Introducing the LEGO Mission Profile Analysis Methodology

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Introduction of the LEGO Mission Profile Analysis Methodology

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Abstract

This manuscript will introduce a new mission profile analysis methodology for reliability analysis such as health monitoring and lifetime estimation. The model deconstructs the mission profile into stress event bricks which, when combined, can report the health and damage state of the analysed system.
The model offers an alternative to the dated Rainflow Counting method. The presented model will take advantages of modern analysis software such as circuit simulators, finite element analysis software and general purpose numerical computing software.
The manuscript will detail the methodology and end with a case study implementation of the methodology. Special focus will be placed on the categorising and loading evaluation steps in the methodology.
The resulting data from the analysis provide several insights to the application and the mission profile. The methodology can be used as loading input to improve lifetime and optimise loading profile. Using the methodology on a mission profile to compare to a power cycling strategy will enable a quantifiable analysis of the acceleration factor between the two. Alternatively the results from the methodology may be used to design power cycling tests with a specified acceleration factor.

1 Introduction

Today most products experience fatigue and life testing to ensure reliable operation during the lifetime of the product. These tests are primarily performed using highly magnified loading levels to test the life of the product within a fraction of the expected lifetime.
For power electronics such an accelerated life test is done through power cycling. Traditionally the acceleration factor and test loading levels are designed using engineering experience rather than actual quantifiable component and failure mechanisms.
While this is the traditional approach it is not without disadvantages. An accelerated life test designed in this way cannot be directly linked to the lifetime during other loading conditions. This usually leads to a number of different loadings points being necessary to characterise the S-N curve, which relates the loading to the number of cycles before failure. As multiple test samples are needed for statistical reliability the number of required power cycling tests quickly becomes an ordeal. Additionally the power cycling tests have a limit to the possible acceleration factor; if the test loading becomes too high, the activated failure mechanisms begin to differ from those activated during normal loading[2].
The ideal analysis of the reliability of a device in an application is achieved by knowing and understanding both the device itself and the application it is used in. This encompasses an understanding of the application from external factors, through the mission profile and circuit operation down to the electro-thermo-mechanical environment the device is in. The better the device and application is understood the fewer of the aforementioned issues are going to become problems.
This paper will present a physics-based methodology for analysing the expected mission profile and designing accelerated testing profiles based on the mission profile, the system topology, the stressed device and relevant simulations of the aforementioned.

2 State of the Art

To asses the foundation this work builds upon, a brief review will be performed on the state of the art of reliability analysis methods incorporating advanced software solutions.
In [1] the effect of a wind power mission profile is evaluated top down from the converter level to the rainflow counting of a mechanical finite element analysis of the power module. Here the mission profile itself is not sorted or categorised beyond the 5 by 5 binning strategy.
[5] combines a fast electro-thermal IGBT model in Simulink with a thermo-mechanical FEM COMSOL simulation to evaluate the loading of the IGBT module during temperature swings. The mechanical simulation is finally used to estimate the lifetime of the analysed IGBT module using the Darveaux fatigue model with generic coefficient values.
[6] performs electrical and thermal analysis of a converter system. Here the electrical analysis has the purpose of determining the energy production. The analysis is carried out for three different converter topologies to compare the energy output and lifetime of the converters. Rainflow counting of the junction temperature is used to estimate the lifetime.
A novel mission profile analysis method is carried out in

[4]. Here a case study is performed for the accelerated life test of a solar inverter application. The mission profile for the inverter is used as the starting point for the generation of two different accelerated life test profiles. One of these was focused on power cycling speed increase and the other was focused on capturing a representative junction temperature swing distribution. The thermal model used was a three node thermal network from the device datasheet.

While many efforts have been made in the field of mission profile analysis, no direct link has yet been found between mission profile loading conditions and power cycling loading conditions, in other words, it is still not possible to determine the acceleration factor until after all tests have been performed.

When it comes to quantifying damage, Rainflow counting is the main method, but half a century has passed since its invention. Strides in in the relevant technological fields should enable a new and improved method.

The problem can be split into two topics, one of which will be the main focus of this manuscript. A new method for evaluating damage is needed, as well as a new way of counting this damage. The latter will be the focus of this manuscript.

3 Problem Statement

A new methodology to analyse power device load identification, counting and analysis should be formulated, preferably with the possibility to link to modern circuit simulation and finite element analysis tools.

4 Method

A new mission profile analysis methodology will be formulated in this paper. The method will be based on data availability of power electronics mission profiles, intelligent sorting/binning and and a strong connection to finite element software.

The section in this report after this section will give an overview of the proposed mission profile analysis methodology. The next section will detail the event sorting concept and process.

The damage modelling step will be discussed and a suggested approach is presented.

The possible applications for this model will be presented. Finally a case study of an example implementation is presented before the paper is concluded.

5 Overall Flow

The overall flow of the analysis is seen in fig. 1.

5.1 Mission Profile Input

The assumed format of a mission profile is a time series of the power transferred by the power electronics system. This may be accompanied by a time series reporting the ambient temperature when relevant for the application. This data has a certain time resolution and duration.

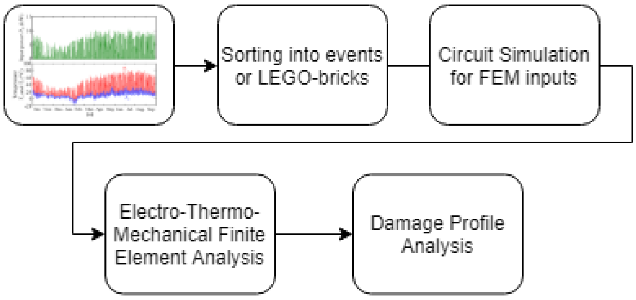

Figure 1 Concept Flowchart

5.2 Binning/Block Separation

The mission profile is initially analysed and sorted in MATLAB. This analysis will categorise each datapoint in the mission profile as a type of event. The event categories are: Zero power, steady state, small transition and large transition.

5.3 Circuit Simulation

Here the blocks from before are modelled in a steady state switching circuit simulation. From this the power losses are recorded for each analysed transistor chip and diode, as well as the currents. Yielding in 6 transistor power loss curves, 6 diode power loss curves and 6 current curves. This simulation is run until steady state is reached at which the previously mentioned waveforms are recorded for the duration of one fundamental period.

5.4 Loading Evaluation

The loading linked to certain events are evaluated using a electro-thermo-mechanical simulation in COMSOL Multiphysics.

5.5 Damage Analysis

Finally the damage is returned to MATLAB ready for further analysis. A short discussion of possible applications of this analysis is presented in section 8.

6 Sorting Process

To understand the data contained in the mission profile it is important to understand the system experiencing the profile.

Initially a finite element simulation was performed to evaluate the electro-thermo-mechanical response time of the system. If any significant delay exists from the timing of the mission profile to the loading of the power modules, either from system or control dynamics, these must be evaluated as well.

The sorting process can be seen in fig. 2

Depending on the specific details of a mission profile certain event type may be identified in different ways. An example of this could be a year long mission profile for a photovoltaic connected inverter, for this application it is safe for most locations to assume that approximately half of the datapoints occur during night, thus making them

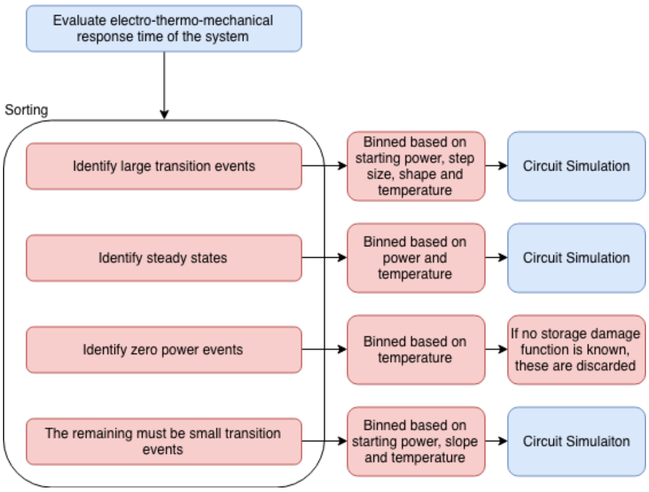

Figure 2 Main Sorting Flow.

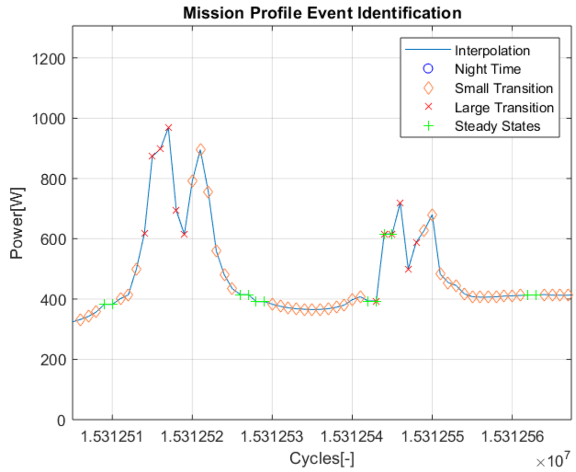

Figure 4 Analysis of about 30 seconds.

zero power points. An understanding of the application is paramount for mission profile analysis and sorting.

For many applications timepoints with no power correspond with no temperature swing and thus no damage for the power devices. Because of this, these states are discarded from further analysis.

Steady states should be defined as successive states with no or very little change in amplitude.

Large events are transitions so large that the system will take more than timestep to settle to steady state.

Small events are transitions that settle to steady states within 1 second.

Examples of analysed profiles can be seen in figs. 3 and 4. In fig. 3 a few days can be seen, with the days comprised of steady state, small and large events and these days are connected by periods of night time. In fig. 4 the micro-sorting of steady states, small and large events is clear.

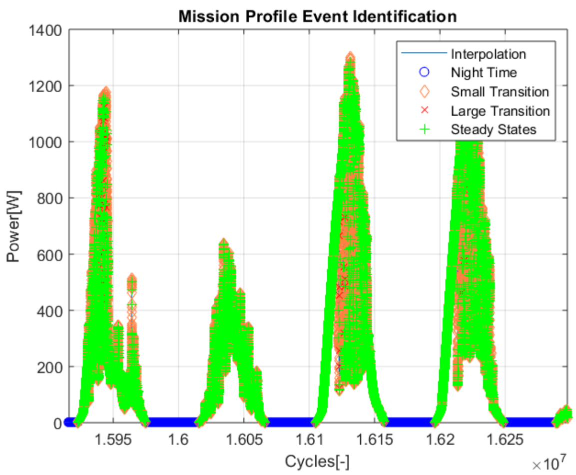

Figure 3 Analysis of a few days.

7 Damage Modelling

Damage is usually modelled using either Coffin-Manson or Paris's Laws, however as time affects the damage mechanisms and material properties or an object a time dependent loading model must be found or formulated.

The first term is based on same premise as the Paris Law and Coffin-Manson Equation, that the component cycling causes damage.

$$\Delta D \propto \Delta x \tag{1}$$

Where x is any of stress, strain, stress intensity, temperature or other loading quantities.

If the damage is related to changes in subject loading it is natural to transform the above relationship to a time-based equation in the following form:

$$\Delta D \propto \frac{d}{dt}x \tag{2}$$

The second term of the equation is based on the following assumptions:

$$D \propto a \tag{3}$$

And a Paris law relation:

$$\frac{da}{dn} = Cf(\sigma)^p \tag{4}$$

Thus:

$$D \propto \int (Cf(\sigma)^p)\, dn \tag{5}$$

Based on xyz we think both transitions and steady states at power are potentially damaging events and so we are evaluating the loading signal like so:

$$D = \int \left(a \left[\sqrt{\left(\frac{dx}{dt}\right)^2} \right]^b + c(x)^d \right) dt \tag{6}$$

Where x is the system loading quantity.

As a direct result of equation 6 the steady state events can be reduced to time invariant simulation.

8 Applications

As the work on this model was initiated to find a modern replacement for rainflow counting in power electronics the

methodology should be applicable to the cases where rainflow counting have been used historically. However, as this methodology is more time consuming than rainflow counting, some use cases, where simplicity or speed are the main requirements, may continue to use rainflow counting.
The resulting damage distribution and relative loading from the analysis methodology give insight into whether not certain events in a mission profile damage the device more than others. This can be used to optimise the design or the control of the converter system to avoid these events.
If the methodology is applied to both the application mission profile and the power cycling profile for a specific converter system, the acceleration factor for the power cycling strategy can be evaluated directly, yielding a quantitative rating for power cycling strategies.
The identified events of the mission profile can be used to construct a mission profile calibrated accelerated life test load profile. Using this approach the acceleration factor is directly available and the test profile can be ensured only to activate the failure modes of the field application.

9 Example Implementation

The flow and concept of LEGO-block analysis will be described using a practical case.

9.1 Topology

The analysed application is a three-phase inverter operating as link between PV and a grid.
The module is a gel filled module with 6 IGBTs and 6 diodes. No parasitic components are included in the example. Also for the sake of example; the input voltage source and grid source are considered ideal and constant apart from power in/output. The analysed circuit is seen in fig. 5.

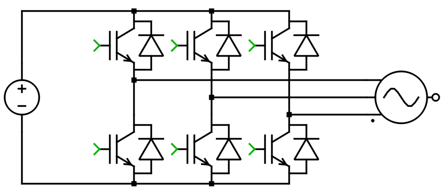

Figure 5 The Example Inverter Topology.

9.2 Mission Profile

The analysed mission profile contains the power and ambient temperature data on a per second time resolution for an entire year. The mission profile is seen in fig. 6. The system and topology is assumed to experience the power and temperature of the mission profile instantly, no delays come from the hypothetical PV source represented by the voltage source.

9.3 Analysis

From a power impulse simulation in COMSOL the time constant of the system was found to be 0.3 seconds. From an evaluation of the largest power step it was concluded that the system would not have time to settle within one second after a large power step like this. The power step limit was found, thus enabling the categorisation of a transition event as small or large.
From this the following distribution of events were identified:

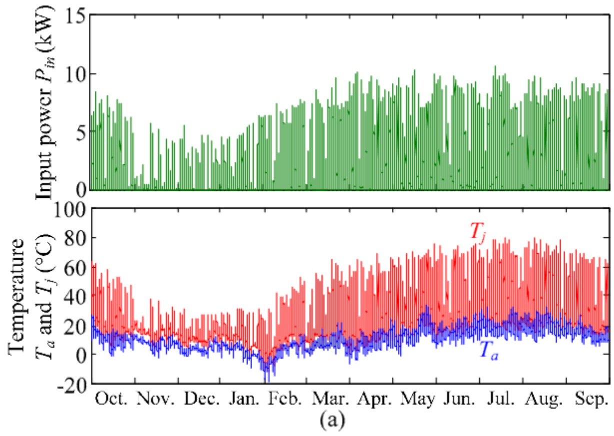

Figure 6 The Example PV Mission Profile.

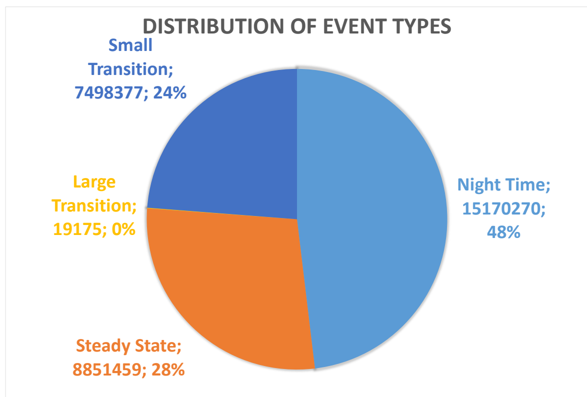

Figure 7 Event Distribution.

A fear within reliability engineering is that certain dangerous events has a large effect on the lifetime. For this application and mission profile the large transitions accounted for 0.68% of the loading even though only 0.03% of the total time consisted of large transition events. So while they contribute considerably more damage per event than the other event types, a complete elimination of these large events would only reduce total loading by less than 0.68%.
However if one were to perform an accelerated life test based on the single most damaging event. An event lasting three seconds and consisting of 2.2748e-04% of the loading of the year. With repetitions of this event the entire loading of the year could be realised in just over 15 days (15.26 days).

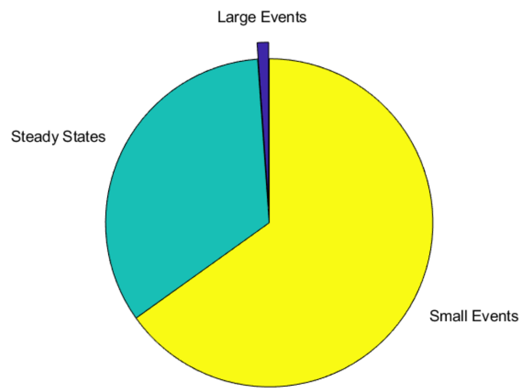

Figure 8 Damage Distribution.

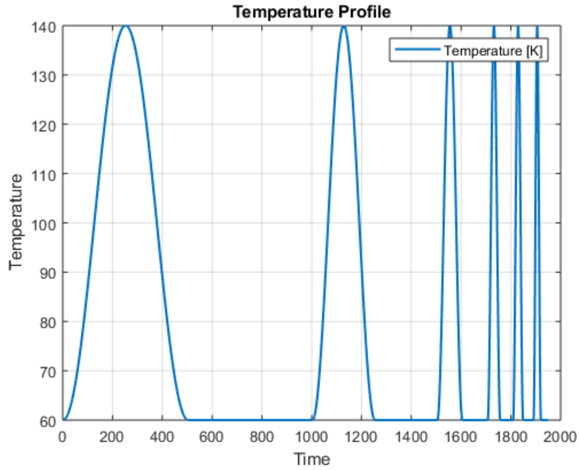

Figure 11 Basic Verification Profile.

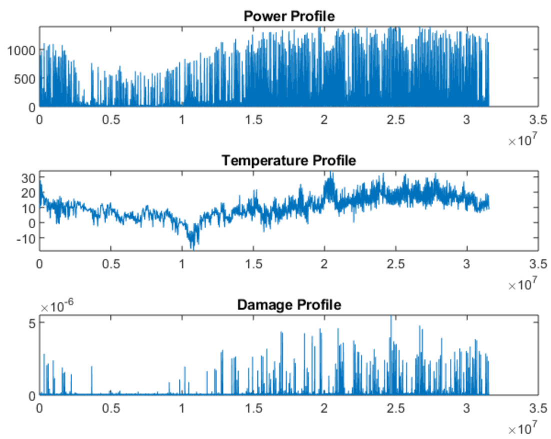

Figure 9 Mission Profile with damage.

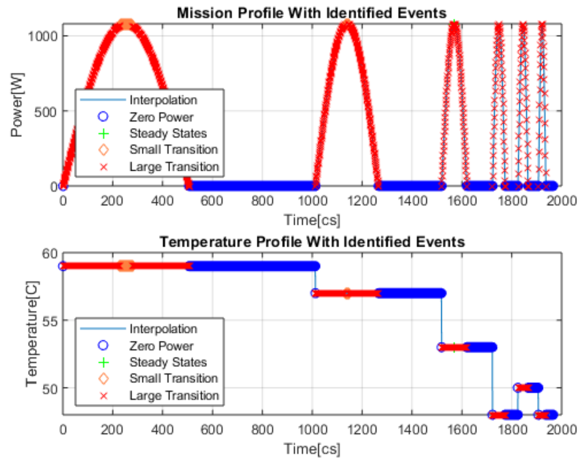

Figure 12 Verification Profile Event Analysis.

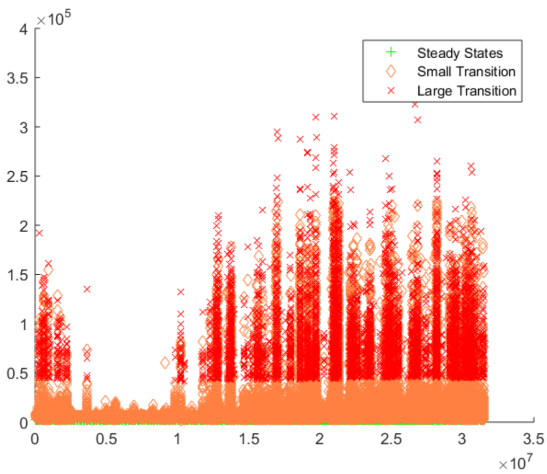

Figure 10 Damage Profile.

10 Basic Verification

The power cycling data from Uimin is known. Both the loadings and the results.
The testing profile is seen in fig. 11.

The verification profile was analysed using the same algorithm. The events in this profile were characterised as seen in fig. 12. Here it is clear that the algorithm categorises the power cycling pulses exactly as expected, the power pulses are uninterrupted transition events divided by periods of zero power. As the loading is sinusoidal it never reaches steady state.
As events are defined as beginning and ending in steady state the verification profile only contains six "active" loading events, and five zero power events. As the results are known for power cycling of pure sequences of each of the type of pulses featured in figs. 11 and 12, the relative loadings of the pulses are known. These are seen in table 1.
The events identified in fig. 12 were evaluated using a finite element digital twin simulation as described in section 5. Using a selection of evaluation methods the loading factors can be evaluated. In [3] it was shown that the damage of the testing conditions follows a linear damage accumulation.
The methods from fig. 13 and table 1 are:
Method A: Value range during period of the Enthalpy evaluated with volume integration over entire geometry.
Method B: Max rate of change during period of Stored Energy evaluated as the sum over critical points.

Table 1 Acceleration Factors for the test conditions, compared to test condition 6.

Cond.	1	2	3	4	5
Empirical	1.6385	1.3208	1.2138	1.1367	1.0694
Meth A	1.6141	1.3241	1.1449	1.1591	1.0883
Meth B	1.4231	1.3485	1.2613	1.1794	1.1646
Meth C	1.4590	1.3151	1.1899	1.2071	1.1146

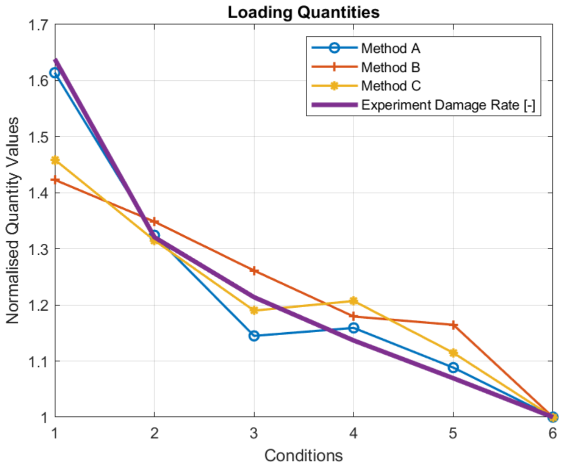

Figure 13 Experimental damage rates and digital twin simulations.

Method C: Value range during period of the Displacement evaluated using volume integration over bond wire domains.

11 Conclusion

In this paper a mission profile analysis method was presented. The main methodology consists of three processes, based on an input and yield a loading profile for the analysed application.

The methodology assumes an input mission profile of power and temperature with a given time resolution. Based on system and finite element analysis the control-electro-thermo-mechanical response time of the application is evaluated. This enables the sorting of mission profile events into zero power, steady state, small transition and large transition events. The categorisation of a certain event determines how it is further processed. The thoroughness of the further processing depends on the suspected damage of the event category, the large transition category, which is suspected to contain the most damaging events, is most thoroughly investigated. For some applications the zero power events may be discarded entirely.

The sorting methodology was detailed in this paper,

The loading of the

A PV application was used as an example case for the analysis methodology. The mission profile and topology were presented, as was the results from the analysis. It was concluded based on the damage distribution among the event categories that the large events, while individually more damaging, only contributed a small fraction of the total loading. Additionally it was concluded that the loading of the entire years mission profile could be tested using only 15.26 days of stress testing.

While this methodology was developed for power electronics the general methodology may be applicable to reliability engineering within other fields.

12 Literature

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