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Uncertainty analysis of capacitor reliability prediction due to uneven thermal loading in photovoltaic applications

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Abstract

Because of the high cost of failure, the reliability performance of capacitors is becoming a more and more stringent factor in many energy conversion applications. Since temperature is one of the main stressors that leads to the wear-out of capacitors, it is important to understand the uncertainties introduced by the capacitor thermal modelling within its reliability prediction process. Thus, in this paper, the uncertainties introduced by uneven thermal loading, and their impact on the reliability of a photovoltaic application DC-bank are investigated. Based on a generic model-based reliability assessment procedure, a reliability evaluation tool is initially developed and used in order to quantitatively analyse the impact of these uncertainties. The lifetime evaluation of the individual capacitors/DC-bank is estimated and afterwards benchmarked under even/uneven thermal loading conditions. The outcomes of the uncertainty analysis indicate that the uneven thermal distribution among DC-link capacitors can have a significant impact on both component and system-level reliability performance.

1. Introduction

Due to their essential role within many applications, the reliability of the power converters is one of the main factors that influences the overall efficiency and cost of the system [1]. However, as it has been shown in [2], based on failure information of a photovoltaic (PV) plant operated throughout the course of 5 years, the inverter represents one of the most critical sub-assemblies of the PV system.

Consequently, numerous studies have been carried out in order to determine the main causes of failure in power electronic systems, and it has been concluded that the capacitors are among the most fragile components of the power converter, with respect to reliability [3]. According to [4], the predominant sources of stress in electronic equipment are the steady state and cycling temperatures, which are mainly caused by the fluctuating load of the converter and environmental temperature variations, which can lead to a faster wear-out. The unexpected wear-out failures of the capacitors [5] will lead to an increase in maintenance cost, and a cutback in the total energy production of the system, and thus resulting in a higher cost of energy conversion.

In order to address the given issue, and to achieve a better balance between lifetime and cost, a more accurate reliability assessment procedure for the DC-link capacitors is required. By understanding the underlying uncertainties and assumptions behind the model-based reliability assessment analysis [6], a more confident lifetime estimation can be achieved. Many of these uncertainties can be introduced either by the operating/environmental mission profiles [7], loss and thermal behavior modeling, damage accumulation method or by the lifetime model itself [8].

The uncertainties related to the thermal modelling of the capacitor are mainly caused by the self-heating effect (internal temperature rise) induced by the variations in the ESR and/or capacitance. Additional uncertainties are caused by the mutual-coupling effect between the different capacitors of the DC-bank, which will result in a difference in case temperature, and inherently in the lifetime expectancy.

Thus, in this paper, a method to quantitatively analyze the impact of these uncertainties on the

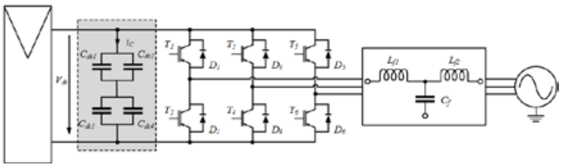

Fig. 1. System diagram of PV application study-case.

capacitor reliability prediction is proposed. According to a generic reliability assessment procedure, a model-based reliability evaluation tool is initially proposed and used in order to estimate the component/system-level reliability for a 3-phase photovoltaic application study-case, as shown in Fig.1. Finally, the uncertainty analysis is performed under even and uneven thermal loading conditions, and the outcomes are highlighted and benchmarked.

2. Model-based reliability assessment procedure for DC-link capacitors

A generic reliability assessment procedure has been developed and presented in Fig. 2. The given method can be successfully applied for both active [9] and passive power electronic components, but within this paper it will be used in order to investigate the lifetime estimation of the capacitors/DC-bank of the study-case PV application.

2.1. Mission profiles and system specifications

The annual environmental mission profiles shown in Fig. 3, together with the system specifications given in Table 1, will represent the inputs to the system-level mission profile modelling block. In order to meet the DC-link voltage requirements of the study-case application, a DC-bank configuration consisting of four Nippon Chemi-con KMQ 400 V 680 μF capacitors connected as shown in Fig. 1, are employed.

Table 1
Parameters for PV system study-case

Parameters	Symbol	Value
Rated power	P_o	10 [kW]
Fundamental freq.	f_o	50 [Hz]
Grid voltage	V_{grid}	230 [Vrms]
Switching freq.	f_{sw}	20000 [Hz]
DC-link voltage	V_{dc}	700 [V]
Filter inductance 1	L_{f1}	4.05 [mH]
Filter inductance 2	L_{f2}	4.05 [mH]

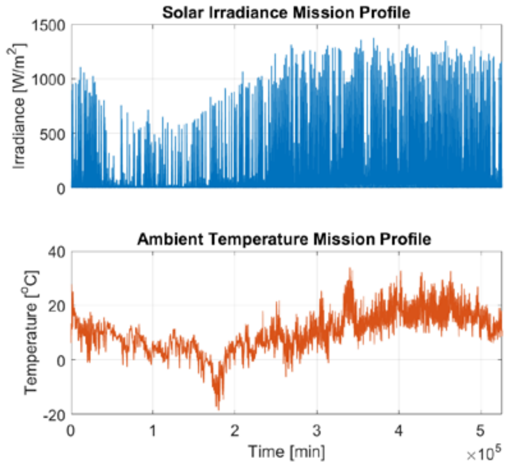

Fig. 3. Long-term environmental mission profiles of the PV systems study-case.

2.2. Component/system-level reliability evaluation

During the first stage of the reliability assessment procedure the environmental mission profiles and the specifications under which the PV system is operated are inputted in the system-level models [10], where the electro-mechanical dynamic behaviour of the study-case PV application will be investigated, and thus the converter-level electrical loading can be determined.

Afterwards, the resulting converter-level mission profiles (e.g. converter voltage and current) can be introduced into the converter-level mission profile modelling block, where the electrical simulation of the power converter is performed, and the local electrical stress of each component can be identified.

In the following, the voltage and current stress of the DC-link capacitors will represent the input to the component-level mission profile modelling block. Within this stage of the capacitor reliability evaluation procedure, the electrical stress will be translated into the thermal stress (internal hotspot temperature), by means of electro-thermal models [11]. The power losses generated by the capacitor are calculated according to Eq. 1:

$$P_{C,loss} = I_{C,rms}^{2} \cdot ESR(\omega) \quad (1)$$

where, $I_{C,rms}$ represents the current flowing through the capacitor, and $ESR(\omega)$ represents the frequency dependent equivalent series resistance (ESR) characteristic of the capacitor, as given in the datasheet. Thus, the hotspot temperature of the capacitor is given as,

$$T_h = P_{C,loss} \cdot R_{th} + T_a \quad (2)$$

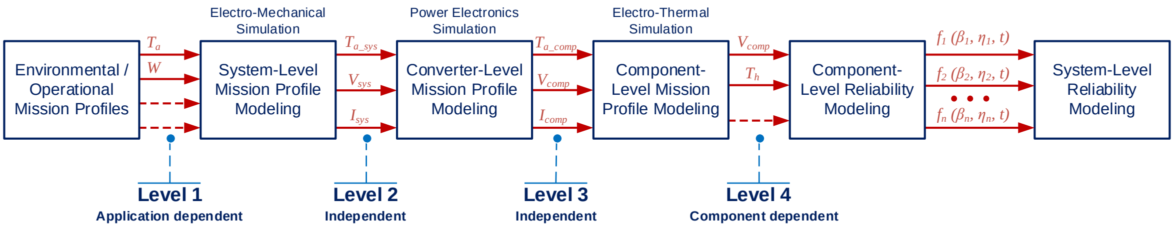

Fig. 2. Generic model-based reliability assessment procedure for DC-link capacitors.

where, R_{th} represents the thermal resistance of the capacitor, and T_a represents the local ambient temperature [12]. The capacitor thermal resistance can either be found in the manufacturer datasheet, or it can be determined according to its physical dimensions [13].

The component-level mission profiles (e.g. hotspot temperature, voltage, etc.) can then be translate into the capacitor lifetime estimation by means of strength models. Although many capacitor lifetime models have been discussed throughout the literature [5, 14, 15], a simplified model for aluminum electrolytic capacitors will be employed:

$$L = L_0 \cdot \left(\frac{V}{V_0}\right)^{-n_1} \cdot 2^{\frac{T_0 - T}{n_2}} \tag{3}$$

where, L and L_0 are the lifetimes under operating and reference conditions, respectively, V is the voltage under operating condition, V_0 is the voltage under reference condition, T represents the temperature under use condition and T_0 is the temperature under reference condition. Additionally, n_1 represents the voltage stress exponent (usually varies between 3.5 and 9.4) and n_2 represents the temperature stress exponent (varying between 10 and 13) [5].

Finally, the reliability information of each individual capacitor can be used in order to determine the reliability of the DC-bank, through Reliability Block Diagram (RBD) analysis [16]. Thus, the unreliability of the DC-bank sub-assembly can be calculated according to the following equation [17]:

$$F_{sub}(t) = 1 - \prod(1 - F_{Comp(i)}(t)) \tag{4}$$

where, F_{sub} represents the sub-system failure function, and $F_{comp(i)}$ represents the individual component failure function.

2.3. Reliability assessment tool platform

In order to facilitate a fast and straightforward reliability analysis, all the models employed in the

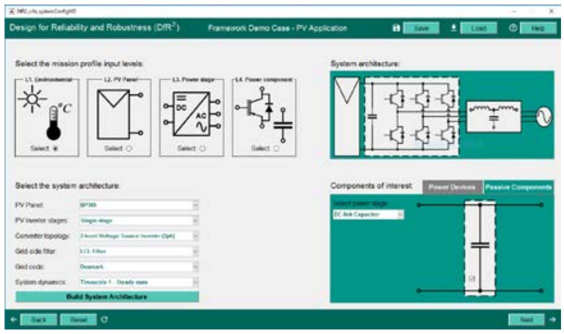

Fig. 4. DfR² reliability tool – Graphical interface [9].

reliability assessment procedure have been implemented in a tool (Design for Reliability and Robustness – DfR²), as shown in Fig. 4. The main tool framework has been designed with a generic and modular approach in mind, and thus allowing for various power electronic applications to be implemented in investigated according to the reliability evaluation method presented in Fig. 2.

The study-case PV application shown in Fig. 1 has been integrated in the DfR² tool, and the capacitor reliability evaluation has been carried out based on the mission profiles shown in Fig. 3, and under the assumption that the temperature is evenly distributed among all four capacitors of the DC bank. Thus, as expected, the resulting capacitor hotspot temperature and accumulated damage, which are presented in Fig. 5, are the same for all capacitors of the DC-bank.

Under the given assumptions, all four capacitors will show the same reliability performance. The unreliability information of each individual capacitor is taken into account and used in order to determine the unreliability curve of the entire DC-bank configuration. From the total cumulative failure due to E-Cap wear-out shown in Fig. 6, it can be noticed that the expected lifetime of the DC-bank is 17 years, considering a 1 % probability of failure (B1). Moreover, considering a 10 year operating lifespan requirement, 0.18 % of the population will fail under the given operating conditions and assumptions.

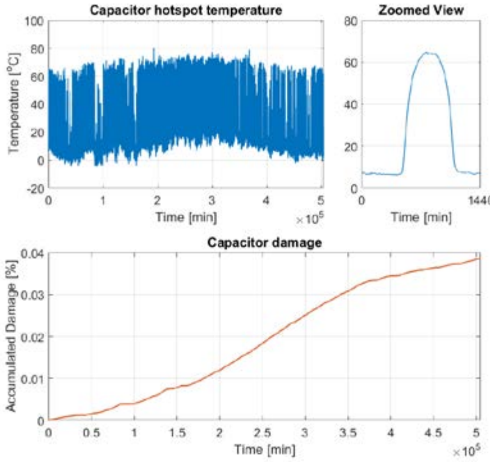

Fig. 5. Capacitor stress under even thermal loading.

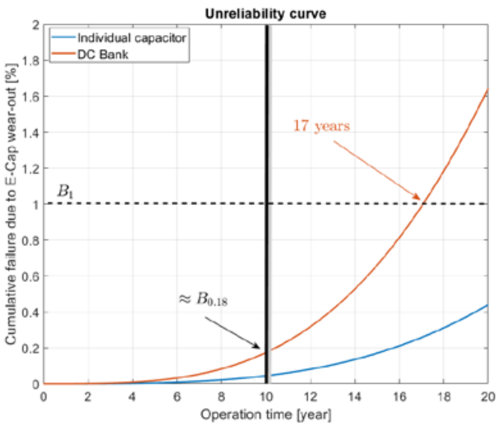

Fig. 6. DC-bank unreliability under even thermal loading.

3. Impact of uneven thermal loading conditions on the capacitor reliability prediction

Normally, the local ambient temperature among the capacitors of the DC-bank is unevenly distributed. This is due either because of the mutual-coupling effect between the capacitors and/or other power components, or due to the different placement of the capacitors on the PCB layout [18].

Therefore, an uneven thermal distribution is assumed among the capacitors of the DC-bank of study-case PV applications. The capacitor C_{dc1} is considered as the reference, C_{dc2} is assumed 1ºC colder, while C_{dc3} and C_{dc4}, hotter by 3ºC, respectively 4ºC. The impact of the different local ambient temperatures on the hotspot temperatures of the capacitors can be clearly seen in Fig. 7. Since temperature is the main stressor that leads to the wear-out of aluminium electrolytic capacitors, it is expected that the temperature difference will have a significant impact on the lifetime expectancy of the capacitors, and inherently of the DC-bank.

As shown in Fig. 7, a higher damage will occur on the hotter components, with an increase of approximately 25% damage increase in C_{dc4} with respect to the reference C_{dc1}, and thus leading to a shorter lifespan expectancy.

The individual reliability metrics of each capacitor is used in the RBD analysis in order to determine the reliability of the DC-bank, which is shown in Fig. 8. The uneven thermal distribution will lead to a decrease DC-bank lifetime, with a 14 year lifetime expectancy for 1 % probability of failure. The decrease in lifetime is more notable especially when considering higher probability of failure requirements. Considering the 10 year lifetime requirement, it can be noticed that approximately 0.37% is expected to fail.

Finally, in order to quantitatively analyze the impact of the uncertainties related to uneven thermal loading on the lifetime estimation of the capacitors/DC-bank, an uncertainty analysis is performed. The outcomes of the uncertainty analysis are highlighted in Fig. 9 and Fig 10.

Considering a 90% confidence interval, the B_1 lifetime expectancy of the DC-bank under uneven thermal distribution is between 11.5 and 16.5 years, and between 14 and 20 years respectively, when considering an even thermal distribution among the capacitors. The probability density function (pdf) for the two cases can be seen in Fig. 9.

Similarly, if the 10 year lifetime requirement is considered for the DC-bank, a significant difference can be noticed in its cumulative failure distribution, under the even and uneven loading conditions. As shown in Fig. 10, it can be assumed that with a 90 %

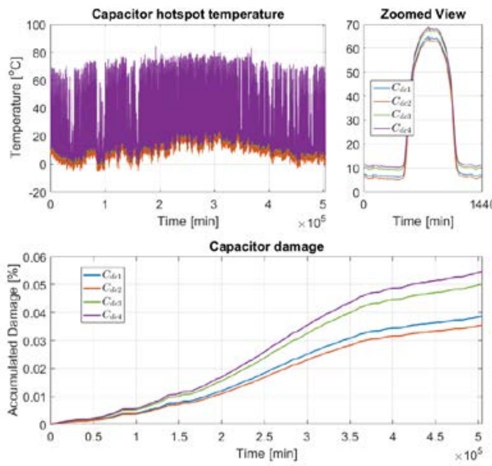

Fig. 7. Capacitor stress under uneven thermal loading.

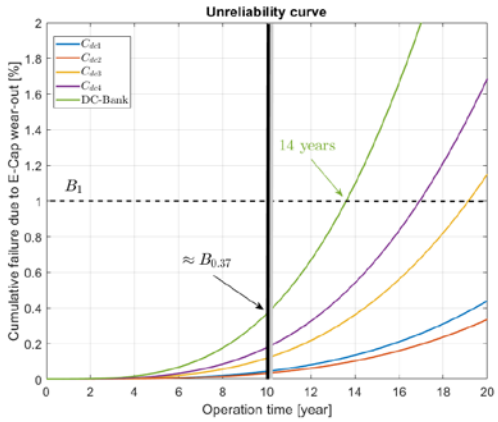

Fig. 8. DC-bank unreliability under uneven thermal loading.

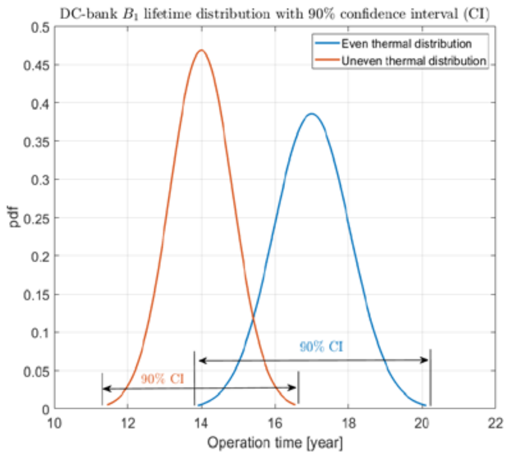

Fig. 9. DC-bank B_1 lifetime distribution under even/uneven thermal loading conditions.

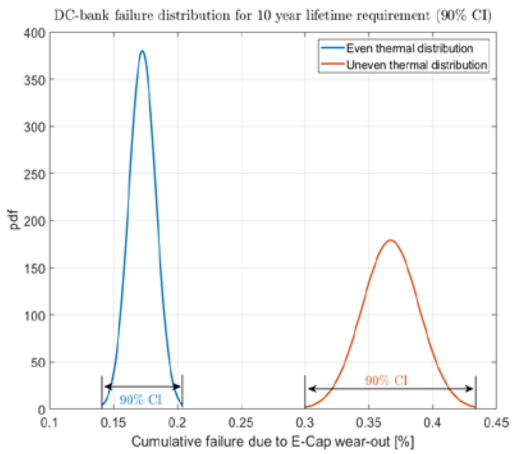

Fig. 10. Cumulative failure under 10 year lifetime requirement under even/uneven thermal loading conditions.

confidence interval the cumulative damage of the DC-bank under even thermal distribution will be between 0.14 % and 0.2 %, while for uneven thermal distribution between 0.3 % and 0.42 % of the population will fail until reaching the specified lifetime requirement.

4. Conclusions

In this paper, the impact of the uneven thermal loading condition on the capacitor reliability prediction has been investigated. A modular reliability assessment procedure for the capacitors/DC-bank of a PV application study case has been proposed and its models have been briefly introduced. The models employed within the generic the reliability evaluation method have been integrated within a reliability tool (DfR2). The DfR2 tool has been used in order to investigate reliability performance on both component and system-level of DC-bank under even and uneven thermal loading conditions. Finally, the outcomes of the uncertainty analysis have been investigated by means of probability density function, and the results indicate a significant deviation in lifetime as a result of uneven thermal distribution among the capacitors of the DC-bank.

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