).

However, particularly for high-quality sound capacitors, the impedance angle is close to 90 degrees and the loss angle is near zero. With these angles, the angle measurement error is greatly magnified by the tangent function, making it nearly impossible to monitor the condition using the DF. To evaluate this, an error function is defined as:

$$Err(\delta, \theta_e) = 1 - \frac{tan(\delta + \theta_e)}{tan(\delta)} \tag{6}$$

Equation (6) shows the error of calculating the DF due to θ_e degrees of error in measuring a specified loss angle (δ). Fig. 4 presents the absolute value of the percentage error calculated based on (6) for positive measurement error values (θ_e). A similar chart can also be drawn for negative error values.

According to Fig. 4, even a small angle measurement error, at angles close to zero or 90 degrees will lead to errors of several hundred percent on the DF calculations. The angles of about 45 degrees also result in minimum errors in estimating the DF. In other words, the closer to 45 degrees the loss angles are, the smaller the effect of the angle measurement error on the DF calculation error. The exact value of the optimal angle for having the minimum error in the DF calculation can be achieved by taking the derivative of (6) as:

$$\frac{\partial Err(\delta, \theta_e)}{\partial \delta} = -\frac{tan(\theta_e)\,(tan^2(\delta) + 2\,tan(\theta_e)\tan(\delta) - 1)}{(1 - tan(\theta_e)\,tan(\delta))^2\,tan^2(\delta)} \tag{7}$$

To obtain the optimal angle, the roots of (7) are calculated:

$$\delta_{1,2} = tan^{-1}\left(-tan(\theta_e) \pm \sqrt{tan^2(\theta_e) + 1}\right) \tag{8}$$

Considering $0° \leq \delta \leq 90°$, only one of the roots can be acceptable.

$$\delta = tan^{-1}\left(-tan(\theta_e) + \sqrt{tan^2(\theta_e) + 1}\right) \tag{9}$$

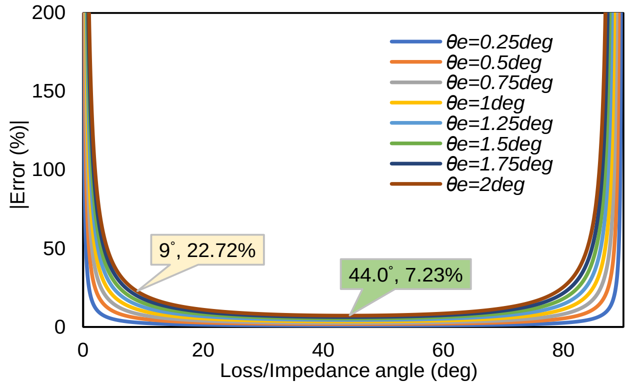

Fig. 4. DF calculation error for different angle measurement errors at different loss angles.

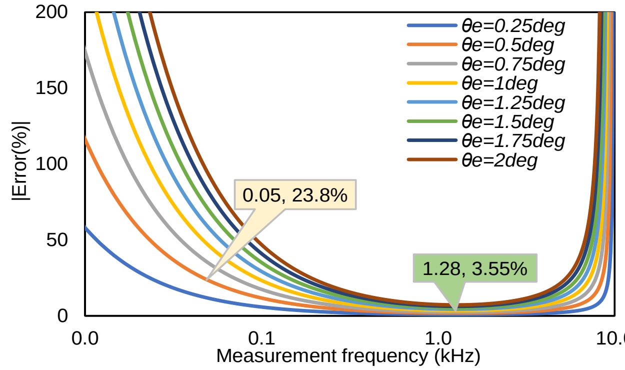

Fig. 5. DF calculation error for different angle measurement errors at different measurement frequencies.

Also, since θ_e is usually very close to zero, (9) can be further simplified as:

$$\delta = tan^{-1}\left(-\theta_e + \sqrt{\theta_e{}^2 + 1}\right) \tag{10}$$

As explained earlier, angle measurement error leads to minimal DF calculation error at angles of about 45 degrees. Therefore, the loss angle must be increased to reach 45 degrees. According to (2), the loss angle depends on the capacitance, ESR, and frequency. Since the capacitor ESR and capacitance are uncontrollable characteristics, the only way to increase the loss angle is to increase the frequency of the impedance angle measurement. In other words, it is necessary to measure the phase difference between the high-frequency components of the capacitor current and voltage. The current high-frequency component may also flow normally through the capacitor during converter operation or it can be injected from an external source.

For an electrolytic capacitor with specifications in Table I [23], the corresponding measurement frequencies for different loss angles have been calculated and Fig. 4 has been redrawn. This time, however, the angle measuring frequency has been substituted for the loss or impedance angle (Fig. 5).

The ESL effect is also taken into consideration when calculating the frequencies corresponding to the loss angles. According to Fig. 5, as the measurement frequency approaches the capacitor cut-off frequency, the loss angle reaches about 90 degrees, and the DF estimation error due to the angle measurement error is maximum. For different values of the angle measurement errors, Table II shows the optimal measurement angles and frequencies based on (9), as well as the expected errors of the DF calculation.

Accordingly, the error of estimating the DF due to angle measurement error at a frequency of approximately 1.3 kHz is minimum. In other words, if the impedance angle is obtained by measuring the phase difference between the 1.3 kHz components of the capacitor current and voltage, the errors in the angle measurement will have the least impact on the DF. Although, variations of the capacitance and ESR due to frequency or temperature changes may shift the optimum frequency range.

TABLE I
SPECIFICATION OF THE ELECTROLYTIC CAPACITOR

Manufacture Part No.	Capacitance (mF)	Max. ESR 25 °C, 10 kHz (mΩ)	Cut-off Freq. (kHz)
Cornell Dubilier 500R112M500BC2B	1.1	108.8	10

TABLE II
OPTIMAL ANGLES AND FREQUENCIES TO MINIMIZE THE DF ESTIMATION ERROR

θ_e (deg)	Optimal angle (deg)	Optimal Frequency (Hz)	DF expected estimation error
-2	46.00	1351.9	6.74%
-1.5	45.75	1340.6	5.10%
-1	45.50	1329.4	3.43%
-0.5	45.25	1318.2	1.73%
0.5	44.75	1296.2	1.76%
1	44.50	1285.3	3.55%
1.5	44.25	1274.5	5.38%
2	44.00	1263.7	7.23%

According to Fig. 5, estimating the DF by measuring the loss angle at the grid frequency might result in a significant error. For example, just 0.5 degrees of the angle measurement error at 50 Hz leads to about 24% error in the DF estimation.

In addition, the loss angle changes over time as the capacitor characteristics drift. The measurement frequency should not be set too high, otherwise, the initial loss angle will be too large. Consequently, as the loss angle increases over the life of the capacitor, the DF estimation error may become unacceptable. In other words, the measurement frequency must be adjusted such that the loss angle varies around 45 degrees during the life of the capacitor. By way of example, if the DF is expected to increase by 100% over the life of the capacitor, the measurement frequency must be set such that the initial loss angle is about 35 degrees and reaches about 55 degrees when the capacitor is fully derated. To realize such a scheme for the capacitor of Table I, a measurement frequency of about 1 kHz should be selected.

III. DF INDICATOR CONSIDERATIONS

Apart from the accurate measurement of the aging indicators, there are other factors to consider in the condition monitoring process as shown in Fig. 6. A key factor to the effectiveness of any monitoring method is the selection of a

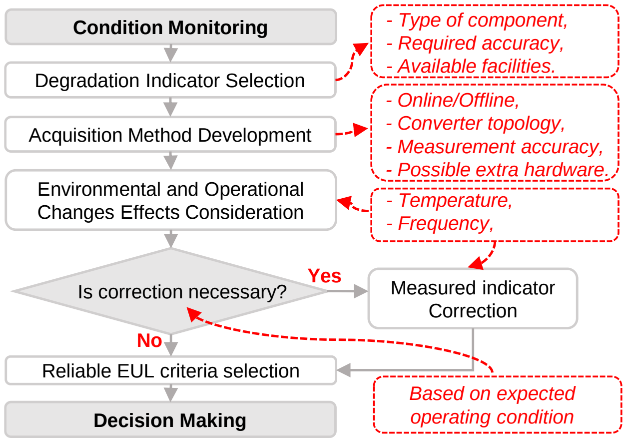

Fig. 6. Different stages of the condition monitoring process.

proper EUL criterion. If the appropriate end-of-life criteria are not applied, the equipment may either fail before the condition monitoring system detects EUL, or an early replacement or repair signal may be triggered when the equipment is still capable of functioning for a considerable period of time.

Taking environmental changes into account is the next step. An appropriate aging indicator must give an alarm only when the equipment ages. Therefore, changes resulting from other factors must either be removed or corrected. Temperature change is one of the factors that affect degradation indicators such as capacitance or ESR. Most condition monitoring studies suggest methods to eliminate the temperature effect. Some correct the temperature effect based on information provided by manufacturers. In the following, using laboratory studies on the DF, the above cases have been evaluated.

A. EUL Criterion Based on the DF

Different end-of-life criteria have been introduced for electrolytic capacitors operating under various conditions. End-of-life criteria for electrolytic capacitors most commonly involve a 20% decrease in the capacitance or 100% increase in the ESR [11]-[12]. A 30% reduction in electrolyte volume has also been introduced but has not been widely employed due to the complexities involved in measuring the electrolyte volume [24]. Several studies have tried to determine the capacitor EUL by establishing correlations between different indicators such as weight and electrical indicators. Accordingly, [25] introduces a new criterion for determining the EUL of a particular capacitor based on the weight. A similar approach is taken in the following to provide a new criterion for determining the EUL of electrolytic capacitors based on the DF. The accuracy of the proposed criterion has then been evaluated by laboratory examination.

According to [22] and [26], the capacitance of AL-Caps changes directly with the changes in the electrolyte volume over time. Whereas, their ESR is inversely proportional to the square of the electrolyte volume based on [24], i.e.:

$$\frac{C}{C_0} = \frac{V_e}{V_{e0}} \tag{11}$$

$$\frac{ESR}{ESR_0} = \left(\frac{V_{e0}}{V_e}\right)^2 \tag{12}$$

Substituting (11) and (12) into (4), the DF can be calculated based on the electrolyte volume as:

$$\frac{DF}{DF_0} = \frac{ESR}{ESR_0} \times \frac{C}{C_0} = \frac{V_e}{V_{e0}} \times \left(\frac{V_{e0}}{V_e}\right)^2 = \frac{V_{e0}}{V_e} \tag{13}$$

According to (13), the DF appears to be inversely proportional to the electrolyte volume. However, since (12) only takes into account the electrolyte resistance, and according to (1), the capacitor ESR is composed of three components, of which the electrolyte resistance is just one component, the capacitor ESR seems to increase at a higher rate than expected by (12). Hence, the DF will also rise faster than the rate suggested by (13).

As explained earlier, the capacitor EUL criterion based on the DF can be derived using the accepted criteria based on the capacitance and ESR. According to (4), if the capacitance drops by 20% and the ESR increases by 100%, the DF would rise by about 60% during the useful life of the capacitor. However, the correctness of this criterion depends on the assumption that the capacitor EUL criteria based on capacitance and ESR occur simultaneously. Of course, this assumption is not always true. It should be noted that the end-of-life criteria based on the capacitance or ESR, are provided for indirect estimation of a capacitor thermal or voltage limits. With rising ESR and increasing power loss, the capacitor approaches its thermal limit, while with decreasing capacitance and rising capacitor voltage peak, it nears its voltage limit. Whenever the capacitor reaches either the voltage limit or the thermal limit, it will fail. Thus, the criteria based on the capacitance and ESR do not necessarily result in similar end-of-life moments.

A laboratory study on nine 56 μF- 35 V electrolytic capacitors has been carried out in order to more accurately evaluate the DF change over the capacitors life. Repeating the test on several capacitors will lead to more reliable results. For 2000 hours, capacitors were exposed to a nominal voltage of 35V and a current of 0.3 amp. Approximately every 200 hours, the capacitors parameters were measured by an "Agilent E4989" type RLC meter and the results are shown in Fig. 7. The measured values are normalized with respect to the initial values in order to facilitate analysis.

In Fig. 7, the averages of the data are labeled. The first point of interest is the huge difference in the end-of-life detection times based on the EUL criteria for capacitance and ESR. Based on Fig. 7. The majority of the studied capacitors have reached their EUL at about 1000 hours (green label) if a 100% increase in the ESR is considered as a sign of a capacitor nearing the end of life. By contrast, if a 20% reduction in the capacitance is used as a decision criterion, the useful life of capacitors would almost double, increasing by 1000 hours (yellow label).

According to Fig. 7, a decrease of about 10% in the capacitance has led to a tenfold increase in the ESR. Of

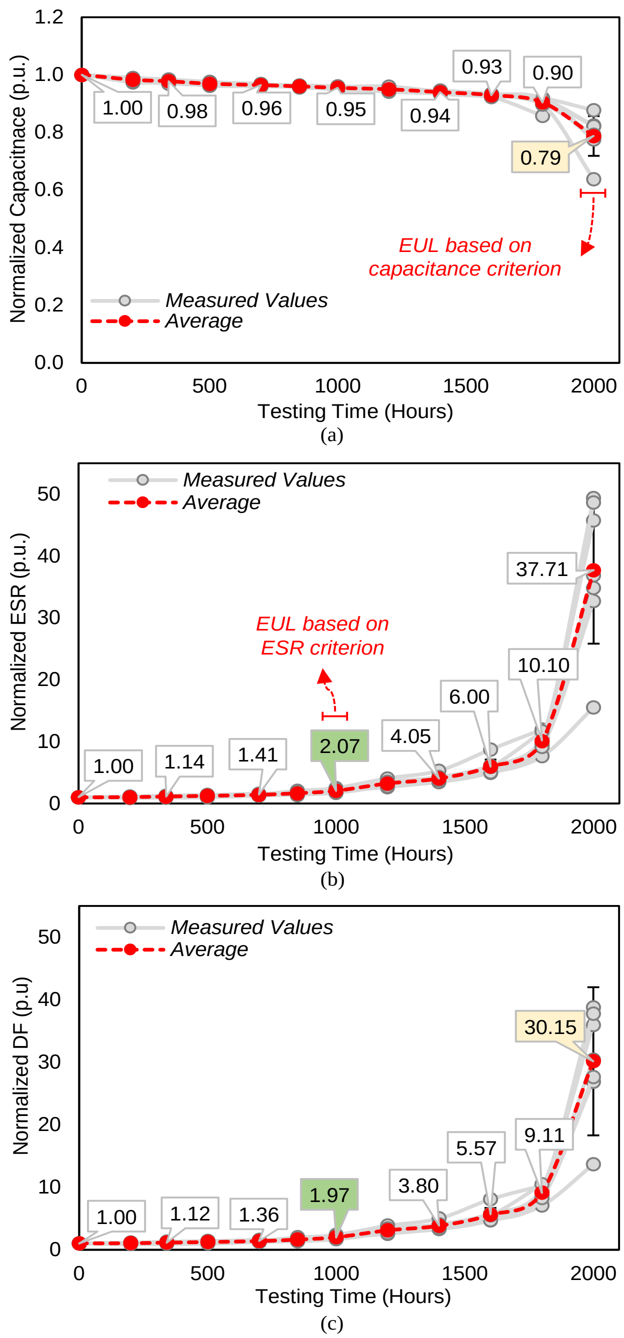

Fig. 7. Experimental results: Impact of capacitor aging on the normalized values of (a) capacitance, (b) ESR, and (c) DF.

course, another group of capacitors may experience a faster change in the capacitance. That is why AL-Caps should be monitored by measuring simultaneously their capacitance and ESR [17], [27]-[29]. Consequently, observing the condition of the capacitor based on the DF may be of great advantage since it can show both the capacitance and ESR variations. However, before it can be used effectively, it must be supported by a reliable EUL criterion.

The end-of-life criteria for various degradation indicators refer to the moment when the rate of change of that indicator starts to increase considerably. Based on the data in Fig. 7, the DF changes are more affected by the changes in the ESR, suggesting that a 100% increase in the DF can also provide a good indication of the EUL of an electrolytic capacitor.

B. DF Temperature-Frequency Profiles

Along with the equipment aging, degradation indicators are affected by other variables such as environmental conditions and frequency. Monitoring the condition of equipment requires recognizing the effect of aging from other factors. Therefore, the effect of any factor that alters degradation indicators by a mechanism other than aging must be

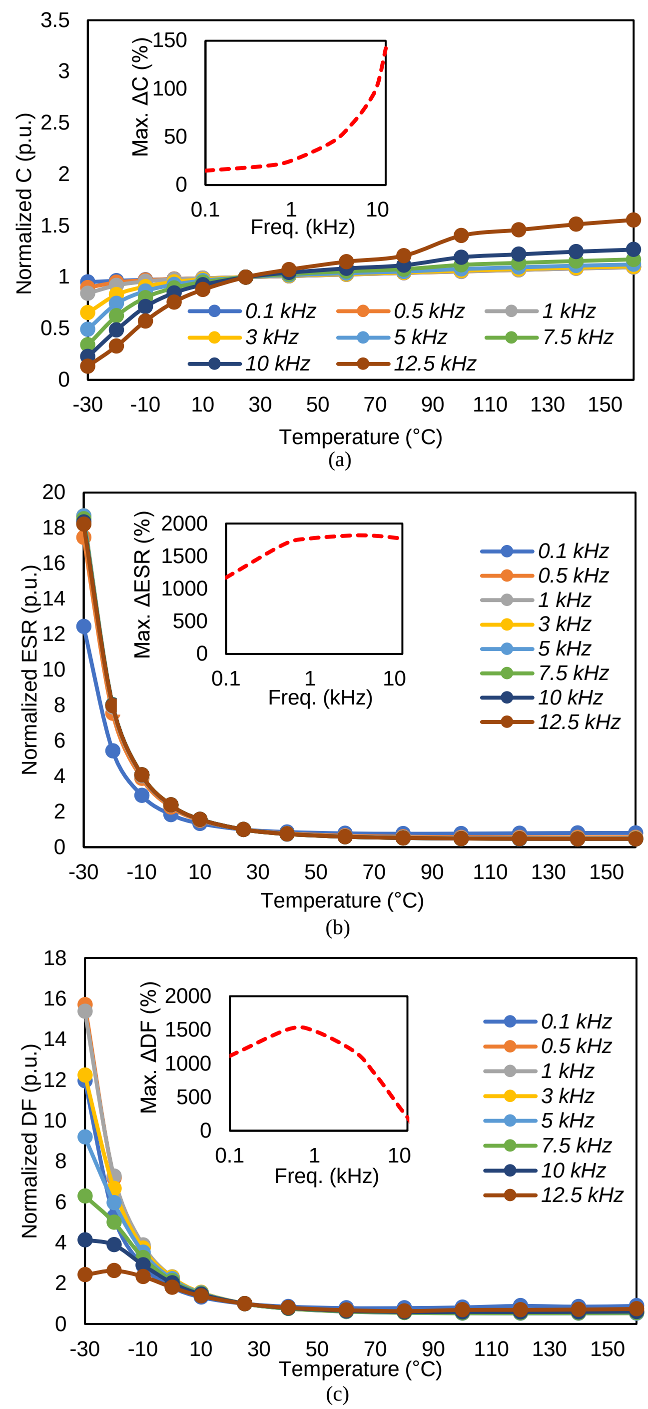

Fig. 8. Experimental results: Impact of temperature and frequency on the normalized values of (a) capacitance, (b) ESR, and (c) DF with respect to the values at 25 °C.

eliminated or corrected. Temperature and frequency are the main external factors that can affect the capacitor lifetime indicators such as capacitance, ESR, and consequently the DF through a mechanism other than aging. Therefore, their effects must be removed or corrected in some way.

On the same capacitor tested in the previous section, experiments are conducted to investigate the effects of temperature and frequency on the DF. During these experiments, the temperature is changed from -30 °C to +160 °C, and the capacitance, ESR, and DF are measured with an RLC meter in the frequency range of 100 Hz to 12.5 kHz. Further increasing the frequency leads to a loss angle near 90 degrees, making measurement of the DF impossible. The measured values are normalized to the values at 25 °C and the results are shown in Fig. 8.

Changes in the capacitance and ESR with temperature are entirely consistent with the expectations. With increasing the temperature and mobility of the carriers, the capacitance increases, and ESR decreases. As a result of freezing the electrolyte, a sharp increase in the ESR can also be observed. The small diagrams on each figure show the maximum variation of the parameters due to the temperature changes from -30 to 160 °C at different frequencies. With increasing frequency, temperature-induced changes in the capacitance and ESR sharply increase, while the maximum change in the DF drops. The DF exhibits a better high-frequency performance because the ESR increases sharply at low temperatures while at the same time the capacitance decreases. Therefore, according to (2), the DF rises less than the ESR as the temperature drops.

The temperature-related changes in each parameter should, of course, be compared with the expected changes range resulting from aging. Although the temperature-induced changes in the capacitance appear to be less pronounced than the changes in the ESR, and DF, it should be noted that capacitance is expected to change by only about 20% due to aging, while the expected range of changes in the ESR and DF is 5 times wider.

Furthermore, the converter application and possible temperature fluctuations should also be taken into account. In aerospace applications, for example, the converter may operate over a wide range of temperature changes, making it necessary to consider a temperature measurement system to differentiate between the effects of temperature and aging. While in many applications, capacitor temperature may never fall below 40 °C (assuming 25 °C as the ambient normal temperature and an additional 15 ° due to capacitor losses). In this case, considering the scale of temperature changes and its effects on aging indicators, it would be wise to evaluate the necessity of measuring temperature and correcting its impact. Accordingly, Fig. 9 shows changes in the capacitance, ESR, and DF for the capacitor of the previous section at various frequencies and varying operating temperature ranges (up to 160 °C).

If a 10% change in the ESR, or DF and 2% change in the capacitance due to temperature variations can be overlooked (one-tenth of the expected changes with capacitor aging), and

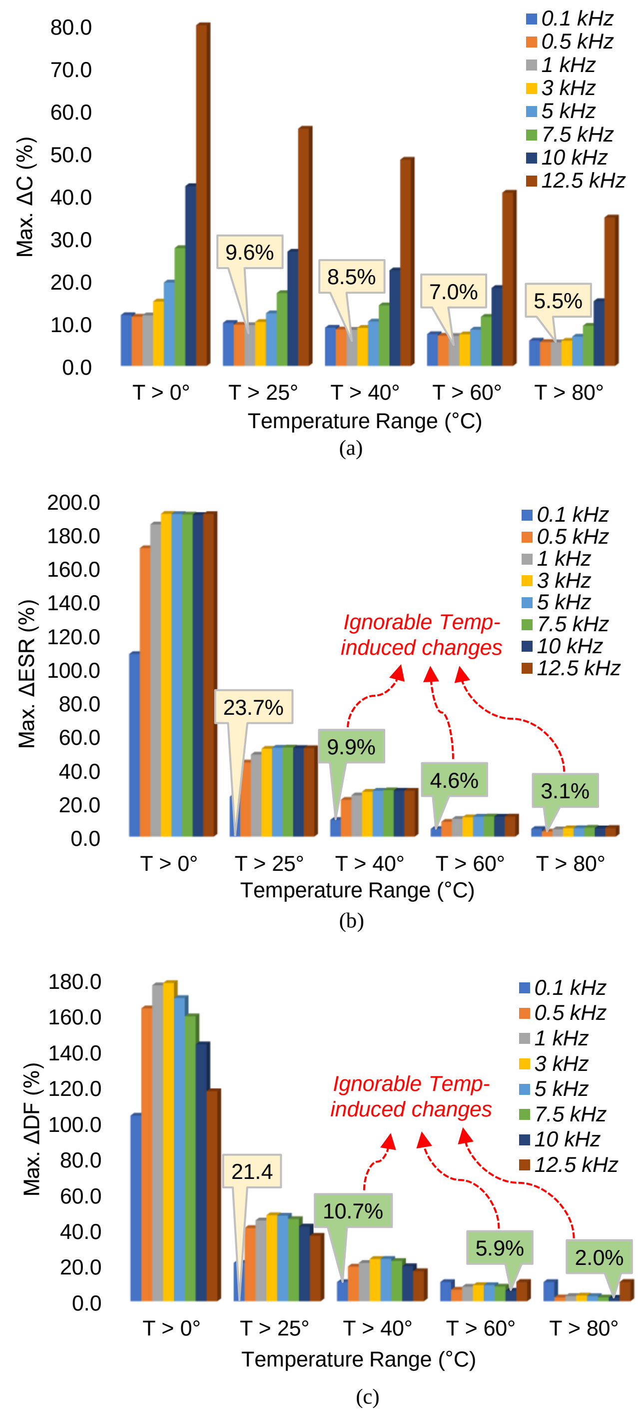

Fig. 9. Maximum temperature-induced changes in (a) capacitance, (b) ESR, and (c) DF for different temperature ranges (up to 160°) and frequencies.

if the operating temperature range of the capacitor is greater than 40°C, it may not be necessary to measure and correct the effects of temperature on the ESR and DF. However, despite the fact that the capacitance is affected by temperature more gently, the impact of temperature cannot be ignored as the temperature effects on the capacitance are still significant when compared to those caused by aging. Therefore, if the capacitance is used as an aging precursor, to ensure proper operation of the condition monitoring system, it is necessary to measure the capacitor temperature and correct its effects.

IV. Conclusion

The main goal of this paper is to highlight the possibility of using the DF as an electrical lifetime indicator along with the capacitance and ESR. A feasibility evaluation has been conducted on the use of the DF to encourage future studies to develop acquisition methods based on the measurement of this indicator as recently done in [21]. A solution for accurate measurement of DF based on capacitor impedance angle has been proposed, and an optimal frequency range has been calculated to minimize the effect of angle measurement error on the DF estimation. Accordingly, by increasing the measurement frequency and corresponding loss angle to 45 degrees, the DF calculation error can be minimized. In other words, if the measurement frequency increases to the point when the energy dissipated at that specified frequency is equal to the stored energy, the best result will be obtained for condition monitoring based on the DF.

In the second part of this study, considerations related to the use of the DF as a degradation precursor are addressed. According to the experiments, the change in the DF during the life of the capacitor is more affected by changes in the ESR, and therefore, the same end-of-life criterion should be considered. However, DF will be a more reliable indicator since it provides information about both capacitance and ESR. The effect of temperature changes on the DF at different frequencies is also considered. According to the results, the full-range temperature change of the DF falls with increasing the measurement frequency. In the temperature range above 40 degrees, the DF is least affected by the temperature after ESR.

In conclusion, even though this paper focuses on electrolytic capacitors, the possibility of using DF to monitor the condition of film and ceramic capacitors is not ruled out. Due to the low ESR of film capacitors, it is not feasible to monitor their situation based on this indicator. Therefore, using the DF measured at reasonably higher frequencies, as an alternative to the ESR can be very attractive.

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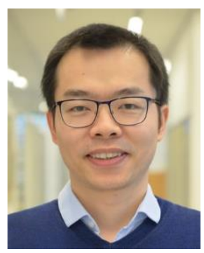

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