

Lifetime Prediction of DC-Link Film Capacitors using a Stochastic Model Combined by Random Variable and Gamma Process

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ABSTRACT

In electronic vehicles (EVs) or hybrid electronic vehicles (HEVs), an inverter system has a direct-current-link capacitor (DC-link capacitor) which provides reactive power, attenuates ripple current, reduces the emission of electromagnetic interference, and suppresses voltage spikes. A film capacitor has been used as the DC-link capacitor in high level power system, but the film capacitor's performance has deteriorated over operating time. The decreasing performance of the film capacitor may cause a problem when supplying and delivering energy from the battery to the vehicle's power system. Therefore, the lifetime prediction of the film capacitor could be one of critical factors in the EVs and HEVs. For this reason, the lifetime and reliability of the film capacitor are key factors to show the stability of the vehicle inverter system. There are a lot of methods to predict the lifetime of the film capacitor. Those methods have been researched include using physical or chemical equations. However, these previous researches have a problem with robustness with respect to uncertainty. In this paper, a new prediction model is proposed for the lifetime and stability of the film capacitor which is guaranteed by stochastic methods. Capacitance loss is introduced and modeling of two types of capacitance loss. The parameters of each model are obtained by using curve fitting algorithm and Expectation-Maximization algorithm (EM algorithm). Comparing the predicting result and the real experiment result shows that the new proposed prediction model gives a good performance.

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INTRODUCTION

These days, electronic vehicles (EVs) and hybrid electronic vehicles (HEVs) have been processed rapidly due to high cost of fossil fuel, and for protecting environment from pollutant [1] [2][3][4]. As electronic systems become more relevant and are more common in the vehicles, batteries and electronic motors are one of main parts of the vehicle energy development. Between the batteries and the motors, there is an inverter system which delivers the battery energy to the electronic motor. More specifically, at the middle of the battery and inverter system, there is a direct-current-link capacitor (DC-link capacitor). Figure 1. shows the concept of the position of the DC-link capacitor.

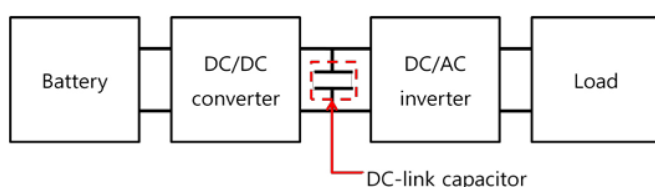


Figure 1. The concept of the position of DC-link capacitor

The DC-link capacitor works to provide reactive power, attenuate ripple current, reduce the emission of electromagnetic interference, and suppress voltage spikes caused by leakage inductance, and switching operations [5].

During initial development period, electronic capacitors have been used as DC-link capacitors. Recently, film capacitors are much more frequently used as the DC-link capacitors rather than electronic capacitors. There are a lot of reasons why. The film capacitors can withstand higher levels of surge voltage and root-mean-square (RMS) currents, and operate at relatively high temperature. In addition, the film capacitors have higher reliability than the electrolytic capacitor due to self-healing characteristics. Thus, the film capacitor might be the most suitable energy storage component in pulsed system with harsh environment [6][7][8][9]. The summary of comparing film capacitors with electronic capacitors is below Table 1 [10].

Table 1. Comparing film capacitors with electronic capacitors.

Factor / type	Film capacitors	Electronic capacitors
Life	Over 100,000 hours	Less than 100,000 hours
Voltage	Over 1000V	Less than 1000V
Ripple current	High	Low
Capacitance	Low	High
ESR	Low	High
Energy density	Low	High
Costs	High	Low

In the Table 1, excluding the “Costs” factor, the film capacitors have better characteristics than the electronic capacitors. The cost between film capacitors and electronic capacitors is not much. In addition, the gap between the film and electronic capacitors has decreased. Therefore, the gap will be close.

Even though the film capacitor is performing better than the electronic capacitor, the film capacitor has problems with three bottle-neck problems which are size (and weight) reduction, cost reduction, and reliability improvement [11]. This paper focuses on the reliability improvement portion of the three bottle-neck problems.

For a long time, studies and industry researches have predicted the lifetime of capacitors using methods with physical or chemical equations such as Arrhenius temperature equations. Specially, the relationship between temperature and life is common. For example, the equation about temperature with Equivalent Series Resistance (ESR) or lifetime with temperature and voltage are proved and introduced [12][13][14][15][16][17][18][19][20][21][22][23]. However, all of former studies and research have trouble dealing with reliability with respect to uncertainty. In this paper, a new prediction model about the lifetime and stability of the film capacitors is proposed.

Before making the stochastic model of the film capacitor, capacitance loss is introduced as a failure detecting indicator. The capacitance loss can be separated as two types: natural and sudden loss. The natural loss has steady losing character and the sudden loss has random losing character. Therefore, it is needed to make two models for two types of capacitor loss. For the natural loss, random variable deterioration model is introduced and used. The random variable deterioration model considers only sample and steady loss. For the sudden loss, gamma process deterioration model is introduced and used. The gamma process deterioration model is ideally suited to model gradual damage that monotonically accumulates over time. After making two models about the natural loss and the sudden loss, a new model combined by the random variable deterioration model and the gamma process deterioration model to consider the natural loss and the sudden loss of the film capacitor is proposed. The parameters of the random variable deterioration model are obtained by using curve fitting algorithm based on real experiment data. For estimating the parameters of the gamma process deterioration model,

Expectation-Maximization algorithm (EM algorithm) is used. Using these models and algorithms, the lifetime and the stability of the film capacitor is calculated and predicted. Comparing the predicting result and the real experiment result shows that the new proposed prediction model gives a good performance.

This paper is structured as follows. Two types of capacitance loss are described and each modeling type is introduced. After that, each model's parameters estimating methods are discussed. To prove this model, result about comparing the simulation results and real experiment data is shown and discussed. The final section consists of the conclusion of this paper.

MODELING

When modeling a film capacitor deterioration model, capacitor loss has to first be introduced. The capacitance loss is main factor to predict the lifetime of film capacitors. The capacitance loss is separated into two types: natural loss and sudden loss which have different characteristic each other. Therefore, different modeling methods are used for two types of capacitance loss. The natural loss is modeled by random variable deterioration model and the sudden loss is modeled by gamma process deterioration model. After making two models about the natural loss and the sudden loss, a new model combined by two models is proposed.

Capacitance Loss

Before introducing capacitance loss, it needs to define failure. Failure can be divided into two groups [24]:

1. The failure that may be predicted by one or several condition monitoring indicators. This failure is referred to as a gradual failure. It also called soft (or degradation) failure.
2. The failure whose probability is completely random. The failure cannot be predicted by either condition monitoring indicators or measuring the age of the asset. The asset ceases to function without any indication. This kind of failure is referred to as a sudden failure. It is also termed as hard failure.

In this paper, capacitance loss is considered as failure. Capacitance loss means percentage of gap between the origin capacitance and current capacitance. The capacitance loss has two different types, natural loss and sudden loss [25]-[26]. The natural loss is same to gradual (or soft, degradation) failure. Therefore, the natural loss can be considered as normal loss and it has consistent characteristic. The sudden loss equals sudden (or hard) failure. The sudden loss does not have steady characteristic and it is occurred spontaneous. The sudden loss is random and usually happened due to manufacturing technology such as vaporization, heat treatment, and the deterioration, and it could greatly shorten the lifetime. The natural and sudden capacitor losses are shown in Figure 2.

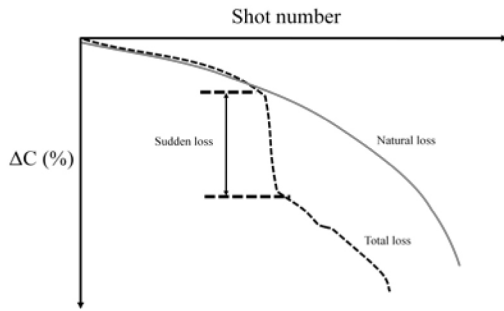


Figure 2. Natural and sudden capacitance loss

The percentage of capacitance loss is defined as

$$C_{loss} = \frac{C_{init} - C}{C_{init}} \times 100 [\%] \quad (1)$$

where C_{init} is the initial capacitance and C is the current capacitance. Generally, the termination of the lifetime of the film capacitors is defined as a 5% capacitance loss of the initial capacitance [27]. The reason is it after a 5% loss is because the capacitance loss is accelerating. Therefore, it is hard to keep the original capacitor performance. In this paper, 5% loss is defined as the failure threshold.

Random Variable Deterioration Model

Except sudden loss, the capacitance loss shows steady characteristic. For this reason, natural loss is considered as random variable deterioration model [28]-[29]. The random variable deterioration model does not account for temporal uncertainty and only care sampling uncertainties. The random variable deterioration model is shown in Figure 3.

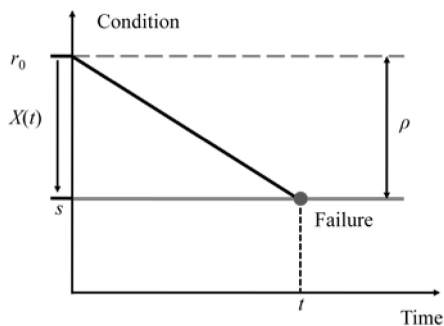


Figure 3. Random variable deterioration model

The random variable deterioration model considers only sample and steady loss.

The deterioration of remain lifetime follows

$$R(t) = r_0 - X(t) = r_0 - At \quad (2)$$

where r_0 is the initial lifetime, A is the deterioration rate, and t is the time.

And let s is failure terminated point of the model. So, the equation of lifetimes limits

$$\begin{aligned} R(t) - s &\leq 0 \\ &= (r_0 - s) - X(t) \leq 0 \end{aligned} \quad (3)$$

And let ρ is margin of the model or a deterioration threshold. The equation of ρ is

$$\rho = r_0 - s \quad (4)$$

From Equation (3), the cumulative probability distribution function of the lifetime, T , can be simply written as

$$\begin{aligned} F_T(t) &= P[T \leq t] = P[(\rho / A) \leq t] \\ &= P[A \geq (\rho / t)] \end{aligned} \quad (5)$$

Gamma Process Deterioration Model

Gamma process deterioration model is suitable The sudden loss model. The gamma process is ideally suited to model gradual damage that monotonically accumulates over time [30][31][32][33][34][35][36]. The sample paths of the gamma process are discontinuous and monotone, as shown in Figure 4.

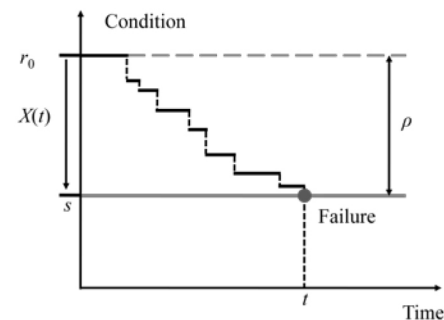


Figure 4. Gamma process deterioration model

In the gamma process, increments are independent and non-negative random variables having a gamma distribution with an identical scale parameter and a time dependent shape function. The gamma process has following characteristics [37]:

If the gamma process is consider as $\{X(t), t \geq 0\}$,

1. $X(0) = 0$.
2. The process $\{X(t), t \geq 0\}$ has independent increments.
3. For all $0 \leq t_1 < t_2$, the random variable $X(t_2) - X(t_1)$ has a gamma distribution with parameters $(\lambda(t_2) - \lambda(t_1), \beta)$, with probability density function