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Benchmarking of Capacitor Power Loss Calculation Methods for Wear-Out Failure Prediction in PV Inverters

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Abstract

Aluminium electrolyte capacitors (e-caps) are one the most prone to failure components in power electronics systems. The thermal stress is one of the most important factors which affect lifetime of dc-link capacitors. Therefore, the power loss and temperature estimation are critical steps in lifetime prediction of these components. This paper aims to benchmark different capacitor losses estimation methods from the system level reliability point of view. Four different equivalent series resistance (*ESR*) models are benchmarked for 2 different mission profiles based on complexity, estimated power losses, thermal stresses, and B_{10} lifetime: 1) constant *ESR*, 2) temperature dependent *ESR*, 3) frequency dependent *ESR*, and 4) frequency/temperature dependent *ESR*. For the lifetime model and parameters employed, the results indicate a maximum difference of 7.1 % in the B_{10} lifetime estimated by approaches 1 and 4.

1. Introduction

Dc-link capacitors play an important role in power electronic systems, providing energy storage and limiting the voltage ripple for suitable operation [1]. The capacitive dc-links are employed in most of power converters for adjustable speed drives, uninterruptible power supplies, and renewable energy conversion systems [1], [2].

In single-stage photovoltaic (PV) inverters, the dc-link capacitor bank is an interface between the PV array and the switching power converter, shown in Fig.1a. Its main function is to absorb the current ripple generated by the converter's switching characteristic, leading to smooth voltage and current at the solar array terminals [2]. Furthermore, the voltage at the dc-link becomes one of the states of the system and can be used to perform a maximum power point tracking (MPPT) [3]. In order to fulfil voltage and current requirements, the physical composition of the dc-link is usually multiple series and parallel connections of capacitors.

In most of the products available in the market, aluminium electrolyte capacitors (e-caps) are employed. Industrial experience based surveys indicates, however, that Al e-caps are one the most prone to failure components in power electronics systems [4-5]. Considering the high competitiveness of the PV market, more reliable PV inverter are desired to reduce the cost of energy [6]. Thereby, many studies have recently developed methodologies and tools for reliability evaluation in PV inverters [7]–[9].

The thermal stress is one of the most important factors which affect lifetime of dc-link capacitors. As a rule of thumb, the lifetime of Al e-caps is reduced by half for every 10 °C increase in operating condition [10]. Therefore, the power loss and temperature estimation are critical steps in lifetime prediction of these components.

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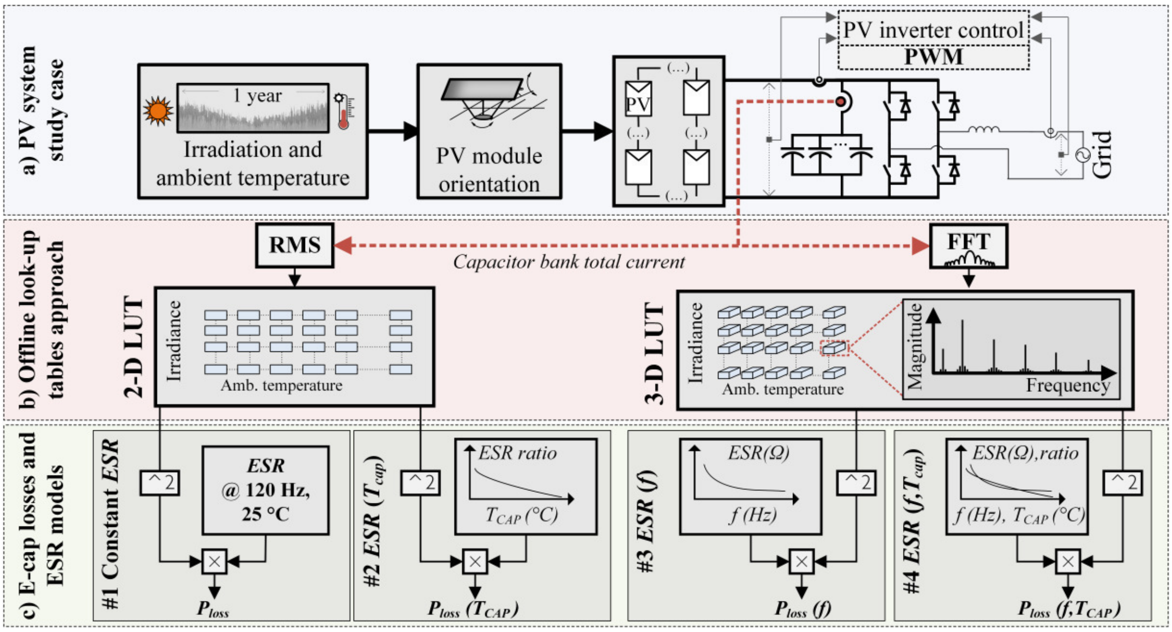

Fig 1. Methodologies for power loss evaluation in the dc-link capacitors.

The power losses in aluminium e-caps are dependent on its equivalent series resistance (*ESR*) and different approaches are proposed in literature for modelling such losses in dc-link capacitors. References [11]–[13] uses a simple model assuming a constant *ESR* and computing the power losses as a function of the RMS current ripple. While in [1], [14] the dependence of *ESR* with frequency is considered to obtain a more accurate estimation. Alternatively, in [2] the relationship of the *ESR* with both the frequency and temperature is considered and modelled in look-up tables; nevertheless, the side-band harmonics generated by the inverter switching are not taken into account.

In fact, when the frequency dependency of *ESR* is included, the complexity of the needed methodology and algorithms increases considerably. This happens in reason of the Fast Fourier Transform (FFT) that must be applied to compute the harmonic currents [1]. The complexity is even higher when the operating temperature dependency of dc-link capacitors is also considered, especially due to the fact that not all manufacturers provide this kind of information.

For these reasons, this paper aims to benchmark different capacitor losses estimation methods from the system level reliability point of view. Four different *ESR* models are compared based on complexity, estimated power losses and thermal stresses, and B_{10} lifetime: 1) constant *ESR*, 2) temperature dependent *ESR*, 3) temperature dependent *ESR*, and 4) frequency/temperature dependent *ESR*. The study case is based on a 3.5 kW PV single-stage single-phase PV inverter and two different mission profiles of solar irradiance and ambient temperature are evaluated.

2. Dc-link capacitor lifetime evaluation

This section describes the dc-link capacitor wear-out prediction methodology. The approach follows the flowchart presented in Fig 2.

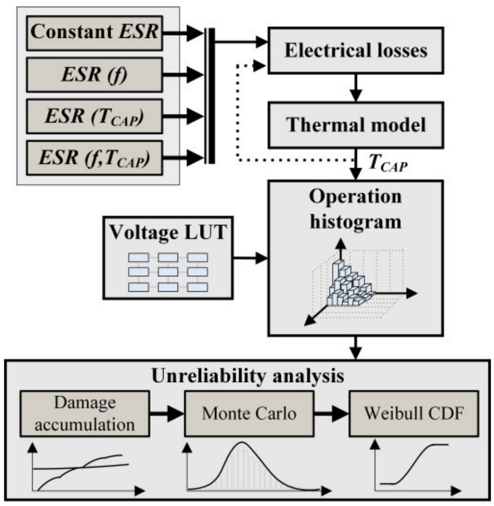

Fig. 2. Dc-link wear-out prediction flowchart.

2.1. Electro-thermal model

A simplified equivalent circuit of the electrolytic capacitor is composed only by the capacitance (*C*) and its equivalent series resistance (*ESR*). The thermal model estimates the capacitor core temperature (T_{CAP}), where the power losses (P_{loss}) are dissipated in the thermal resistance (R_{th}) between the capacitor core and the ambient; τ_{CAP} is the capacitor's thermal time constant and T_{amb} the ambient temperature. Thus, e-cap power losses and core temperature may be calculated through

$$P_{loss} = \sum_{h=1}^{N} I_h^2\left(f_h\right) ESR\left(f_h, T_{CAP}\right), \quad (1)$$

where f_h is the h^{th} harmonic frequency, and

$$T_{CAP} = P_{loss} R_{th}\left[1 - \exp^{\frac{-t}{\tau_{CAP}}}\right] + T_{amb}, \quad (2)$$

As previously discussed, e-caps *ESR* dependency with both frequency and temperature is not always included, as shown in Fig. 3, and the impact of its model complexity has not yet been thoroughly evaluated in reliability analyses. In this paper, four different methods for describing the *ESR* and the e-cap electrical model are analysed, as shown in Fig.1.c:

Method #1: *ESR* is constant and equal to the value usually provided by the manufacturer's datasheet, e.g. *ESR* at grid frequency and ambient temperature. In this approach, only the RMS capacitor current look-up tables are needed. This is the simplest and fastest power method (Fig.1b-c);

Method #2: After an initial estimation of (2), the *ESR* value is corrected as function of the temperature, using the datasheet information (Fig. 3b). An iterative method is needed once T_{CAP} is a function of the *ESR*;

Method #3: Datasheet information is used to model the *ESR* value in function of frequency (Fig. 3a). Here, the fast Fourier transform (FFT) algorithm must be performed (Fig.1b-c), increasing both processing time and needed memory;

Method #4: No simplifications are made and methods 2 and 3 are combined. This is the most demanding method since it requires both FFT to calculate the power losses as also an iteration process to estimate the capacitor temperature.

2.2. Lifetime model and Damage accumulation

Failures in e-caps may occur due to external and/or random factors such as manufacturing defect, improper design, environmental overstress, abnormal operation condition, among others. These, however, usually occur non-predictably and catastrophically – where single event leads to failure; thus, are hard to model or foresee and are usually treated as random events.

However, the wear-out of electrical parameters in aluminium e-caps is one of the dominant mechanisms that may lead to the failure of either the capacitor itself or of the circuit/control in which the capacitor is inserted. A typical and widely approach used for estimating the useful life of e-caps is through a simplification of the Arrhenius law [10], [15], which yields in lifetime (L) as a function of the capacitor operating temperature and voltage (V_{CAP}) as

$$L\left(T_{CAP}, V_{CAP}\right) = L_0 \cdot 2^{\frac{T_0 - T_{CAP}}{n_1}} \cdot \left(\frac{V_{CAP}}{V_0}\right)^{-n_2}, \quad (3)$$

where L_0, T_0, and V_0 are the capacitor's rated lifetime, temperature, and voltage, respectively, and are usually specified by the manufacturer. In this paper, n_1 = 4 and n_2 = 10 are adopted, which are within the typical range for e-caps [10]. Since the dc-link voltage is controlled and dependent mainly on ambient conditions, V_{CAP} is assumed to be the equal in all *ESR* methods for the same MP. T_{CAP}, however, is different for each *ESR* modelling.

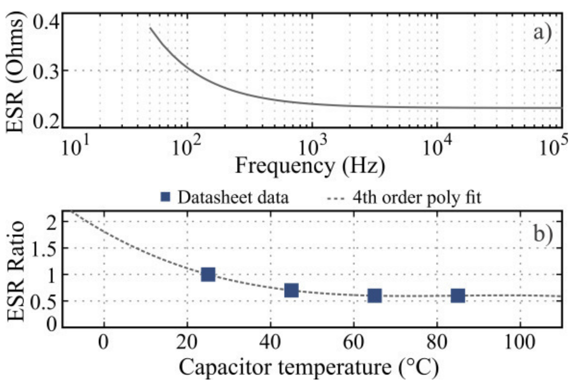

Fig 3. Variation of *ESR* with: (a) frequency; (b) Temperature [].

During day-time, the energy flowing through the PV-inverter system is constantly fluctuating due to changes of weather conditions, resulting in a variability of voltage and thermal stresses in the dc-link capacitors; where the latter is in reason of the varying ambient temperature and current levels, and the former due to MPPT voltage control of the single stage inverter.

A simple solution to quantify how this time-variant stresses impact on the overall lifetime is to use Miner's rule to calculate the ratio between the period in which the capacitor operated in each stress level, t_{Li}, and the estimated period, given by (3) it could endure at that given condition, as in

$$AD = \sum \frac{t_{L_i}}{L_i\left(T_{cap}, V_{CAP}\right)} . \quad (4)$$

Typically, the failure is assumed when the accumulated damage (AD) calculated by (3) reaches one. Although Miner's rule considers that all stress levels have the same effect on lifetime, it is still a useful figure to compare the impact of different mission profile and/or models in the damage suffered by the capacitor.

2.3. Monte-Carlo Simulation and B_{10} Lifetime

Since not all capacitors are identical and even their degradation may occur differently for the same stress level, a statistical approach is used to calculate the B_x lifetime – which is the time when x% of the samples would fail [7]. The commonly adopted B_{10} is used in this paper.

To determine the B10 values of the capacitors analysed in this paper, a Monte Carlo simulation with 10.000 samples is performed. The stochastic parameters T_{CAP} and V_{CAP} are initially converted into static values T'_{CAP} and V'_{CAP}, using (3) and (4) for the condition in which the AD is equal to one, based on the methodology proposed in [7].

The Monte Carlo simulation output is the capacitors lifetime distribution, which usually follows the Weibull distribution given by:

$$f\left(x\right) = \frac{\beta}{\eta^{\beta}} \cdot x^{\beta-1} \cdot \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right], \quad (5)$$

where β is the shape parameter, η is the scale parameter, and x is the operation time. The cumulative density function (CDF) $F(x)$, where

$$F\left(x\right) = \int_0^x f\left(x\right) dx . \quad (6)$$

The B_{10} lifetime is the time *10 %* of the samples have failed, which means $F(x)$ = 0.1. This indicator is used to benchmark the four power losses methods.

3. Study case: Single-phase PV inverter

A comprehensive study case of a PV system in long-term operation is done to evaluate how the electric model affects the capacitor reliability estimation using two distinct PV mission profiles, following the methodology in [16]. The first MP is established as the PV system operating in a horizontal fixed mounting, e.g. as in a rooftop, at Lindenberg (LIN), Germany (52 N,14 E). Whilst in the second mission profile the PV system is assumed to be using 2-axis mechanical trackers and installed in Petrolina (PTR), Brazil (09 S, 40 W).

These PV MPs are composed of real measurements of both solar irradiance and ambient temperature over a long period and averaged minute-by-minute using the same timestamp for different years, forming a typical average year (TAY) of weather conditions.

The 1-year typical average surface irradiance and ambient temperature, for both mission profiles previously described, are shown in Fig. 4. The main parameters of the studied PV system and dc-link capacitor bank are described in Table 1. The analyses are carried out using the capacitors manufactured by Cornell, part number 380LQ681M400A452.

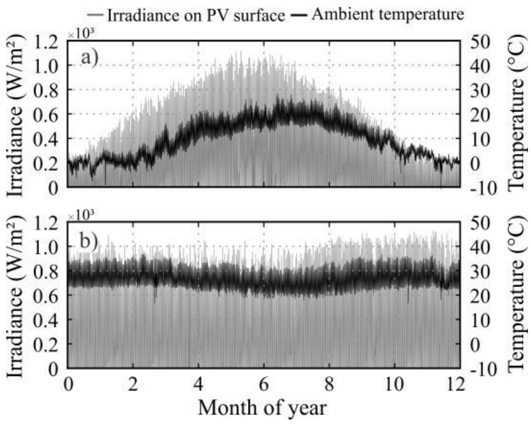

Fig 4. Solar irradiance and temperature mission profiles used in the case study: (a) LIN; (b) PTR.

Table 1
Parameters of the PV system analysed.

Parameter	Value
Panel SunEarth TPB60-60-235p rated power	235 W
Number of PV panels in series	14
Inverter rated power	3.5 kW
Switching frequency	10 kHz
Dc-link nominal voltage	380 V
Dc-link maximum ripple voltage	14 V
Grid frequency	60 Hz
Grid voltage (line-to-neutral, RMS)	220 V
Capacitor rated capacitance	0.68 mF
Number of parallel capacitors in dc-link	6
ESR @ 120 Hz, 25 C	0.293 Ω
Capacitor thermal resistance	12.58 K/W
Capacitor thermal time constant	480 s

3.1. Look-up table approach

The energy flow from the PV array into the grid is dependent, mainly, on ambient conditions and the available solar power. Therefore, by changing both the solar irradiance and the ambient temperature, in steps, the PV system entire range of operation is assessed offline.

Current and voltage values of the inverter and dc-link capacitors are stored in look-up tables (LUT) as function of the input irradiance and ambient temperature, as depicted in Fig.1.b; these LUTs are then accessed and interpolated during the long-term mission profile analysis.

4. Results

Firstly, the steady-state power losses in the dc-link capacitors were evaluated for different irradiance levels. The results are presented in Fig. 5. As observed, the increase of solar irradiance results in higher generated power and higher losses. The method 1 (constant *ESR*) results in an overestimation of the power losses when compared to the other methods. The method 4 (frequency and temperature dependent) presents the lowest losses, since the *ESR* reduces with both temperature and frequency.

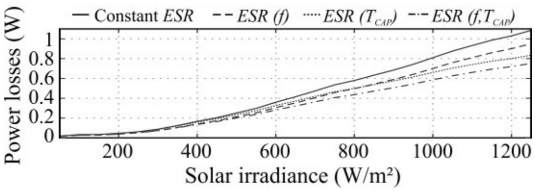

Fig 5. Power losses in a individual capacitor for different irradiance levels and 25 C of ambient temperature.

Using the power losses evaluation methods, the dc-link capacitors core temperature is computed. The distribution of estimated capacitor temperature per year is shown in Fig. 6 for the methods 1 and 4. Due to the higher average and lower variability of ambient temperature at PTR (Fig. 5b), dc-link capacitors operates in a considerably higher temperature range and for longer periods throughout the year than LIN. Notably, the constant *ESR* model results in higher values of T_{CAP}. This is consistent in both analysed MPs and indicates that the constant *ESR* method gives a worst-case scenario when estimating thermal stresses.

Considering both mission profiles, the accumulated damage can be computed. The results are shown in Fig. 7. Figure 7a shows in detail the failure probability for PTR MP, while Fig. 7b shows the failure probability for LIN MP. As observed, the higher core temperatures at PTR results in a higher damage in the capacitors and shorter lifetime. The failure probability curves follow the same pattern of Fig. 5. In such conditions, method 1 is the most conservative.

Table 2 compares the power loss computation methods based on the B_{10} lifetime. In accordance to the previous results, the constant *ESR* method for both MPs, in reason of the higher estimated thermal stresses. Furthermore, the results reveal that the temperature dependence curve of *ESR* affects more the results that the frequency dependence curve. The maximum difference observed is lower than 7.1 %.

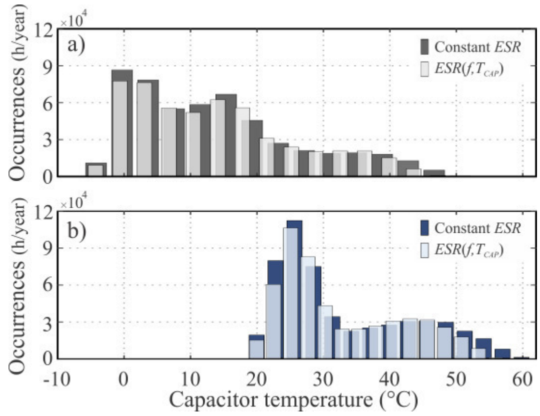

Fig 6. Core temperature distribution in the dc-link capacitors for methods 1 and 4: (a) LIN; (b) PTR.

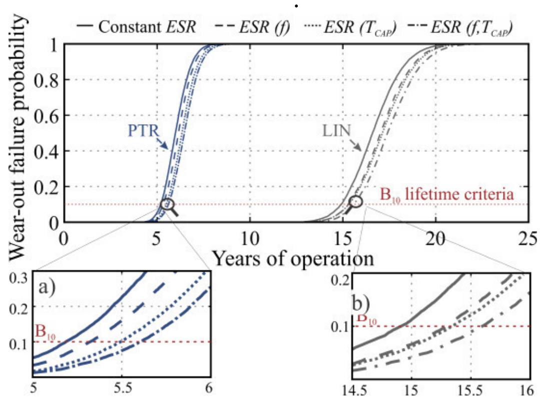

Fig 7. Wear-out failure probabilities of the dc-link capacitors for all methods: (a) Detailed view for PTR MP; (b) Detailed view for LIN MP.

Table 2

B_{10} lifetime of the dc-link capacitors for the evaluated methods.

		Method			
		1	2	3	4
LIN	B_{10} lifetime	14.882	15.343	15.324	15.593
	Error relative to $ESR(f,T_{CAP})$	-4.6%	-1.6%	-1.7%	-
PTR	B_{10} lifetime	5.209	5.514	5.310	5.608
	Error relative to $ESR(f,T_{CAP})$	-7.1%	-1.7%	-5.3%	-

5. Conclusions

In order to obtain fast tools for reliability evaluation of multiple components and long-term analysis, methods with reduced complexity and still acceptable accuracy must be employed.

Therefore, this paper benchmarked 4 capacitor power loss calculation methods for wear-out failure prediction in PV inverters. The method 1 (constant *ESR*) is the simplest since it requires only the capacitors RMS current. The frequency dependence (included in methods 3 and 4) requires the harmonic components of the capacitor current. Thereby, FFT is employed and the computational effort increases.

The maximum difference observed in the dc-link B10 lifetime was 7.1% for Petrolina and 4.6 % for Lindenberg mission profile. Regarding to methods 2 and 4, these values reduced to 5.3 % and 1.7 %, respectively.

Finally, Table 3 benchmarks the discussed power loss evaluation methods. The symbols indicate good performance (+++), average performance (++) and poor performance (+).

Table 3
Benchmarking of the power loss computation methods.

Figure of Merit	Method			
	1	2	3	4
Required model information	+++	++	++	+
Accuracy	+	++	++	+++
Complexity	+++	++	++	+
Required processing time	+	+	+++	+++

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