Multi-timescale Modelling for Reliability Analysis of Power Electronic-Based Systems

Fogsgaard, Martin Bendix

DOI (link to publication from Publisher):
10.54337/aau588631957

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

MULTI-TIMESCALE MODELLING FOR RELIABILITY ANALYSIS OF POWER ELECTRONIC-BASED SYSTEMS

BY
MARTIN BENDIX FOGSGAARD

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

Multi-timescale Modelling for Reliability Analysis of Power Electronic-Based Systems

Ph.D. Dissertation

Martin Bendix Fogsgaard

Dissertation submitted month 07, 2023

Dissertation submitted:	September 2023
PhD supervisor::	Prof. Frede Blaabjerg Aalborg University
Assistant PhD supervisors:	Prof. Francesco Iannuzzo Aalborg University
	Assoc. Prof. Amir Sajjad Bahman Aalborg University
PhD committee:	Associate Professor Sanjay K. Chaudhary (chairman) Aalborg University, Denmark
	Professor Li Ran University of Warwick, Unite Kingdom
	Professor Leonids Ribickis Riga Technical University, Latvia
PhD Series:	Faculty of Engineering and Science, Aalborg University
Department:	AAU Energy

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-627-0

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Stibo Complete, 2023

Biography

Martin Bendix Fogsgaard

Martin Bendix Fogsgaard received his B.Sc. and M.Sc. respectively in 2016 and 2018 at AAU Energy (formerly the Department of Energy Technology) at Aalborg University with a specialization in Power Electronics and Drives. For the final year of his Master's Degree he worked closely with GOMSpace on design of power converters using GaN HEMTs for space applications.

After that he was a Research Assistant at the same department where he worked on the modelling of reliability and degradation of power electronics. In his time at the department he has worked with power electronics reliability with external companies and on projects such as APETT and REPEPS. The PhD project falls within the REPEPS project which is introduced in the first chapter of this thesis.

His main research interests include power electronic devices, their reliability, the physics of operation and degradation and the modelling and prediction of the same.

Abstract

Electrical power systems worldwide are changing and will change even more in the coming years as more renewable sources of generation will be integrated in to the power system. Power electronics are a key technology for renewable generation, as well as for electric vehicles. It is also an enabler for efficiency gains in some electrical systems.

Power electronics is therefore also a critical technology. If all of the power electronics of a wind turbine generator fail, it ceases to provide power to the grid. If the power electronics in an electrical vehicle fail, the vehicle cannot drive. As a result, the importance of reliable power electronics is greater than ever.

This PhD project examines the current state-of-the-art of reliability analyses of power electronics and develops new methods for reliability analysis of power electronics.

One challenge to do wholistic reliability analysis of power electronics is the spread of relevant dynamic phenomena across different timescales. This means that some effects occur in the range of milliseconds and some effects occur in the range of years. One way to solve this issue is to neglect some of the effects and thus reduce the timescales for modelling. This thesis will develop methods to unify the modelling of effects across the timescales and thus enable multi-timescale modelling of power electronics.

The work of this thesis will focus on photovoltaic(PV) generator systems also known as solar cells, but the analyses carried out are applicable for other systems as well. The physics and timescales of PV inverters are examined, and the developed models are used as a foundation for the rest of the analyses in the thesis. The PhD project proposes a new method for evaluation of experimental loading based on the developed knowledge of the device modelling.

The project also proposes an alternative to the cycle-based damage evaluation commonly used for power components in the engineering field today. A mission profile simplification methodology has been developed and further improved upon.

The project also investigates ways to integrate damage and degradation modelling with the modelling of the regular operation of a PV inverter system, which culminates with a case study of two commercial PV inverters subjected to multi-timescale degradation integrated modelling.

Finally, the research question was answered when a method was developed achieving multi-timescale reliability modelling of PV inverter systems.

Resumé

Elnettene verden over er i stor forandring. De vil fortsat ændre sig, i takt med at mere og mere energi kommer fra vedvarende energikilder. Effektelektronik er en nøgleteknologi for vedvarende energiproduktion, elbiler, færger osv. Desuden kan introduktionen af effektelektronik i nogle tilfælde bidrage til øget effektivitet af de systemer det anvendes i.

Effektelektronik er også en kritisk teknologi. Hvis al effektelektronikken i en elbil står af, kan bilen ikke køre. Hvis al effektelektronikken i en vindmølle går i stykker, stopper vindmøllen med at forsyne elnettet med strøm. Derfor er pålideligen af effektelektronik vigtigere end nogensinde.

Dette PhD projekt undersøger den nyeste viden indenfor pålidelighedsanalyse af effektelektronik og udvikler nye metoder til at udføre pålidelighedsanalyse af effektelektronik.

En af udfordringerne ved en holistisk pålidelighedsanalyse er spredningen af relevante fænomener over mange forskellige tidsskala. Det betyder at nogle fænomener optræder i løbet af et par millisekunder og andre fænomener tager år om at udspille sig. Normalt kommer man omkring dette ved at negligere nogle af fænomenerne og derved reducere den modellerede tidsskala. I dette projekt er der udviklet metoder til at inkludere disse fænomener, og derved opnå multi-tidsskala modellering af effektelektronik.

I dette projekt fokuseres der på solcellesystemer (også kaldet PV systemer), men analyserne vil også kunne bruges til andre systemer med effektelektronik. De fysiske mekanismer og relevante tidsskala for PV invertere er blevet undersøgt, og de udformede modeller udgør fundamentet for de efterfølgende analyser. PhD projektet fremlægger en ny metode til at evaluere eksperimentel belastning baseret på den opnåede viden om modellering af effektelektronik.

Projektet foreslår også et alternativ til den gængse cyklusbaserede skadeberegning på komponenter. En metode til at simplificere effekt- og temperaturprofilerne er også blevet udviklet og videreudviklet på.

Projektet undersøger også nye måder at integrere skade- og udslidningsmodellering, med modelleringen af den normale drift af PV systemet. Afhandlingen slutter med en pålidelighedsanalyse af to kommercielle PV invertere hvor udslidning er integreret i en multi-tidsskala model. Hermed blev problemstillingen i starten af afhandlingen løst.

Contents

Thesis Details

Thesis Title: Multi-timescale Modelling for Reliability Analysis of Power Electronic-Based Systems

Ph.D. Student: Martin Bendix Fogsgaard

Supervisors: Prof. Frede Blaabjerg, Aalborg University Prof. Francesco Iannuzzo, Aalborg University Assoc. Prof. Amir Sajjad Bahman, Aalborg University

The main part of the dissertation is based on the following publications:

Journal Papers

1) Fogsgaard, M. B., & Iannuzzo, F. "FEM-aided damage model calibration method for experimental results." *Microelectronics Reliability*, Vol 114, [113915]. https://doi.org/10.1016/j.microrel.2020.113915 (2020).

2) Fogsgaard, M. B., Bahman, A. S., Iannuzzo, F., & Blaabjerg, F. "PV mission profile simplification method for power devices subjected to arid climates." *Microelectronics Reliability*, Vol 126, [114328]. https://doi.org/10.1016/j.microrel.2021.114328 (2021).

3) Fogsgaard, M. B., Bahman, A. S., Iannuzzo, F., & Blaabjerg, F. "Mission Profile Simplification Method for Reliability Analysis of PV Converters." *Microelectronics Reliability*, Vol 138, [114651]. https://doi.org/10.1016/j.microrel.2022.114651 (2022).

4) Fogsgaard, M. B., Bahman, A. S., Y. Zhang, Iannuzzo, F., & Blaabjerg, F. "Lifetime Analysis of Two Commercial PV Converters using Multi-Year Degradation Modelling." *e-Prime*, Vol 5, [100205]. https://doi.org/10.1016/j.prime.2023.10020 (2023).

Conference Papers

5) Fogsgaard, M. B., Bitsch Nørgaard, J., & Iannuzzo, F. "Artificial Intelligence-Based Approach for Damage Estimation of Power IGBTs from Real Mission Profiles." *PCIM Europe digital days 2020: International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (s. 985-989). VDE Verlag GMBH.* (2020).

6) Fogsgaard, M. B., Reigosa, P. D., Iannuzzo, F., & Hartmann, M. "Mechanistic Power Module Degradation Modelling Concept with Feedback." *EPE'20 ECCE Europe: The 22nd European Conference on Power Electronics and Applications (s. P.1-P.7)*
https://doi.org/10.23919/EPE20ECCEEurope43536.2020.9215897 (2020).

7) Fogsgaard, M. B., & Iannuzzo, F. "Introducing the LEGO Mission Profile Analysis Methodology." *CIPS 2020; 11th International Conference on Integrated Power Electronics Systems (s. 455-459). VDE Verlag GMBH.*
https://ieeexplore.ieee.org/document/9097725 (2020).

Co-Authored Papers

8) Jiang , M., Fu, G., Ceccarelli, L., Du, H., Fogsgaard, M. B., Bahman, A. S., Yang, Y., & Iannuzzo, F. "Finite Element Modeling of IGBT Modules to Explore the Correlation between Electric Parameters and Damage in Bond Wires." *Proceedings of 2019 IEEE Energy Conversion Congress and Exposition (ECCE) (s. 839-844). [8912236] IEEE Press. IEEE Energy Conversion Congress and Exposition* https://doi.org/10.1109/ECCE.2019.8912236 (2019).

9) Jiang, M., Fu, G., Fogsgaard, M. B., Bahman, A. S., Yang, Y., & Iannuzzo, F. "Wear-out evolution analysis of multiple-bond-wires power modules based on thermo-electro-mechanical FEM simulation." *Microelectronics Reliability*, 100-101, [113472]. https://doi.org/10.1016/j.microrel.2019.113472 (2019).

10) Zhang, K., Fogsgaard, M. B., & Iannuzzo, F. "Intelligent DC- and AC Power-Cycling Platform for Power Electronic Components." *2022 IEEE Applied Power Electronics Conference and Exposition (APEC) (s. 307-311). IEEE. I E E E Applied Power Electronics Conference and Exposition. Conference Proceedings* https://doi.org/10.1109/APEC43599.2022.9773518 (2022).

This dissertation has been submitted for assessment in partial fulfillment of the Ph.D. degree. Based on the publications shown above, the thesis serves as a summary of those, highlighting the primary outcome of the Ph.D. project. Parts of the results are used directly or indirectly in the extended summary of the thesis. The co-author statements have been made available to the assessment committee and they are also available at the Faculty of Engineering and Science, Aalborg University.

Preface

This Ph.D. Thesis summarises the work I have done and the results I have achieved during my Ph.D. project. This project, titled "Multi-timescale Modelling for Reliability Analysis of Power Electronic-Based Systems", was carried out at AAU Energy at Aalborg University, Denmark. The project is funded by the Villum Investigator Programe with the project: Reliable Power Electronic based Power Systems (REPEPS).

Thank you to my main-supervisor Frede Blaabjerg who always acted as the guiding beacon for the work of this project. Your supervision helped me grow as both a researcher and as an engineer.

To my co-supervisor Francesco Iannuzzo, thank you for hiring me as a research assistant which lead me to my PhD and helped my find my passion for reliability engineering.

To my co-supervisor Amir Sajjad Bahman, thank you for all of the help and advice you have given me over the years.

Thank you to my mentors in my external collaboration with Grundfos, Niels Høgholt Petersen and Søren Jørgensen. Your feedback was invaluable on our work together.

I want to express my gratitude towards my colleagues at AAU Energy, especially Mads Graungaard Taul, Martin Kjær, Joachim Steinkohl and Shih-Feng Chou. You made work feel like home.

I want to thank my family, my wife Karoline, and my children Linus, Balder and Frigga for their unending patience and support. This thesis and this work are for you.

To my late mother who passed away in January 2020, thank you for everything, I wish you were still here.

To my father, my sibling and the rest of my family, thank you for all of your support.

Martin Bendix Fogsgaard

Aalborg University, July 20, 2023

Part I

Ph.D. Dissertation

Chapter 1

Introduction

1.1 Background

Power electronics is an engineering field where electronic devices such as transistors and diodes are used to control and convert electric power. Power electronic technologies play an ever-increasing role in both the generation and consumption of electrical power. It is a key technology necessary for technologies such as wind turbines, solar generators (also known as PV or photovoltaic plants), electric cars, chargers for the same, power supplies for consumer electronics and more. Today, 70% of electricity generated worldwide is processed by power electronics. Additionally, the usage of power electronics will only increase with increased electrification of transportation and more renewable generation [1].

Power electronics-based energy conversion is highly efficient and power electronics-based technologies can also reduce the power consumed by various industrial applications. E.g. motor control can reduce power consumption by up to 30% and pump/air conditioner power consuption can e.g. be reduced by 20% [2].

With an increasing amount of power electronics come the need for better design of robust and reliable power electronics. Additionally, it becomes increasingly important to be able to accurately predict the reliability and lifetime of a power electronic system [3] both in the design phase as well as in the operation phase.

1.1.1 Power Electronics Reliability Engineering

A power electronic system is inherently *multi-physical*. In this thesis, the work will be focused on power electronic converters for solar generation applications, also known as Photo Voltaic (PV) converters. The primary function is conversion of *electrical* energy. As the energy conversion is lossy, *heat* is generated in the converter. This causes an increase in temperature of the components which directly leads to *mechanical stress* due to the mismatch in the thermal expansion of materials used in the power electronic system. As the system is used, the performance will slowly become worse due to the *degradation* of the system, and its components.

Such a system also experiences various phenomena that are not directly tied to a field of physics and which affect the behaviour of the system at different timescales. These can be of both endogenous and exogenous origin. Endogenous phenomena are phenomena that are generated from within the system itself, whereas exogenous phenomena are generated outside of the system.

In this project the term phenomenon will be used to describe physical events, mechanisms or couplings present in power electronic systems. Temperature increase caused by lossy power conversion, degradation and device failure are all considered examples of phenomena relevant to the power electronic reliability analysis.

One such phenomenon is the *control* of the converter, which is responsible for the behaviour of the system both in transient and steady-state operation.

The exogenous inputs such as solar irradiance and ambient temperature determine the power inputs from the PV panels and directly affect the thermal stress on the components. These inputs are commonly described in the form of a so-called *mission profile*. These inputs are present even at faster timescales, but do not experience dynamics much faster than at the per-second scale. The inputs can even be categorized for PV systems as the daily cycle, the yearly cycle, and the irregular weather effects.

The *degradation* of even a single component can change the behaviour of the entire system. This is a slow phenomenon, but it is also the driver of component and system failure, either by exceeding a wear-out threshold, or even by causing an explosive failure.

The above phenomena and physics will be described in the thesis with three different timescales: *Device timescale* which contains the physics and phenomena relevant to the power electronic device, as well as its basic operation. *System timescale* will describe the operation of the power electronic system. The *degradation timescale* is a collection of degradation, and eventual wear-out, and defined end-of-life for the system and its devices.

1.1.2 The REPEPS Project

Due to the importance of power electronics in modern society, great engineering efforts are conducted to continuously improve the technology. The REliable Power Electronic based Power System (REPEPS) [4] project was initiated at Aalborg University in collaboration with RWTH Aachen, Germany and CALCE, University of Maryland, US in order to solve three engineering challenges [4]:

- *How to keep a high power system reliability with an increasing penetration of power electronics*
- *How to reduce the combined costs of failures, downtime and maintenance for renewable generation systems*
- *How to reduce the testing time for validation of power electronic product reliability*

To this end, six research thrusts are conducted with a number of Ph.D. and Post Doc projects which are:

- Failure mechanism of power electronic and power system components
- **Multi-timescale modelling and system assessment**
- Power electronic system modelling and analysis
- Control of power electronic based power system
- System probabilistic and reliability assessment
- Validation of the proposed methods

This project falls under the second research thrust: "Multi-timescale modelling and system assessment". This research thrust and this thesis uses knowledge of the failure mechanisms of power electronic components as a foundation for both modelling and analysis. The developed tools of this thesis can be used for analyses conducted in research thrust 3-6.

The research thrusts of REPEPS [4] are naturally inspired by the more and more power electronic-based modern power systems. As power electronics become a larger part of the critical infrastructure, the importance of performing reliability analyses increases. The fundamental structure of the REPEPS project can be seen in Figure 1.1.

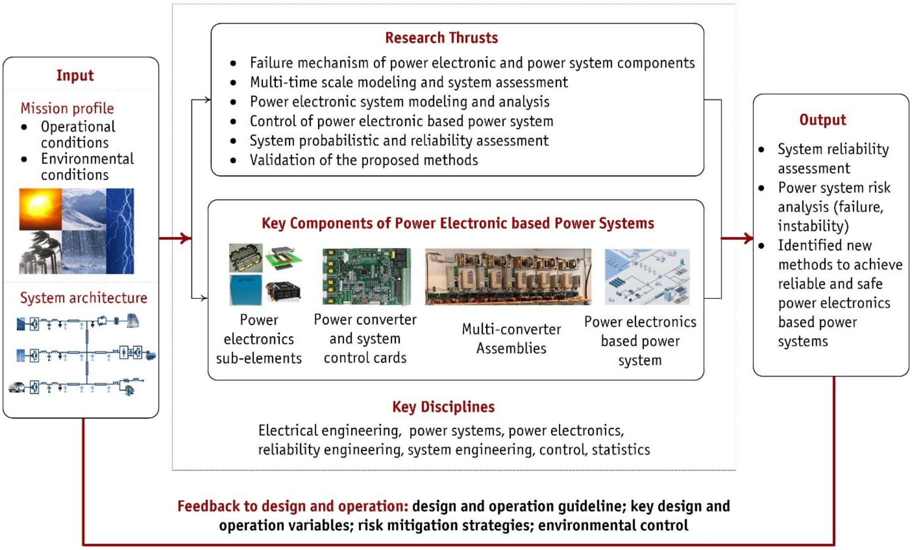

Fig. 1.1: The structure of the REPEPS project. The main inputs and outputs as well as the research thrusts and the key components can be seen. Featured is also a feedback loop from the research outputs to the input to improve the analysis methods based on the outcomes of the different activities [4].

1.2 Reliability Analysis of Power Electronics

Reliability in engineering terms refers to the ability of a system or component to function without failure for a specified amount of time [5].

It is important to be able to accurately analyse the reliability of various power electronic systems, both in order to design the power electronic products to be as reliable as possible, but also to enable accurate lifetime predictions of components.

Accurate lifetime prediction is a key part of determining the overall system profitability for commercial systems. An example could be offshore wind turbines comprising power electronics, which, if they fail, totally stops the generation of power of the turbine. The cost of such a failure is high, both because of the cost and difficulty of getting to the turbine itself, but also due to the loss of production from the time of failure to the time of repair. For this reason, most offshore wind turbines are subjected to preventive maintenance where critical components are replaced before they fail.

In systems with preventive maintenance, the accuracy of lifetime prediction of the components is important. If the lifetime is shorter than predicted, there is a risk of system failure and loss of production. Whereas, if the lifetime is much longer than predicted, the components will be replaced before needed, leading to higher operating costs for the entire system as well as a greater environmental impact, caused by the increased production of electronic components.

1.2.1 System Reliability

Reliability is modelled as a system with an input (the mission profile), and an output (the damage or lifetime prediction). The modelling between the two contains the system behavioural modelling and the damage modelling. An example workflow can be seen in Figure 1.2. The yellow box contains the model inputs, the green boxes make up the model and the red box with lifetime prediction is the output.

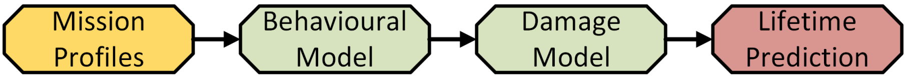

Fig. 1.2: Example lifetime prediction workflow. Depicted is the input (yellow box), the behavioural models (green boxes), their links with black arrows and the final output prediction in the red box.

Adaptions of the workflow in Figure 1.2 are used for other applications. Sources [6, 7, 8, 9, 10, 11] all use variations of this workflow, while adapting it to suit the application or e.g. enhancing it with an Artificial Neural Network to find optimal design parameters for high reliability [11].

In [6] the Physics-of-Failure approach to reliability analysis is presented as an alternative to the statistical approach based on a component's Mean-Time-to-Failure [12]. The Physics-of-Failure approach to reliability analysis is based on an understanding of the active failure mechanisms of the analysed component or system caused by the loading conditions (mission profile) of the analysed application.

As physics of failure is based on understanding the failure mechanism, the analysis will naturally focus on the most failure-prone components. For power electronic systems, the main points of failure are the power devices and the capacitors.

1.2.2 Device Reliability

In this thesis the use of "device" will refer to the active and passive electronic devices making up a complete power electronic system. These devices can be various types of transistors, diodes, capacitors, inductors etc. The work in this thesis will focus on the reliability of power electronic switches, i.e. transistors and diodes, and as a result, the reliability of the other devices will be neglected, but can in some cases be critical components.

A power electronic switch is a complex assembly consisting of a range of materials; the active chip is commonly made of silicon, and various interfaces and connections are commonly made of aluminium and copper[13]. The complete assembly in a discrete device or module has several interconnections known as bond-wires, the silicon chips are attached with a solder layer, and they are covered with a metallization layer.

The main failure mechanisms for silicon power devices are bond-wire lift-off, solder layer delamination and metallization layer degradation. Reference [14] offers a review of the state of the art for lifetime prediction of power electronics devices. The review examines numerous empirical damage models, delves into degradation monitoring techniques, and explores power cycling methodologies. Fundamentally, two damage modelling concepts exist; empirically-fitted damage models and microstructural crack modelling.

The traditional damage approach is used in [15], where this approach adds a complex thermal model degradation feedback loop to model the effects of damage accumulation on the thermal characteristics of the device. This is included because the accumulated degradation of the device can have a substantial influence on its behaviour over time, and it can significantly impact the ability to predict the device's lifespan using parameter monitoring. The flow of this is shown in Figure 1.3. However, when testing this method experimentally, it was found that the predicted rate of degradation was too slow and that the predicted life-time was much longer than the actual lifetime [15].

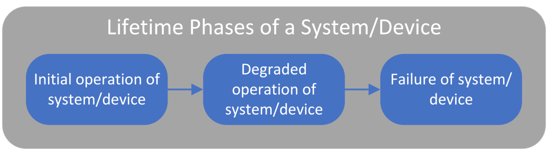

Fig. 1.3: The operational phases of a device.

A practical implementation of the traditional empirical approach to reliability modelling was thoroughly discussed in [16]. The authors conducted an analysis of a comprehensive DC micro-grid system that included PV generation, battery storage, fuel cells, and load profiles from a clinical and an apartment application. The final result of the paper is a reliability assessment of the entire system. In this work the converter is in pristine operation for the entire life, the thermal model is very simplified and the parameters of the electrical model is input to a look-up table, which outputs the junction temperature [16]. This means that any thermal dynamics in the real system are neglected for the entire operation.

Alternatively, an effective although demanding approach to damage modelling can be found in the microstructural mechanics used for IGBT (Insulated Gate Bipolar Transistor) solder layers in [17]. This approach was found to accurately model both the crack initiation and crack propagation of solder joints. However, this approach requires extensive analysis of the analysed subject, and extensive computational time.

In [18] a range of damage models for IGBT fatigue are reviewed. One of the key conclusions was the limitation of cycle-based damage models, underscoring the need for the incorporation of time-dependent damage modelling. Reference [18], however, fails to provide a complete damage modelling approach, even in subsequent papers [19].

This thesis will focus on bond-wire lift-off and solder layer delamination, but other degradation mechanisms are also relevant for transistors such as the ageing of the metallization layer. Over time, the grains in the metallization layer will grow and become coarser, this will change the properties of the layer and can also lead to a decrease in performance over time. Metallization layer ageing has been investigated in literature, such as in [20] and [21].

The reliability of capacitors in power electronic applications have also been investigated in literature. Many types of capacitors have been developed over time and the physics of failure of capacitors depend on the device physics. An overview can be found in [22] and more in depth work can be found in papers such as [23] and [24].

1.2.3 Power Electronics Modelling

The lifetime of a given component or system depends both on the durability of the component or system, and the stress it is exposed to. The loading of a PV generator over time is described with a mission profile. The mission profile for a PV generator system typically consists of the solar irradiance or PV power profile and the ambient temperature profile over time as the converter system is mostly located outside. Using this profile and the appropriate behavioural models can translate the mission profile into a thermal load profile, which can be used to assess the damage resulting from the mission profile.

Because of this, relevant representations of the control, electrical and thermal behaviour of a system are required for reliability analysis.

Depending on the classification and delimitation of different timescales, the converter and system control can be considered to lie within a single time-scale [25] but also multiple time-scales [26]. The delimitation of the different timescales is conceptual. What matters most is if the effects of the implemented control is included.

Thermal simulation is essential for power device stress evaluation. Two extremes exist in thermal modelling. The simplest one is through a thermal impedance network, while the most accurate one is through FEM(Finite Element Methods). In [27] the IGBT was modelled through a lumped thermal model, achieving accurate results including thermal coupling effects much faster than using FEM. The thermal coupling effects were detailed in [28].

Reference [29] presents a novel co-simulation approach of electro-thermal modelling of SiC power MOSFETs. This approach attempts to couple PSpice electrical modelling with a FEM-based thermal network model, linking these with MATLAB/Simulink. The model is experimentally validated showing good accuracy of the approach.

In [30] the operation, damage and degradation of an IGBT module is modelled through a successive series of single physics-based simulations, resulting in an multi-physics, multi-stressor modelling approach. Subsequent simulations is based on the results of the previous ones, and previous simulations are updated if the model requires it. While the model is more complex and includes more physical couplings, it is also more computationally demanding.

Normally, degradation effects are neglected from reliability analysis as they are difficult to model with the power electronics behaviour. However, in reference [31], the influence from degradation was found to have a significant effect on experimental SiC MOSFET lifetime.

> **Research Gap 1**
>
> Typical reliability analysis efforts focus on a damage mechanism and do not integrate phenomena from different timescales. As these effects can have a significant impact on the predicted lifetime [31], efforts should be made to perform multi-timescale reliability modelling.

1.2.4 Timescales for Power Electronic Systems

Reliability assessment of any component is an inherently multi-timescale problem. A multi-timescale system is defined as a system with dynamics and physical effects at multiple timescales. Figure 1.4 shows an overview of the timescales of a PV system and where different phenomena occur. For instance, the fundamental frequency of a grid-connected inverter lies on a different timescale from the ambient temperature variation during a day and will have different effect on the system.

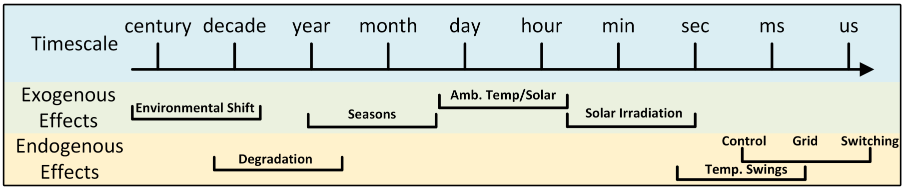

Fig. 1.4: An overview of the timescales and factors affecting power electronic systems and devices (based on [25]). The effects have been sorted by their origin, some effects come from the system/device itself and thus are endogenous, while some come from outside sources and are exogenous. The effects have been placed on the timescale approximately where they commonly exist, though this varies from system to system and from application to application.

The timescale phenomena are related to the physical system structure. A structural system hierarchy can be seen in Figure 1.5. This hierarchy is split into three levels; Device, Converter and System Levels. As operation of the entire system is based on the behaviour of all layers, it is clear that the different levels are coupled and will interact, e.g., the degradation of a component at one level will affect the operation of the next level.

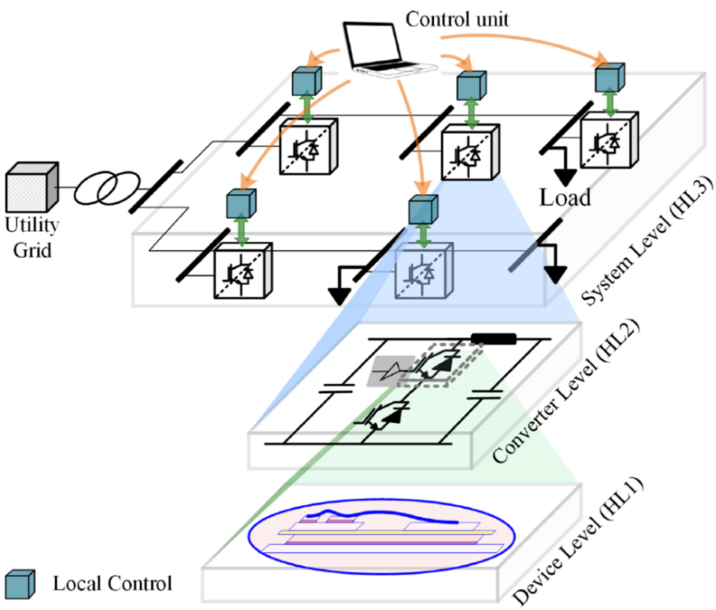

Fig. 1.5: Physical hierarchical Levels (HL) of a Power System[1]. Generally, the effects that occur at lower hierarchical levels exist at lower timescales, but exceptions exist in practice.

Phenomena may occur at one timescale but have effects at a different timescale. To give an example of how this may happen, one can imagine the failure of a component caused by a propagating crack inside of it. This crack will grow depending on the loading at the microscopic location of the crack, yet it may take years for the crack to grow to a length which will disrupt the operation of the component itself. This, in turn, can lead to a catastrophic failure of the entire system through the affected converter.

While some components may be omitted in the performance- and behavioural modelling at different timescales, the reliability of a single component may be affected by the effects modelled at the other timescales. These coupled effects must be identified to maintain accuracy while neglecting non-critical phenomena.

Almost paradoxically, wear-out failures of power electronics originate and propagate in very small physical regions of single components, while the loading conditions are affected and caused by the dynamics and operation of the entire system. Additionally, while the lifetime of one such component may be years or even decades, the loading occurs with dynamics in the milliseconds or even microseconds timescale, and therefore demands multi-timescale modelling.

Modelling is used to evaluate and validate reliable and stable operation of the power systems in the future. The reliability of a single component may have a large impact on the reliability of the entire converter system as well as the end of the power system. Ideally, a holistic approach to system modelling should be conducted to couple the different levels, phenomena and timescale effects.

1.2.5 Multi-timescale Modelling Approaches

Multi-timescale modelling has been extensively investigated in literature.

One approach can be seen in [25]. Here a PV inverter system is modelled at different coupled physics and timescales. Here, three modelling concepts are presented, one for each time-scale level. This simulation is efficient and the modelling approach is suitable for when one timescale is in focus. Unfortunately the three modelling levels are not linked, so the simulation is more accurately described as having multiple models, rather than being a multi-timescale model.

Reference [32] proposes a condition-mapping simulation scheme to achieve multi-physical couplings in a computationally efficient way. The method is a conceptual continuation of using look-up tables to reduce simulation time. The method however relies on the assumption that the 1-year mission profile input contains no dynamics, which would result in a transient response in the resulting junction temperature profile.

In [33] another approach is taken to efficiently conduct multi-physics and effectively multi-timescale modelling. This is achieved by analysing the mission profile-based electrical loading and dividing the one year profile into a number of bins. This enables the inclusion of multi-physics finite element modelling into the evaluation of the yearly loading for a converter system. This approach suffers from the same drawback as seen in [32], where sections of the mission profile are put into the bins according to characteristics such as amplitude and not their dynamic shapes. This causes the methodology to neglect all mission profile timescale dynamics.

In [34] a multi-timescale approach is taken to predict IGBT junction temperature. Here, three timescales are identified; microsecond, millisecond and second. The IGBT is modelled at each timescale using different loss and thermal models. The final modelling approach achieves accurate results in a much shorter time than the reference used for comparison. However, as the timescale models are not coupled in any way, the models should be considered as three single-timescale models rather than one multi-timescale model.

Research Gap 2

The work conducted in literature leaves gaps which align with the challenges focused on in the REPEPS project, as well as gaps which fit with the goals of the six defined research thrusts. For the research thrust of this project, research thrust 2, where the main issue is a lack of efficient multi-physic, multi-timescale models for reliability assessment.

Either the models are too simplified to take all the relevant physical mechanisms into account, or they are too complex and time-consuming and thereby difficult to use. Modelling approaches are needed where sufficient simulation simplifications are achieved, but the relevant physical information is retained. This is the core problem that the "Multi-Timescale Modelling and System Assessment" research thrust and this Ph.D. project seeks to solve.

1.3 Project Motivation and Objectives

The multi-physics and multi-timescale nature of system reliability modelling and the combination of the previously reported efforts still leave open questions with regards to overall methodology and the coupling of different modelling methods. However, the state-of-the-art research works also offers many approaches to implement multi-timescale modelling of power electronics and can be used to build the foundation for new multi-timescale modelling methods of power electronics taking into account degradation effects of the components.

1.3.1 Research Question

The primary goal of this project is to bridge the gap between the long timescale power electronic system modelling down to the almost instantaneous damage increments occurring in the power electronic devices themselves. Additionally, this evaluation must be fast enough for it to be of practical use.

A major research question can be formulated, to sum up the objective of the project:

How can we make a multi-timescale model for power electronics reliability analysis comprising degradation, power variation, temperature fluctuations and switching behaviour for long term mission profile loading, which is efficient enough for practical use?

1.3.2 Main Objectives

Two main objectives are pursued based on the research question in this thesis:

- Introduce multi-timescale phenomena into reliability analysis
- Simplify and speed-up simulation time of lifetime prediction

While distinct and separate, together, these two objectives form the main goal of this thesis, which is to perform multi-timescale modelling as efficiently as the state-of-the-art reduced-order modelling for power electronics reliability analysis. As more physical couplings are added to reliability modelling, it brings with it additional computation burdens and time. Both finite element modelling and the degradation feedback are challenging to include efficiently.

Fundamental frequency transients and year-long or decade-long degradation effects exist on different ends of the timescale spectrum and, though linked, are not normally able to be modelled directly in the same simulation. All of this makes a unified multi-timescale modelling approach inherently problematic to perform. This thesis will discuss how to unify the modelling of the different timescales in power electronic systems.

Delimitation

To limit the scope of this project, and to focus the work on one practical system, this project will specifically be working on a power electronic system in a PV generator application.

Unless specified differently, the work described in this thesis will be conducted on a single-stage 3-phase PV inverter system as shown in Figure 1.6. The system is also based on the experimental system presented in [35].

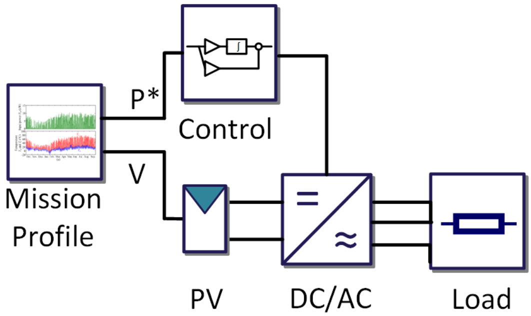

Fig. 1.6: The "standard" power electronic system of this thesis. The system is simplified for clarification, but the conducted analyses can be applied to other systems, such as systems with other topologies, systems that are connected to the grid, or others. Other systems will also be analysed, but unless it is specified, work is conducted on this system.

1.3.3 Key Methods

The thesis will explore alternatives to some of the axiomatic models and methods employed in the state-of-the-art reliability analyses. These alternatives will help to either find new ways of performing the analyses or to reinforce the strength of the common methods.

Modern reliability analysis rest on a foundation consisting of cycle-based damage summation using Rainflow Counting, and to a large extent junction temperature-based damage modelling using a variation of the Coffin-Manson damage model, and reduced-order model simulation of the mission profile load inputs. Alternatives to the common reliability analysis paradigms will be explored.

Work will also be conducted to reach a parameter evolution-based end-of-life concept in contradiction to the dimensionless end-of-life concept used today.

The simulation time of load modelling will be decreased by developing simplification methods based on an analysis of the mission profiles and the affected systems.

1.4 Thesis Outline

This thesis is comprised of six chapters, which are arranged as:

Introduction This chapter introduces the background of the problem as well as the research questions.

Device Timescale Modelling This chapter explain the definition of the device timescale as well as how to model the system phenomena and device behaviour at this timescale.

System Timescale Modelling This chapter discusses the system timescale, the limitations and the models of this timescale.

Damage and Degradation Timescale Modelling This chapter defines the damage and degradation timescale modelling including its basic methods.

Multi-Timescale Modelling Case Study Here, the modelling methods from the previous chapters are combined to perform reliability analysis of two commercial PV generator systems.

Conclusion This chapter concludes the report and the work conducted in the project.

1.5 Papers published during the PhD

The following papers contributes to solve the research question of the thesis. First-authored papers and their works will be focus of the thesis, and co-authored papers will be discussed when relevant.

Journal Papers

1) Fogsgaard, M. B., & Iannuzzo, F. "FEM-aided damage model calibration method for experimental results." *Microelectronics Reliability*, Vol 114, [113915]. https://doi.org/10.1016/j.microrel.2020.113915 (2020).

2) Fogsgaard, M. B., Bahman, A. S., Iannuzzo, F., & Blaabjerg, F. "PV mission profile simplification method for power devices subjected to arid climates." *Microelectronics Reliability*, Vol 126, [114328]. https://doi.org/10.1016/j.microrel.2021.114328 (2021).

3) Fogsgaard, M. B., Bahman, A. S., Iannuzzo, F., & Blaabjerg, F. "Mission Profile Simplification Method for Reliability Analysis of PV Converters." *Microelectronics Reliability*, Vol 138, [114651]. https://doi.org/10.1016/j.microrel.2022.114651 (2022).

4) Fogsgaard, M. B., Bahman, A. S., Y. Zhang, Iannuzzo, F., & Blaabjerg, F. "Lifetime Analysis of Two Commercial PV Converters using Multi-Year Degradation Modelling." *e-Prime*, Vol 5, [100205]. https://doi.org/10.1016/j.prime.2023.10020 (2023).

Conference Papers

5) Fogsgaard, M. B., Bitsch Nørgaard, J., & Iannuzzo, F. "Artificial Intelligence-Based Approach for Damage Estimation of Power IGBTs from Real Mission Profiles." *PCIM Europe digital days 2020: International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (s. 985-989). VDE Verlag GMBH.* (2020).

6) Fogsgaard, M. B., Reigosa, P. D., Iannuzzo, F., & Hartmann, M. "Mechanistic Power Module Degradation Modelling Concept with Feedback." *EPE'20 ECCE Europe: The 22nd European Conference on Power Electronics and Applications (s. P.1-P.7)* https://doi.org/10.23919/EPE20ECCEEurope43536.2020.9215897 (2020).

7) Fogsgaard, M. B., & Iannuzzo, F. "Introducing the LEGO Mission Profile Analysis Methodology." *CIPS 2020; 11th International Conference on Integrated Power Electronics Systems (s. 455-459). VDE Verlag GMBH.* https://ieeexplore.ieee.org/document/9097725 (2020).

Co-Authored Papers

8) Jiang , M., Fu, G., Ceccarelli, L., Du, H., Fogsgaard, M. B., Bahman, A. S., Yang, Y., & Iannuzzo, F. "Finite Element Modeling of IGBT Modules to

Explore the Correlation between Electric Parameters and Damage in Bond Wires." *Proceedings of 2019 IEEE Energy Conversion Congress and Exposition (ECCE) (s. 839-844). [8912236] IEEE Press. IEEE Energy Conversion Congress and Exposition* https://doi.org/10.1109/ECCE.2019.8912236 (2019).

9) Jiang, M., Fu, G., Fogsgaard, M. B., Bahman, A. S., Yang, Y., & Iannuzzo, F. "Wear-out evolution analysis of multiple-bond-wires power modules based on thermo-electro-mechanical FEM simulation." *Microelectronics Reliability*, 100-101, [113472]. https://doi.org/10.1016/j.microrel.2019.113472 (2019).

10) Zhang, K., Fogsgaard, M. B., & Iannuzzo, F. "Intelligent DC- and AC Power-Cycling Platform for Power Electronic Components." *2022 IEEE Applied Power Electronics Conference and Exposition (APEC) (s. 307-311). IEEE. I E E E Applied Power Electronics Conference and Exposition. Conference Proceedings* https://doi.org/10.1109/APEC43599.2022.9773518 (2022).

Chapter 2

Device Timescale Modelling

This chapter will present the published findings and methods for device timescale modelling. The works presented in this chapter will form the multi-physical foundation for the research question given in the introduction.

2.1 Background

The power electronic devices are the driving motor behind the operation of any power electronic system, but depending on the focus of the model to be used, it may not be necessary to explicitly model the behaviour of the devices themselves while only the function of the entire system is needed. As stated in Chapter 1, this thesis focus on analysis of active power switches in power modules. Similar analyses of devices such as diodes and capacitors are also relevant, but has been decided to be beyond the scope of this thesis as mentioned in the introduction.

2.2 The Timescale for Device Modelling

The timescale for power electronic devices spans from their switching to the thermal transients driven by device-related phenomena such as power loss.

The physical devices experience phenomena at numerous timescales such as the change of temperature related to the weather or the seasons changing. Those phenomena originate from outside of the devices, and as such they are not categorised as part of the device timescale in this project. Instead they are categorised as part of the system timescale which will be discussed in Chapter 3.

In this chapter, alternatives to the common junction temperature-based stress representation are investigated to seek new methods for multi-timescale modelling. This is done using digital twin modelling based on experimental power cycling results. But before that, the physics and couplings in a power device will be investigated. While situated on the far-right side of the timescale (as seen in Figure 2.1), the devices themselves act as the focal and meeting point between the system modelling of the operation and the degradation caused by the operation of system. This is because the active devices in a converter are the driving force of the operation [13] and are also the main degrading components [14].

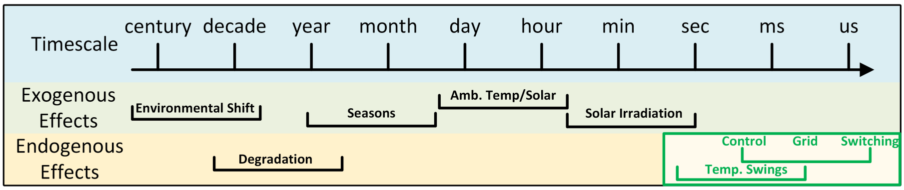

Fig. 2.1: The span of the device timescale modelling (in green).

2.3 Device-Level Multi-Physics Modelling

A wholistic model of a power device require accurate models of the different physical phenomena, as well as an inclusion of the physical couplings.

A basic overview of the physics and their couplings can be seen in Figure 2.2.

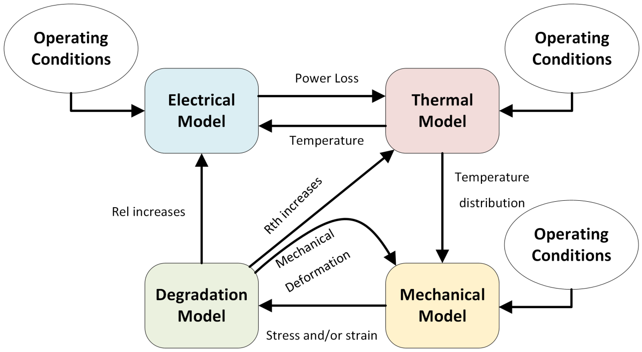

Fig. 2.2: Modelling concept flow for degradation modelling of devices with physical couplings [36].

Here the physical models of a power device or a power module are outlined with their couplings and operating condition inputs. The electrical and thermal models are the main behavioural models for such a device, operating at closely linked timescales. Their main coupling is the feedback of electrical power loss and the resulting temperature increase. The mechanical model mainly serves as the link to the degradation model, which affects and changes the parameters in both the electrical and thermal models. The degradation model can be linked to the thermal model through a dimensionless damage model, in which case the mechanical model in Figure 2.2 is replaced with a damage model. If the degradation can be neglected from modelling the couplings shown in Figure 2.2 can be simplified.

2.3.1 Electrical modelling

In Figure 2.3 the layout of a real power module can be seen. The module under study is a three-phase inverter module and therefore contains 6 transistors and 6 anti-parallel diodes. These switches perform the core function of the module. Additionally, a number of electrical connections exist in the module in the form of bond-wires, copper traces and terminals. Figure 2.3 shows that a complete network with resistances representing every single bond-wire and copper trace would be difficult to implement in a model due to the sheer number of elements this would require. And as the resistances of the connections are not a part of the core functionality, they are often neglected along with the temperature dependence of these resistances.

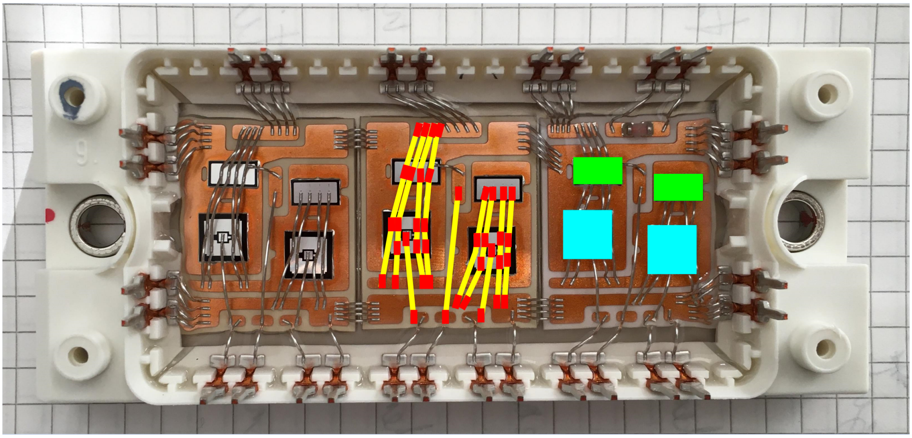

Fig. 2.3: A 3-phase power module. Highlighted are the transistors (blue) and diodes (green) in one leg. And the bond-wires (yellow) and bond-wire feet (red) are highlighted in another leg. The last leg has been left without any highlights.

If the degradation behaviour of the module must be modelled, some of the resistances should be included in the model. In the case of a bond-wire lift-off on one of the chips, the resistance matrix and the current sharing of the remaining wires change. The degrading resistance of a bond-wire can either be modelled as a continuously increasing resistance or as a binary phenomenon with two states:

$$R = \begin{cases} R_{ini}, & \text{if } 0 \leq D < 1 \\ \infty, & \text{if } D \geq 1 \end{cases}$$

Where R is the resistance and D is the damage for the individual bond-wires. Damage is considered to go from 0, i.e. initial condition, to 1, i.e. totally non-functional, this will be discussed more detailed in Chapter 4.

2.3.2 Thermal modelling

The basic thermal behaviour of a chip in a power module can be explained with Figure 2.4. Power loss is generated in the power device which heats the device and increases the temperature. The heat is mainly transferred downwards towards the cooling plate/heat sink, with a small amount travelling through the bond-wires. The bond-wires themselves also generate heat from ohmic loss, but this is usually neglected.

In Figure 2.4 the different layers of the stack-up are represented by different colours. The example stack-up (from top to bottom) consists of top layer metallization of aluminium (dark grey), the power chip of silicon (green), the solder layer of a silver-tin-nickel alloy (blue), top copper layer of DBC (orange), middle ceramic layer of DBC (white), bottom copper layer of DBC (orange) and the aluminium baseplate (light grey).

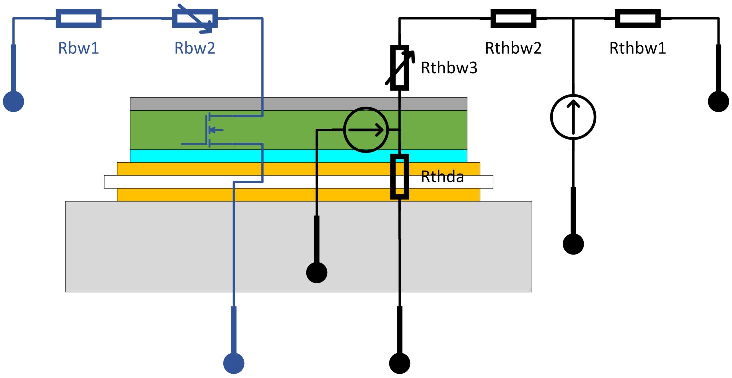

Fig. 2.4: The basic stack-up of a power module, overlaid with a thermal (red) and electrical (blue) networks [36]. The main degrading electrical resistance is named Rbw for the resistance of the bond-wire and the main degrading thermal resistance is named Rth,bw for thermal resistance of the bond-wire.

If the degradation of the thermal resistance of the die attach(blue layer in Figure 2.4) needs to be modelled it can be done in the following simplified way. The resistance R increases continuously with the level of degradation. The resistance of the die attach is assumed to be represented by the resistance of a cylindrical shape.

$$R = \frac{\rho T}{\pi (r - rd)^2} \tag{2.1}$$

Where R is the resistance, ρ is the resistivity of the material, T is the thickness of the die attach, and r is the radius of the die attach. The die attach is considered circular as that allows for a simplified representation of the shape evolution as it delaminates over time. The degradation is d and starts at 0 for a perfectly pristine interface and goes to 1 for a completely disconnected chip.

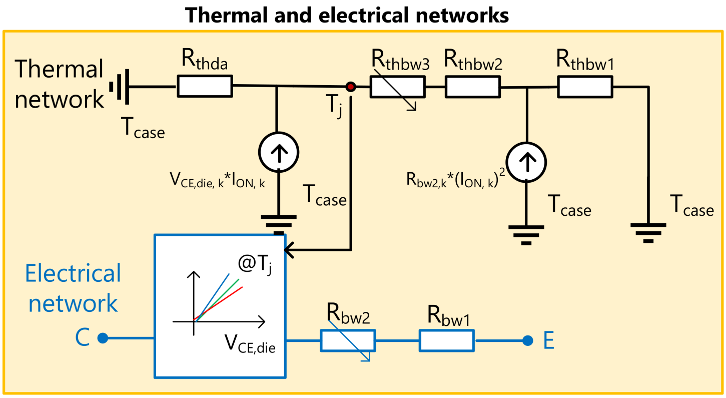

Fig. 2.5: Basic semiconductor thermal (black) and electrical (blue) modelling [36].

Figure 2.5 shows an example of a simple implementation of electrical and thermal network models. R_{thda} is the thermal resistance of the die attach. $R_{thbw1-3}$ are thermal resistances of different parts of the bond-wire. T_{case} is the case temperature. The two black current sources represent conduction loss in the power device and ohmic loss in the bond-wire. T_j is the junction temperature. R_{bw1-2} are electrical resistances of different parts of the bond-wire. C and E are the collector and emitter of the device.

2.3.3 Damage and Degradation Modelling

The most common method for damage modelling of power electronic components is through the Rainflow Counting algorithm and a damage model. This will be described in more details in Chapter 4 where the relevant timescales are analysed too. The basic relation between damage increase due to thermal loading can be described as in Equation 2.2.

$$\Delta D \propto f(\Delta T_j) \tag{2.2}$$

Where ΔD is the damage increment as a function of the junction temperature swing ΔT_j. This is the basic damage concept used in Figure 2.6.

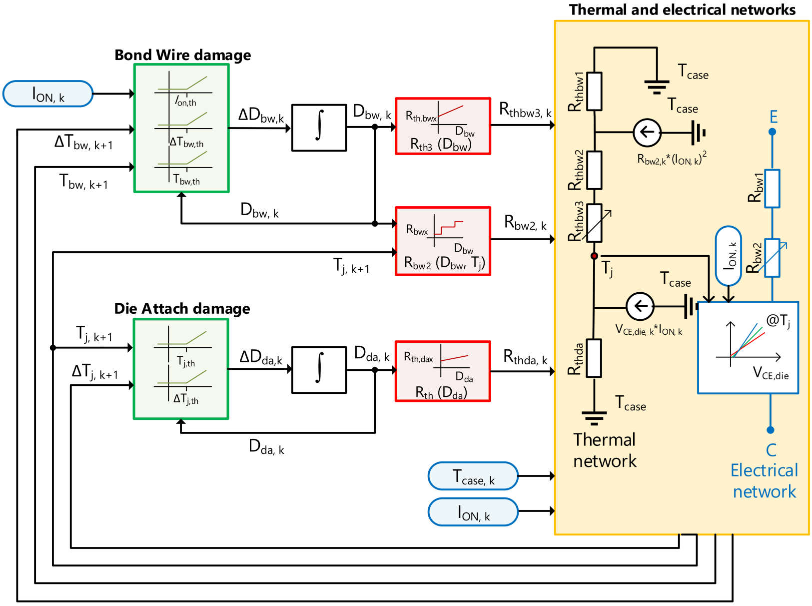

Fig. 2.6: Detailed multi-physics map for power device modelling showing the impact of bond-wire and die attach damage on thermal and electrical modelling via increasing resistances [36].

2.3.4 Example Implementation

Figure 2.6 shows an implementation of the couplings as given in Figure 2.2. The thermal and electrical modelling are done with the networks (yellow box) shown in Figure 2.4. The temperatures at key locations are fed to bond-wire and die attach damage models (green boxes), and affect the parameters in the electro-thermal model through degradation models (red boxes). The operating conditions (such as a mission profile) are input through the blue boxes. D's are damage, R's are electrical resistances, Rth's are thermal resistances and T's are temperatures. bw denotes bond-wire related parameter, da are die-attach related parameters. Parameters with k are calculated for a given time-step, those with k+1 are fed to the next time-step.

The physical couplings in Figure 2.2 and the mechanisms described in this section, form the basis of the device modelling in the rest of this chapter and the rest of the thesis. Each of the physics and mechanisms can be modelled using more detailed models, some of which will be discussed in Chapters 3 to 5. In the device timescale analysis one of the most thorough tools for modelling is Finite Element Analysis. In the context of electro-thermo-mechanical modelling of power electronics it enables the evaluation of the chosen physics using 2D or 3D geometry. It is a strong tool for doing the multi-physics modelling, but it comes with a heavy computational cost as will be discussed in the next section.

2.4 Finite Element Analysis (FEA)-based Digital Twin for Stress Variable Analysis

One of the limiting factors to apply loading variables for damage or life modelling, is the difficulty of measuring physical quantities near the power chips during testing or operation. Temperature on or near the power chips is not trivial to measure, but it is possible using various probing techniques [37, 38, 39]. Junction temperature estimation is also possible with accurate measurements using **Temperature Sensitive Electrical Parameters** (TSEPs).

Mechanical quantities like stress or strain in the chip or the interconnections are difficult to measure, but can be estimated using a digital twin of the physical set-up. A digital twin is a model representation of the system in software, and a 3D Finite Element Thermo-Electro-Mechanical model of a section of a power module is used in this thesis, see Figure 2.7.

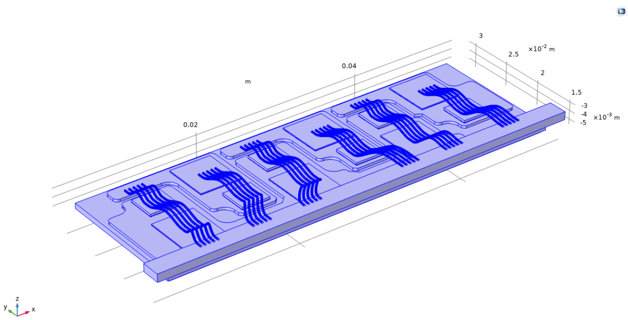

Fig. 2.7: A 3D layout of a power module [40].

If this model is exposed to the same testing conditions as its physical twin, then it should experience the same stress. The digital model then has the advantage that various physical quantities can be extracted that otherwise cannot be measured in the physical set-up. As this extraction is purely digital it is easier to extract a large range of variables which can be swept and their applicability for use as a loading parameter. A workflow for this model creation can be seen in Figure 2.8.

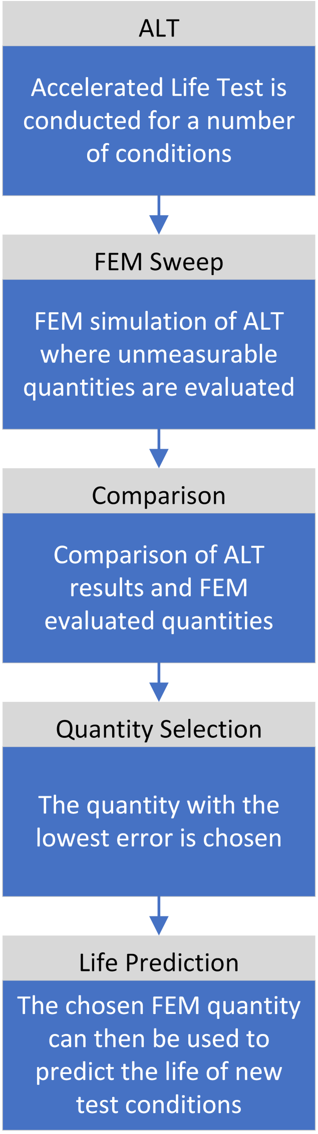

Fig. 2.8: The workflow of [40]. First, power cycling is conducted. Secondly the conditions of the power cycling are replicated as closely as possible using finite element simulation. Then a large range of physical quantities are extracted from the finite element simulation. These are then compared to find the most representative quantity for the loading factor of the experimental test.

Various quantities, geometry selections, volume evaluation methods and time evaluation methods were employed on a 3D model exposed to accelerated test conditions from [41]. The test conditions are presented in detail for discussion in Figure 4.4 and Table 4.2 in Chapter 4.

An overview of the quantities and evaluation methods can be seen in Table 2.1. After the quantities were evaluated for 5 of the 6 different test conditions from [41], they were compared based on their ability to predict the results for the 6th test condition. This resulted in a large matrix of prediction errors, which can be found in [40].

Table 2.1: Overview of loading quantity evaluation methods of power module in Figure 2.7 [40].

Loading Quantities	Active Area Selection	Active Area Evaluation	Temporal Evaluation
Temperature	Module	$\int$ Volume	$\int$ Time
Von Mises Stress	Bond-wires	Max(Volume)	Max Value
Strain Energy	Points(Nodes)	Σ Point(Node)	Max $\frac{d}{dt}$
Displacement		Max(Points)	$\int$ of $\frac{d}{dt}$
Internal Energy			Δ Value
Stored Energy			
Enthalpy			

The evaluation method with the smallest prediction error is fully expressed using the following formula:

$$LF = \int_{Bond-wire} max_t \left(\frac{d}{dt} H \right) dV \tag{2.3}$$

Where H is the enthalpy, LF is the loading factor, the integration volume is the bond-wire geometry and the $\max_t()$ finds the maximum value during the time period. In other words, the loading factor in Equation 2.3 is equal to the bond-wire volume integral of the maximum rate of change of the enthalpy.

The final lifetime predictions using the chosen method and the temperature swing reference equation can be seen in Table 2.2.

Table 2.2: Lifetime prediction using temperature swing and Equation 2.3 [40] and [41].

-	Number of cycles to failure [-]	Error [%]
Experimental Result	2.11e5	-
Prediction using temp swing	1.93e5	8.78%
Prediction using Equation 2.3	2.05e5	2.77%

Interestingly, when this procedure was repeated for another power module the optimal evaluation method was also an evaluation of the enthalpy in the DUT[40]. This may indicate that the physical mechanism associated with the enthalpy could be used as a loading variable that can replace the temperature swing in damage and life modelling such as given in Equation 2.2. It is important to note what this enthalpy is, and how COMSOL Multiphysics calculates it. In the COMSOL Multiphysics simulation, the Enthalpy is equivalent to the evaluation of the Internal Energy of the DUT, which in COMSOL is the thermal energy stored in a volume. The thermal energy, or the flux of the same, may be worth investigating for use in life predictions for power electronics.

2.5 Summary

This chapter focused on answering the multi-physics part of the research question defined in Section 1.3.1 in Chapter 1. The main physical behaviour in a power module were presented along with their couplings in Section 2.3. The basic flow of the multi-physics modelling for power device reliability was also presented. This will be used as the foundation for the works answering the other parts of the research question.

As a major part of research question focused on multi-timescale modelling, this chapter also described and discussed device timescale modelling in the context of power electronics reliability analysis.

A novel approach to do stress evaluation for both accelerated life tests and life prediction was described in Section 2.4. Here a FEM digital twin was used to evaluate various physical quantities, which cannot be experimentally measured. A sweep of evaluation methods are compared to find the optimal methodology. This work can be used as an alternative to the conventional damage modelling using temperature swing. The results of the work also suggests that the thermal energy flux is a more fitting stressor than the temperature swing.

Contributions of this Project

[36] **Fogsgaard, M. B., Reigosa, P. D., Iannuzzo, F., & Hartmann, M.** (2020). Mechanistic Power Module Degradation Modelling Concept with Feedback. *EPE'20 ECCE Europe: The 22nd European Conference on Power Electronics and Applications (s. P.1-P.7)*
https://doi.org/10.23919/EPE20ECCEEurope43536.2020.9215897

This paper presents an overview of the physics, couplings and interactions in a power module, and serves as a foundation of how to interface the different physics included in the developed models of the next chapters.

[40] **Fogsgaard, M. B., & Iannuzzo, F.** (2020). FEM-aided damage model calibration method for experimental results. *Microelectronics Reliability*, 114, [113915]. https://doi.org/10.1016/j.microrel.2020.113915

This paper presents an alternative method to quantify the experimental loading of a power module using a finite element digital twin model. The paper also suggests that the thermal energy flux in a power module may be a more representative stressor for damage calculation than temperature swing amplitude.

Chapter 3

System Timescale Modelling

This chapter will present the system timescale modelling methods. Two approaches have been developed and published [42, 43, 44], an event-based modelling method and a mission profile simplification method. The results will be presented, and some applications will be discussed. It will provide the advancements achieved to meet the second objective of Section 1.3.2 in Chapter 1: The model order reduction and speed-up of lifetime prediction calculations.

3.1 Background

As defined previously, the system timescale comprises the phenomena generated by and affecting the modelling of the power generator and conversion system. This can be seen in Figure 3.1.

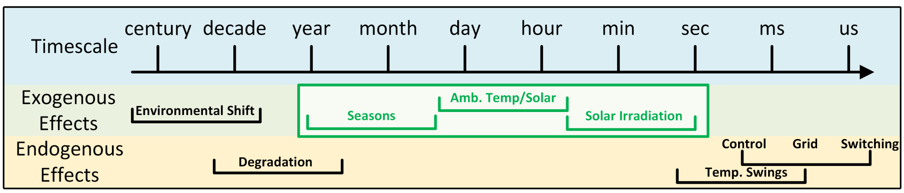

Fig. 3.1: The timespan of the system timescale (in green).

As the yearly loading is commonly used to evaluate the reliability of a power system, the mission profile is a fundamental part of the system timescale modelling.

A mission profile for a PV generator system most commonly includes the ambient temperature and either the input power or the solar irradiation. If it contains solar irradiation, this must be converted to power for continued analysis. An example mission profile can be seen in Figure 3.2. Mission profiles are commonly sampled at a resolution of 1 minute, 5 minutes, 1 hour or somewhere in-between.

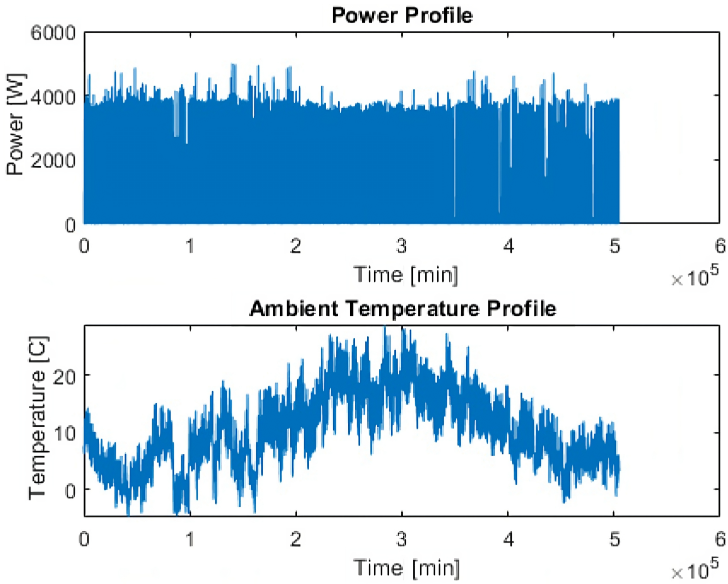

Fig. 3.2: An example of a PV Mission Profile containing electrical power (representing solar irradiance) and ambient temperature profiles during one year.

As described in Section 1.3, this project focuses on PV generator systems. In Figure 3.3, an example of a grid connected 3-phase PV generator system is shown.

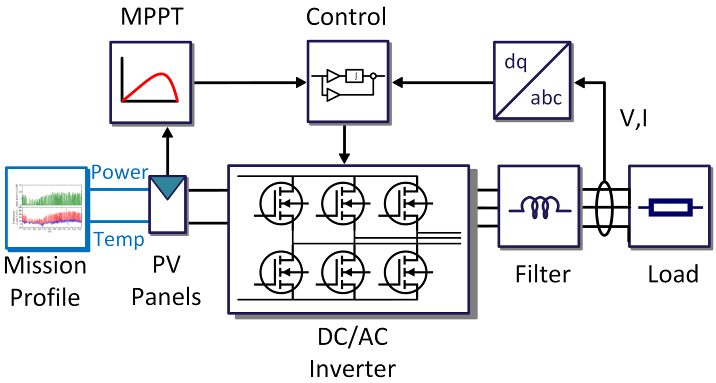

Fig. 3.3: An expanded schematic of the "standard" system of this thesis as first introduced in Figure 1.6 in Chapter 1. This structure is common and is also seen connected to the grid instead of a load.

System level reliability prediction requires simulation of the entire system as shown in Figure 3.3. Because of this, the models used need to be simplified in order for the computation time to be within practical limits.

3.1.1 Model Simplification

Several models exist for converter simulation, representing different levels of accuracy, complexity and characterization and modelling efforts [13]. The purpose of system modelling for reliability analysis is to model the system behaviour which has an effect on the system lifetime. As mentioned before, a main failure mechanism for converters is the wear-out of power devices caused by thermal cycling [14]. This is caused by lossy power conversion, which depends on the operating conditions that change with the loading. The loading of a PV converter is represented by a year-long mission profile and the yearly profile must be simulated to find the junction temperature swings. The thermal swings are the main damage driver in a power electronic module and determine the wear-out of the system.

For practical reasons, the computation time for 1 second in the simulation has to be much less than 1 second, otherwise it would take over a year to simulate the loading of a single system. Therefore the model has to be simple enough, such that an entire year can be simulated within a reasonable amount of time. Examples of this can be found in literature, such as [29, 45, 46]. The approach of [35], using a simplified modelling approach, was found to take around 10 minutes.

3.2 Event-Based Simulation for Long Term Reliability

This section presents the work published in [42] to introduce event-based simulation for long term reliability evaluation.

In the state-of-the-art life prediction for power electronics, it is necessary to evaluate the long term loading for accurate prediction for an application. As mentioned in the previous section, it is necessary to model the behaviour of the system for an entire year, but the models used cannot be too complex, otherwise the computation time will become impractical or even impossibly long.

A compromise could be to classify mission profile subsets being binned in terms of severity. This severity should be a measure of the relative impact of the subset on the damage of the entire profile. It then becomes possible to model the different events with different model complexity.

The proposed methodology is shown in Figure 3.4 and it will require more computational time than simply applying the simplest model to the entire sequence. Here the sections have been classified according to presumed severity. This methodology will enable more accurate modelling of the parts of the sequence that are considered most severe, without modelling the entire time sequence using a computationally heavy model.

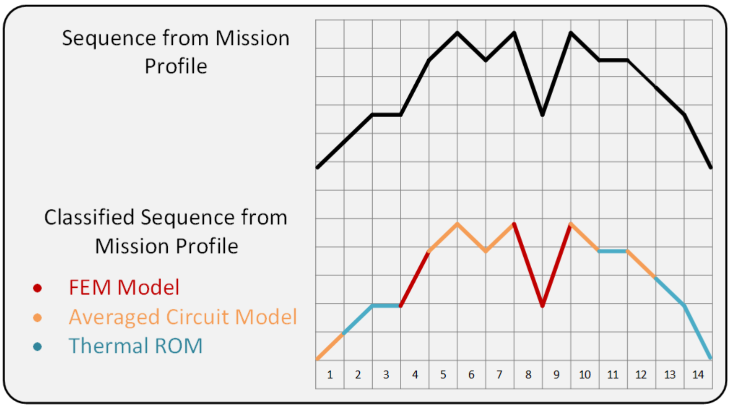

Fig. 3.4: A comparison of an unclassified and classified mission profile. The classified profile comprises different modelling methods for different sections of the profile.

This classification and segmentation of the mission profile may also enable a binning of event types, that allow similar sequences at different times in the mission profile to be calculated using the same simulation. An example of this can be seen in Figure 3.4. Events 5 and 7 are identical in both slope and offset, and, depending on the dynamics of the system and the ambient temperature, may result in similar or even fully identical junction temperature transients. This method is called event-based modelling.

The event-based reliability modelling should be considered an extension of the cycle-based reliability modelling, which the current state-of-the-art models are based on. It offers the ability to discern events based on their rate of change and shape, as opposed to just looking at cycle amplitudes as in the conventional methods. The first-authored paper [42] presents an effort to explore the opportunities offered by this event-based approach.

3.2.1 Methodology

The proposed workflow of [42] for mission profile analysis can be seen in Figure 3.5. The mission profile is the main model input and it is classified into different event types and amplitudes. The main event types used are large transition events, small transition events, steady-state events, and zero power events. For this analysis, all zero power events representing night-time were discarded because it was assumed that they do not affect the system operating lifetime [42]. The night-times add an offset from operational to calendar lifetime, and this effect was ignored, as operational lifetime was the focus.

Then the events are simulated according to the classification of the previous step. The simulation results are compiled and the loading is evaluated to find the damage caused by the profile [42].

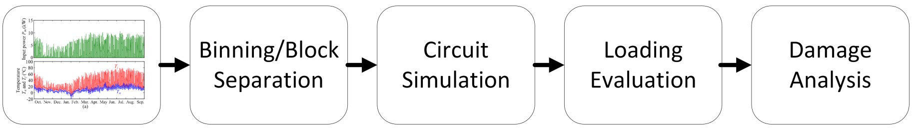

Fig. 3.5: The workflow presented in [42].

Binning/Block Separation

One of the main points of [42] is the event sorting method. The mission profile is scanned and each step is classified into one of the four categories. The sorting sequence (see Figure 3.6) happens in a specific order, namely with the most well-defined types first. The amplitude, which divides small and large transitions are based on the mission profile and the response time of the system. Steady-state events start and end at points where the difference is below the threshold, where no practical change happens to the system. Zero power events occur at night for a PV system and have a power amplitude of zero.

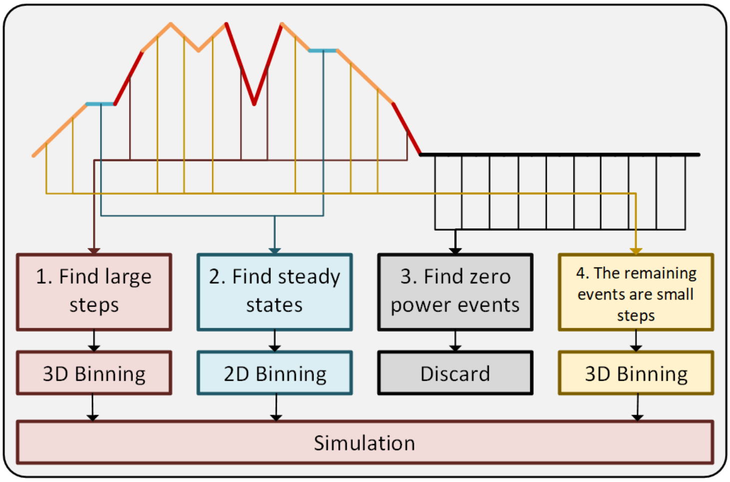

Fig. 3.6: Example of the sorting of a caricatured mission profile. Large and small transitions are binned according to 3 different aspects, steady state are binned according to 2 aspects and zero power events are discarded [42]. These are then simulated according to the categories.

Circuit Simulation

In [42] the simulation methodology used is an averaged model circuit simulation. Based on the number of bins used, different simulation models can be used to achieve a practical computation time. If only a few bins are used, more heavy simulation models can be used as each bin represents more subsections in the mission profile. If many bins are used, the simulation model needs to be less time-consuming as more simulations must be completed to represent the different loadings of the mission profile.

Loading Evaluation and Damage Analysis

The damage modelling is performed with the same principle as described in Equation 2.2, and it will be further discussed in detail in Chapter 4.

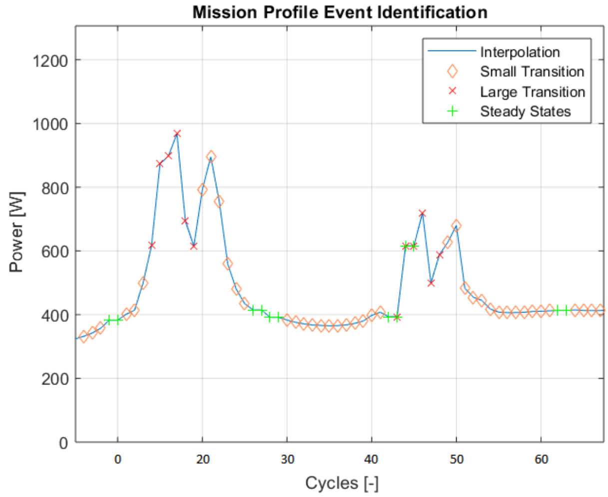

Fig. 3.7: Example classification on real mission profile [42]. In this figure, transitions are the same as steps in Figure 3.6.

The concept of [42] leaves an open question of how to define and confine the events. In [42] an extreme case is used as each event only lasts a few seconds. The method was initially conceptualised with events being loading sequences lasting anywhere from a few seconds to several minutes. With a mission profile of both power and ambient temperature sampled at 1-second resolution, this definition had potentially millions of different shapes of events. To limit the number of different events, the approach of [42] was chosen.

Artificial intelligence methods could be used and it has been investigated for use in event classification [47].

3.3 Mission Profile Simplification

Alternatively, instead of simplifying models to enable simulation of an entire year, the mission profile could be simplified to increase the modelling complexity. This is published in [43] and [44]. Samples of PV mission profiles were inspected for patterns and the following timescale effects were identified:

- Regular Seasonal Variation
- Regular Daily Variation

- Irregular variation from e.g. weather

The hypothesis was formed that a simplified profile could be formed for mission profiles with a low content of the irregular variation, reducing the computation time. Rather than reducing the complexity of the model to save computation time as discussed in Section 3.1.1, this method reduces the length of the mission profile to achieve the same goal and it will keep the same model in all parts of the analysis.

3.3.1 PV Mission Profiles from Arid Climates

Arid climates are defined by their lack of precipitation. Such lack of precipitation is accompanied by a lack of clouds which results in mission profiles which are extremely regular.

Figure 3.8 shows the areas with arid climates.

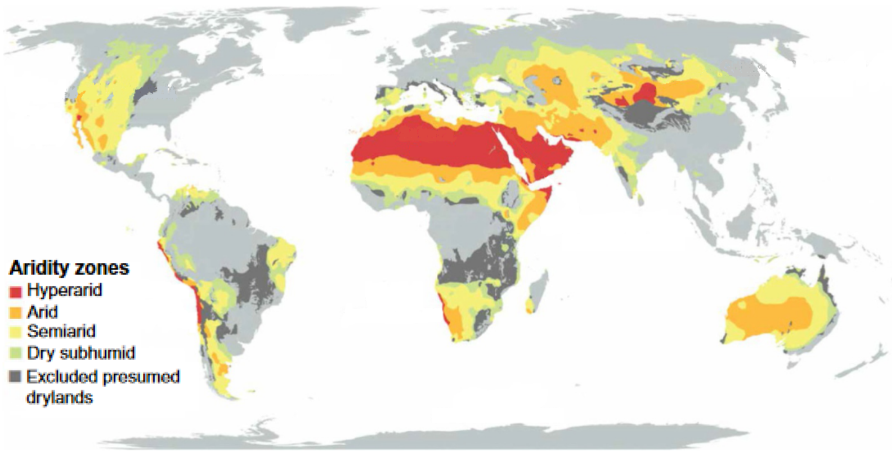

Fig. 3.8: Arid regions of the world where the simplification is valid [48].

Sample mission profiles from arid climates were examined by comparing the days of the profiles and the output junction temperature profile visually and numerically. The days in the arid profiles were determined to contain very little variation. The modelling approach assumes then that if the days in a profile are very similar there is no need to simulate all of them. A few days can be chosen or synthesized and the results can be repeated for the number of days in the profile.

The reference modelling approach can be seen in Figure 3.9. The entire year was simulated using a reduced order loss and thermal model. The resulting junction temperature profile was analysed using the Rainflow Counting algorithm and the total damage suffered by the system over a year was evaluated using a damage model and the linear damage accumulation assumption [43]. The Rainflow Counting algorithm is used to convert cyclic loading into discrete cycles that can be input into damage or life models, the algorithm will be presented in detail in Section 4.2.1. Linear damage accumulation and Miner's Rule will be presented in Section 4.2.1.

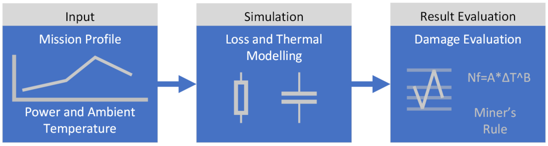

Fig. 3.9: Reduced Order Model for estimation of damage of PV inverter components [43]. Power and ambient profiles are input into the simulation step that results in a device temperature profile. This profile is used to evaluate the damage of the device using Rainflow Counting, Miner's Rule and a damage equation.

The Proposed Methodology

The method starts with a mission profile input. The next step is the preprocessing step where the mission profile is divided into a user-defined number of sections, where a representative daily mission profile is formed for each section.

All of the days in a section are combined to create an average daily profile. This daily profile is then adjusted with a gain such that the peak of the synthesized profile is equal to the average value of the peak power level of all the days in that section. This ensures the representability of the simplified profile.

The conventional reduced order simulation model is then used with the modified mission profile. As the proposed methodology doesn't alter the simulation model and only alters the mission profile input, it can be used with any simulation model having a mission profile input.

At this point a junction-to-ambient temperature profile has been generated for the modified mission profile. This profile is divided into single representative days. The daily representative junction-to-ambient profiles are repeated as many times as there are days in that section and are then superimposed to the ambient temperature profile. This creates a yearly junction temperature profile.

The junction temperature profile can be processed using Rainflow Counting, linear damage accumulation and a damage model to predict the lifetime of the components and therefore the whole system. Damage modelling will be discussed in detail in Chapter 4. A flow chart of the entire methodology can be seen in Figure 3.10.

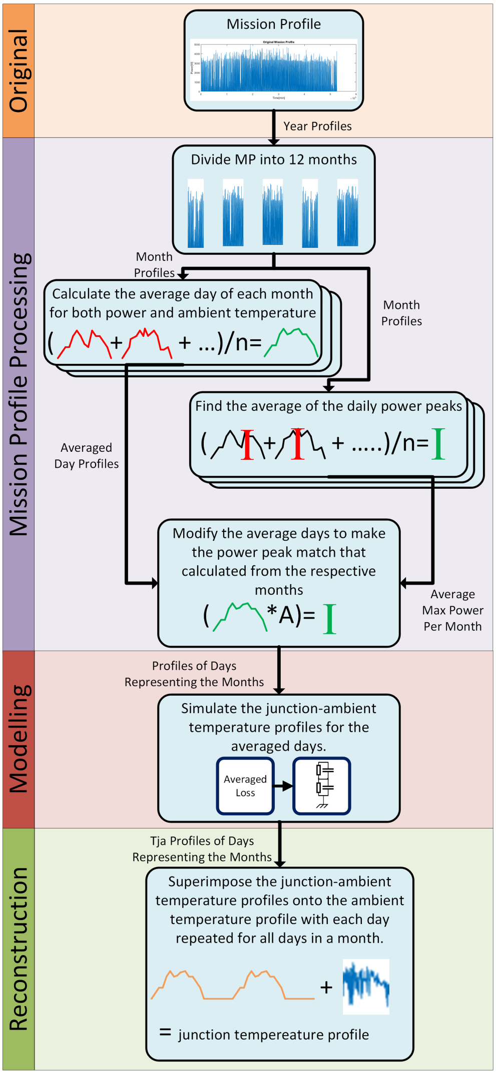

Fig. 3.10: The steps of the proposed method for simplification, simulation and reconstruction of arid mission profiles (MP) [43]. The final result is a reconstructed device temperature profile which can be used to evaluate the damage of the input profile.

Results and Discussion

The first step to verify the representativeness of the synthesized mission profile is to compare the junction temperature output. In Figure 3.11 the original power profile, repeated representative power profile, and junction temperature profiles are seen. The representative profile can be seen to contain artefacts from the different days in the original profile. The two resulting junction temperature profiles contain very similar junction temperature swings.

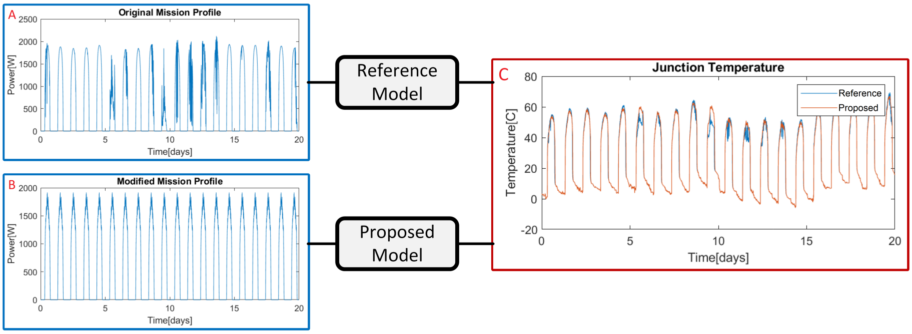

Fig. 3.11: Comparison of results from modelling of original Arizona mission profile and reduced mission profile [43].

This methodology was tested on four different real mission profiles from arid climates. The calculated damage from the reference method and the proposed method were compared, which can be seen in Table 3.1.

Table 3.1: Damage Error and Computation Time Savings [43]

Location	Damage Error	Time Reduction
Arizona	+6.37%	-98.1%
Colorado	+20.02%	-97.9%
Sacramento	+3.43%	-97.7%
Spain	+1.68%	-95.6%

As the number of sections is user-defined, the comparison was repeated for different numbers of sections from 1-50. The damage deviation and simulation time reductions of the different numbers of days can be seen in Figure 3.12.

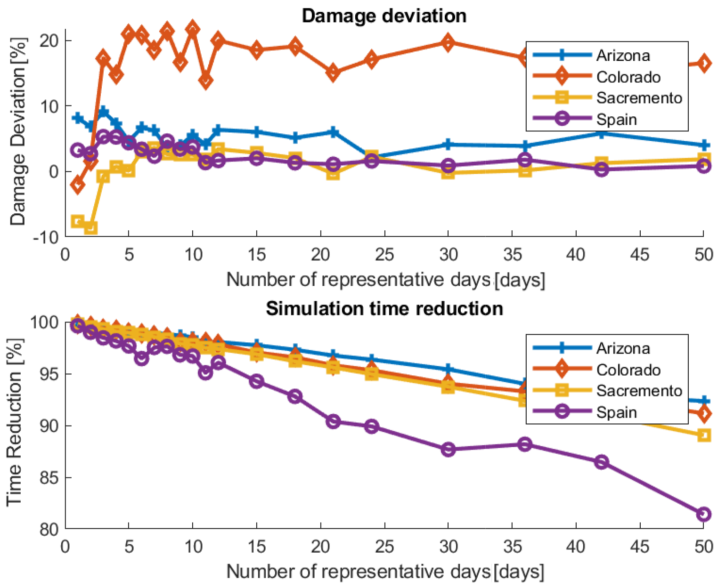

Fig. 3.12: Impact of number of representative periods on error introduced by the simplification method [43].

In Figure 3.12, it can be seen that the methodology introduces more error for the Colorado profile relative to the other profiles. Upon closer inspection of the input profile it was found that, while the profile is from an arid climate with low precipitation, the profile contains a relatively greater amount of cloud-based irregularities. To make the simplification method generally applicable, even within the class of arid climates, the errors caused by clouds must be reduced to a level that is comparable to those of the other profiles. The investigation was repeated for the temperature profiles, but these were found to contain no issues. This is likely due to the relatively lower rate of change of the ambient temperature.

3.3.2 Generalized PV Mission Profile Simplification

As presented in the previous section, the first attempt at a PV mission profile simplification methodology is strongly dependent on a lack of clouds in the modified mission profiles. While three of the analysed arid profiles had a low enough amount of clouds with good results, the fourth profile contained too much cloud content. If this method is to be used, the amount of clouds should be assessed prior to using the model to ensure accurate results.

By inspecting the inputs and outputs of each processing step in [44] and comparing the inputs and outputs of the different mission profiles, the problem with the Colorado profile was found. The main issue was caused by the method for synthesising the representative mission profile. Instead of using averaging to synthesize a representative, an alternative proposed methodology [44] analyses and chooses representative days from the mission profile. This removes the averaging process, which was the cause of deviations for the previous method. As the research question and the objectives of Section 1.3.2 in Chapter 1 does not limit the scope to only arid climates, it is important to develop general methodologies.

Zero Order Modelling

The objective is to find the days in the mission profile that result in the most average amount of damage, and then use those days to represent a section of the mission profile. The "Zero Order" simulation model was developed to get an estimation of the damage of each day without directly simulating the entire mission profile. Figure 3.13 shows the "Zero Order" modelling methodology.

The name is meant to indicate that this is the least amount of effort that can be made which results in an output junction temperature profile. The method is as follows: The power profile is multiplied with a static gain based on the thermal junction-to-ambient resistance of the analysed system and its efficiency. This is summed with the ambient temperature profile and the resulting estimated junction temperature profile can be analysed using Rainflow Counting, a damage model and linear damage accumulation method.

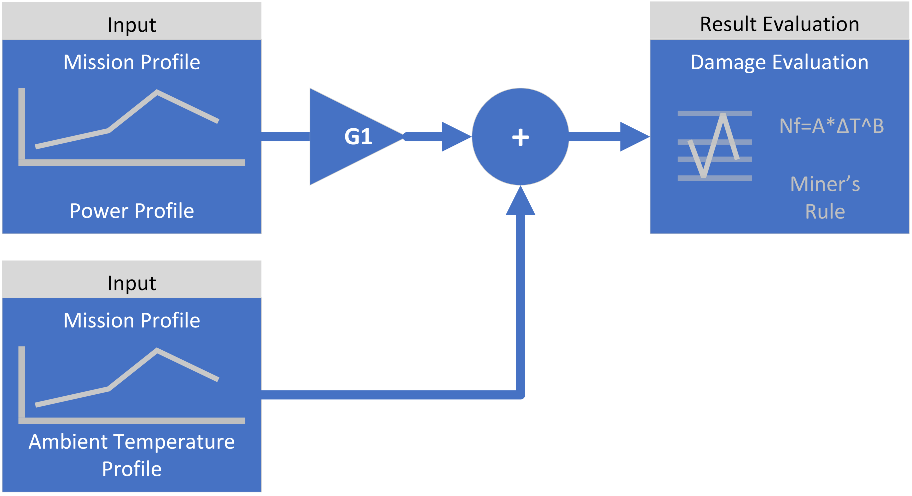

Fig. 3.13: The Zero Order Modelling approach for mission profile simulation [44].

Proposed Method

The steps of the proposed methodology can be seen in Figure 3.14. It is a continuation of the method in Section 3.3.1 and Figure 3.10, but modified for use with mission profiles from more cloudy climates. The initial steps are identical; the input is a power and ambient temperature mission profile. The input profiles are then divided into a user-defined number of sections.

Each section is evaluated with the zero order modelling. The numerical damage of each day in a section are compared to find the day, which results in an amount of damage closest to the average damage of the days in a section.

A representative mission profile is formed with the representative days and this profile is used directly with the user-chosen behavioural model. As seen in [43], the methodology should be considered a modelling framework that is model-independent and may be used with any modelling approach which takes a mission profile as input and results in a junction temperature profile.

The junction-to-ambient temperature profile is isolated, repeated and superimposed on the ambient temperature profile to achieve a year-long junction temperature loading profile. The final resulting damage is then found with Rainflow Counting, linear damage accumulation and a damage model of the device.

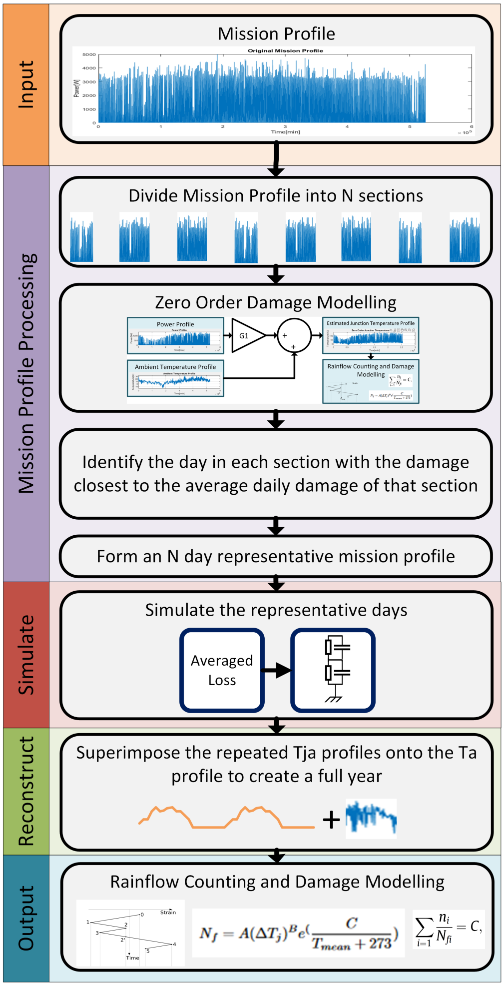

Fig. 3.14: The general methodology proposed in [44]. Input, processing, simulation, reconstruction and output steps are shown and the sequence can be seen. Also resulting in a reconstructed device temperature profile which is be used to evaluate the damage of the input profile.

Results

The proposed approach was applied to four mission profiles from arid climates. As discussed in Section 3.3.2 one of the mission profiles proved to contain enough clouds to be problematic for the previous methodology. Additionally, the methodology was applied to a mission profile from a temperate and non-arid climate. The number of sections for mission profile division is user-defined, therefore for each profile, the number of divisions were swept from 2 until the deviation of the methods settled to a constant level. As can be seen in Figure 3.15, the deviation of damage of the proposed method compared to the reference method is greater at fewer divisions and reduces to less than ±5%. The percentage-wise simulation time saved by using the proposed method is greater with fewer divisions, starting at approximately 99% time reduction with only one division and decreasing linearly to approximately 93% at 20 divisions. This can be seen in Figure 3.16.

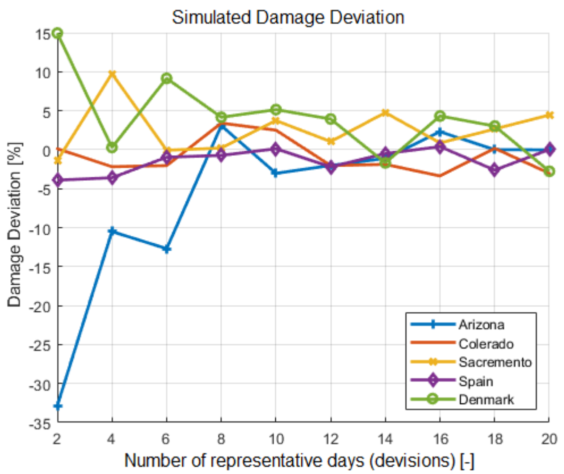

Fig. 3.15: The damage deviation of the proposed method for multiple mission profiles.

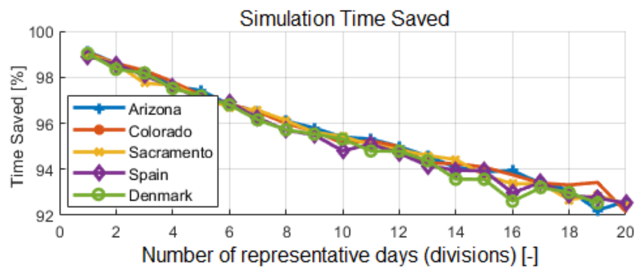

Fig. 3.16: The simulation time reduction of the proposed method for multiple mission profiles.

Parameter Sensitivity

The presented method was developed to meet objective 2 of Section 1.3.2 in Chapter 1. By using the method for simulation acceleration provided by the developed method, some analyses can be performed faster and become more practical.

Parameter sensitivity analysis usually takes many steps, such as in [49].

Using the developed method it can be easier to evaluate the impact of parameter variation directly. In Figure 3.17 the thermal resistance of thermal interface material (TIM) applied at the power module for the PV-inverter was varied and the theoretical lifetime was evaluated using the methodology of Figure 3.14.

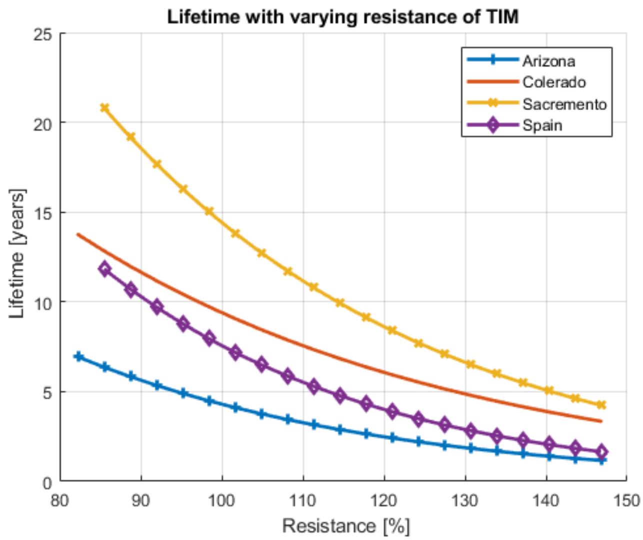

Fig. 3.17: Resulting lifetime of converter with varying thermal resistance of thermal interface material (TIM). Analysis was repeated for 4 locations [44].

If the parameter variation and it's impact are known, as investigated in Figure 3.17, the lifetime variation can be calculated directly. An example of this can be seen in Figure 3.18. Here, a normal distribution of varying resistance was coupled with the resistance-to-lifetime relationship of Figure 3.17 to find the normal distributions of lifetime for the different locations.

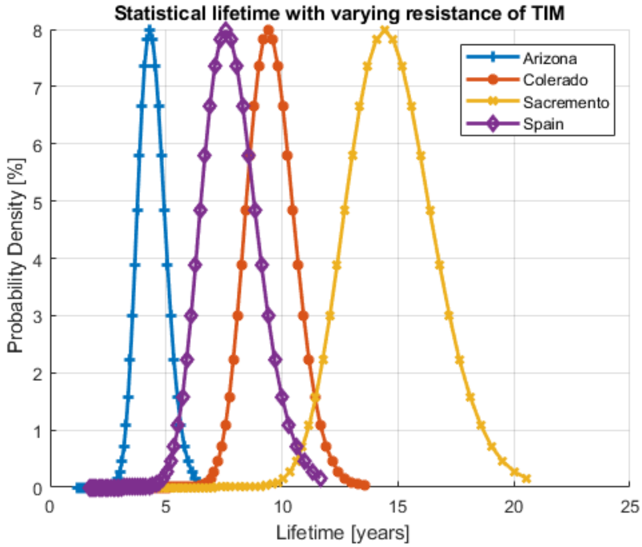

Fig. 3.18: With a known distribution of the thermal resistance, the distribution of lifetime can be directly calculated. In this case only one variable was varied, but it is possible to include variation of multiple parameters. Analysis repeated for 4 locations [44].

The lifetime impact of varying thermal capacitance was also analysed as for thermal resistance variation. As the simulation time is low, the parameter sweeps are practical to simulate for any parameter of interest. The lifetime impact of the thermal capacitance variation can be seen in Figure 3.19.

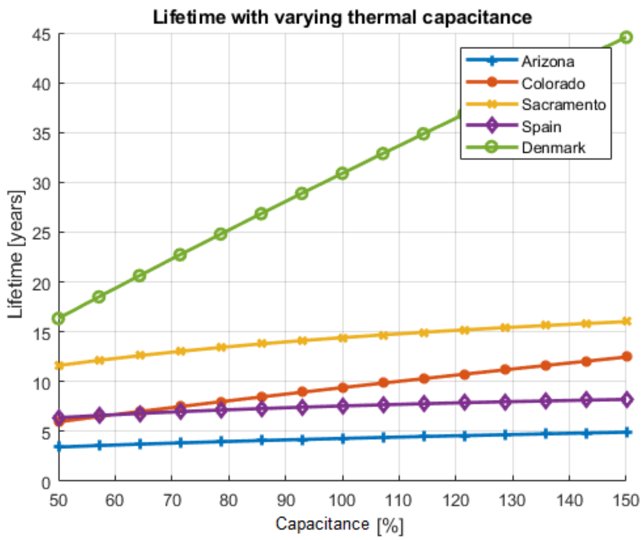

Fig. 3.19: Resulting lifetime of converter with varying thermal capacitance of thermal interface material (TIM). Analysis repeated for 5 locations [44].

System Analysis and Planning

The research question of this thesis formulates a need for multi-timescale reliability modelling of power electronics. The objectives further specify a need for simplification and speed-up of lifetime simulation. This can help to determine lifetime profits for different system configurations and helps system planners to make the optimal investment. An example investment case where the developed methodologies were used can be found in [44].

In the example, an inverter system is investigated to find the optimal system configuration from a investment point of view. First, the system is matched with PV panels of varying power at different locations, and the resulting lifetimes are evaluated using the same method as in the last section.

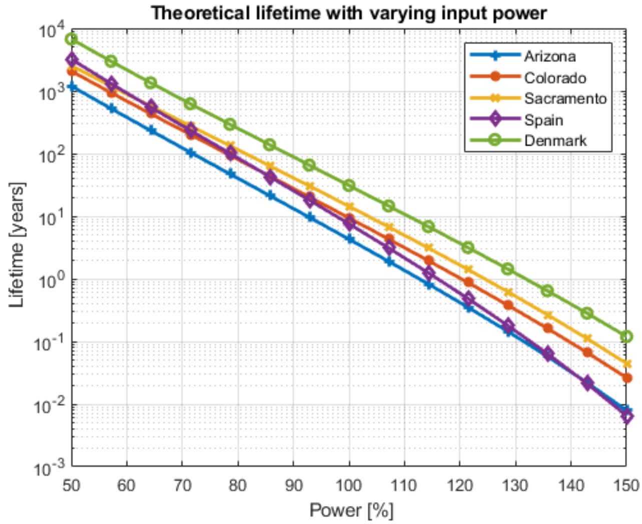

Fig. 3.20: Theoretical lifetime of converter with varying power. Analysis repeated for 5 locations [44].

The net profits for the different system configurations from Figure 3.20 were calculated, taking profits from sold power and a PV system costs into account. The prices used are only for this example and simplifications have been made, such as fixed electricity price of 10 eurocents per sold kWh and system cost of 6700 EUR.

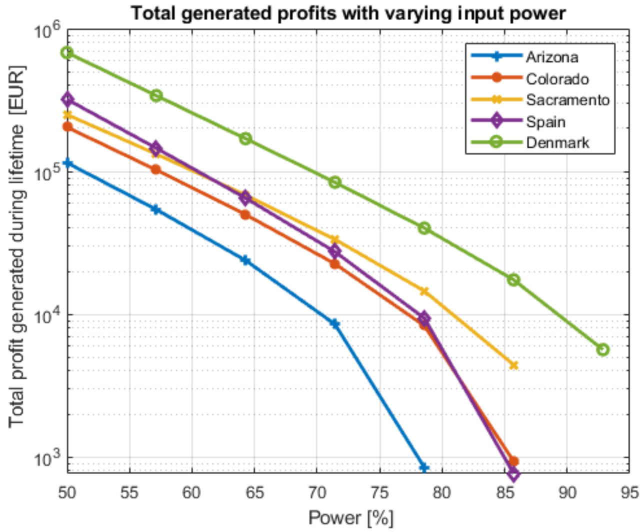

Fig. 3.21: The net profit from PV generator system. Gross profit calculated with fixed power price of 10 eurocents per kWh and a fixed price of 6700 EUR for the PV system. Analysis repeated for 5 locations [44]. In this example the total generated profits decrease with increasing power as that results in increased losses and reduced lifetime. These results are not applicable beyond this simplified example.

Figure 3.22 shows the lifetime of the PV inverter at different PV panel power levels and in different locations. Included is also an indication of when the system has paid for itself at different power levels. To gain profits from such a system, it should be designed to have a higher lifetime than the time it takes for it to pay for itself.

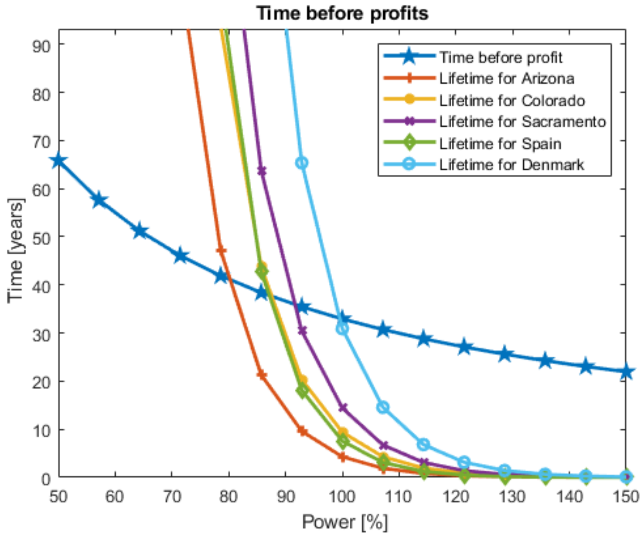

Fig. 3.22: Comparison of the theoretical lifetime of the system and the time it takes for the PV system to pay for itself based on the prices of Figure 3.21. Analysis repeated for 5 locations [44].

Multi-Year Degradation Modelling

Using the simulation acceleration method presented in Section 3.3.2, simulation of a single year becomes so fast that modelling of the continuous degradation effects become possible. This will be detailed and demonstrated in case studies in Chapter 5.

3.4 Summary

In this chapter, system-timescale modelling of power electronics system was presented and developed to meet the second objective of Section 1.3.2 in Chapter 1: Simplification and speed-up of lifetime prediction. Two modelling approaches based on timescale analysis were developed. The event-based simulation method [42] and the mission profile simplification method [43] [44]. The first was based on a short term loading event concept as an alternative to the cycle-based damage modelling, which is currently the state-of-the-art. The concept was developed and published, but some open questions remain for future work on this approach. The main of which is how to delimit the events.

The second approach to reach the objective was based on the shortest regularly repeated time phenomenon in a PV mission profile, the day and night cycle. Here the approach synthesises a simplified replacement mission profile based on the days in the year. This profile is shorter than the original profile and can therefore be used to perform simulations in a much shorter amount of time or to increase model complexity with the same computational time. The accuracy of the representative mission profile proved to be highly dependent on the amount of clouds contained in the profile.

An generalized methodology of the simplification methodology was developed for use beyond mission profiles without clouds. In this method, selected representative days are used rather than synthesized representative days as the synthesis process was found to neglect the cloud content. Five mission profiles were tested from both arid and non-arid climates, and at a 10+ section division the error gave consistently less than 5% across all profiles. This methodology will be a key enabler to meet the first objective of Section 1.3.2 in Chapter 1: The introduction of multi-timescale phenomena into reliability analysis.

Contributions of this Project

[42] **Fogsgaard, M. B., & Iannuzzo, F.** (2020). Introducing the LEGO Mission Profile Analysis Methodology. *CIPS 2020; 11th International Conference on Integrated Power Electronics Systems (s. 455-459). VDE Verlag GMBH.* https://ieeexplore.ieee.org/document/9097725

This paper presented the event-based simulation paradigm. This paradigm has the potential to offer ways of including more factors into damage modelling such as sequence and stress rate.

[47] **Fogsgaard, M. B., Bitsch Nørgaard, J., & Iannuzzo, F.** (2020). Artificial Intelligence-Based Approach for Damage Estimation of Power IGBTs from Real Mission Profiles. *PCIM Europe digital days 2020: International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (s. 985-989). VDE Verlag GMBH.*

This paper presented an attempt to characterise events for event-based damage modelling using artificial intelligence methods.

[43] **Fogsgaard, M. B., Bahman, A. S., Iannuzzo, F., & Blaabjerg, F.** (2021). PV mission profile simplification method for power devices subjected to arid climates. *Microelectronics Reliability*, 126, [114328]. https://doi.org/10.1016/j.microrel.2021.114328

This paper presents a mission profile simplification method for PV converters in arid climates. The method is able to reduce simulation time by up to +95% at a slight deviation of the calculated compared to the original unsimplified method.

[44] **Fogsgaard, M. B., Bahman, A. S., Iannuzzo, F., & Blaabjerg, F.** (2022). Mission Profile Simplification Method for Reliability Analysis of PV Converters. *Microelectronics Reliability*, XXX, [114651].
https://doi.org/10.1016/j.microrel.2022.114651

This paper presents an improvement to the previous mission profile simplification method. This method is climate independent and was found to be able to reduce simulation time by up to 96% while keeping the damage calculation error less than ±5%.

Chapter 4

Damage and Degradation Timescale Modelling

This chapter will present the damage and degradation timescale modelling of the power electronic system and provide the foundation to meet the first objective of Section 1.3.2 in Chapter 1: The introduction of multi-timescale phenomena into reliability analysis.

To merge the damage and degradation timescales in a multi-timescale reliability analysis, the two concepts must be analysed and their interactions must be known. This chapter starts with a discussion of damage modelling, and then one of the degradation modelling methods follows.

4.1 Background

Damage and degradation modelling are fundamentally multi-timescale. The damage may occur in a single moment, in the fluctuations occurring multiple times per second, or over the course of several minutes, whereas the degradation effects are mainly felt months or years later. These two timescales are so far apart that their unified modelling is impractical, and this is the reason why reliability analyses are most commonly performed using only damage modelling, excluding the degradation effects. It is not the case that degradation doesn't occur in the short term, only that its impact is too small to notice.

Figure 4.1 shows the span of the degradation and damage timescales in normal operation. If accelerated test conditions are used instead, the degradation phenomena can occur earlier. Degradation is an endogenous phenomenon and therefore originates in the devices and subsystems that make up the complete system. Damage is the cause and degradation is the effect. Therefore, a discussion of damage must precede the discussion of degradation.

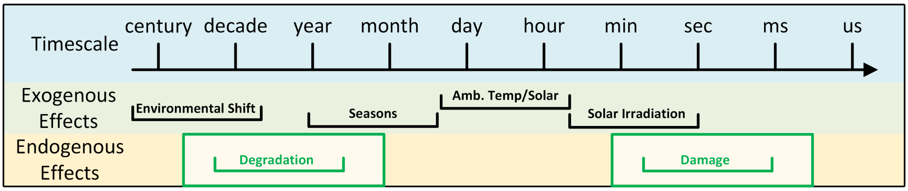

Fig. 4.1: Damage and degradation timescales(in green).

4.2 Cycle-Based Damage Modelling

The main stressor in a power module is caused by the lossy power conversion. Power modules generate losses that drive the temperature fluctuations in the module. The thermal fluctuations cause thermal expansion and differences in the different materials will stress the entire modules, but the material interfaces in particular [14].

Inverter modules experience cyclic stresses from both the fundamental frequency of the operation as well as stresses caused by variation of input power. This is expressed in the mission profile, which is used to represent the inputs the device will experience over time in a certain application.

4.2.1 Rainflow Counting

The temperature fluctuations caused by operation of a PV converter has a cyclic load profile. The Rainflow Counting algorithm is a useful tool in reliability analysis of such cyclic load profiles. The algorithm takes a load profile as input and outputs a table of full and half cycles. This table of reversals reports both the occurrence and the amplitudes of the stress reversals which enables further reliability analysis using a lifetime model of a component [50]. A number of different versions of the algorithm exist but they all offer the following advantages [51] and [50]:

- Easy to use [51].
- Quantifies stress profile into ordered cyclic ranges [52].

- Logical way to combine full cycles from half cycles [51].
- Provides a quantified output which can be used with a damage model directly [51] and [50].

Figure 4.2 gives some very simplified examples of load profiles and resulting cycles.

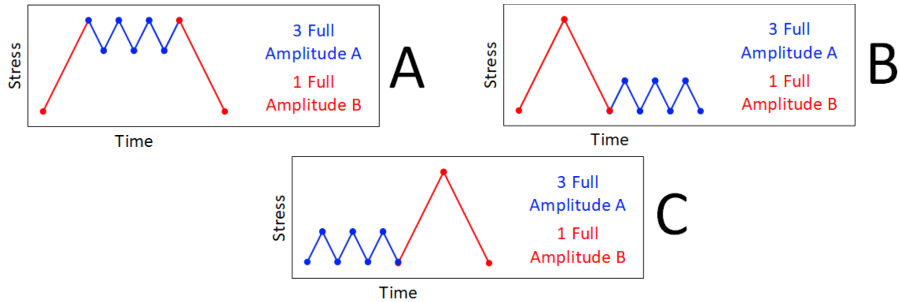

Fig. 4.2: Example Stress Profiles A, B and C for Rainflow Counting.

The resulting "counted" full and half cycles from the Rainflow Counting are then passed to a damage model to see the lifetime effect of the counted cycles.

The CIPS2008 model is a commonly used state of the art damage model for power devices [14]. References [6, 16, 35] use the CIPS2008 damage model to estimate the life-times of their respective power devices subjected to a specific mission profile loading.

References [11, 14, 18, 53] present work where other damage models are used to estimate the life-time of power devices. Table 4.1 shows a selection of damage models with equations and highlighted loading terms in magenta.

Table 4.1: Table of damage models with highlighted loading terms (magenta)

Name	Equation	Ref(s)
Coffin-Manson	$N_f = A(\Delta\varepsilon_{pl})^B$	[54]
Coffin-Manson(Temp)	$N_f = A(\Delta T_j)^B$	
Mod. Coffin-Manson	$N_f = \frac{a+b(\Delta t_{T_j})^{-n}}{a+1}$	[41]
Mod. Coffin-Manson	$N_f = A\Delta T_j{}^{-\alpha} exp\left(\frac{E_a}{k_B T_{jm}}\right)$	[55]
Basquin	$N_f = a(\Delta\sigma_e)^{-b}$	[56]
Bayerer	$N_f = K(\Delta T_j)^{\beta_1} e^{\left(\frac{\beta_2}{T_j+273}\right)} t_{on}{}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6}$	[57]

Positive Offset

Rainflow Counting by default only looks at cycle amplitudes and does not take any positive offset into account. Positive offset refers to an offset difference between two fluctuating loads, an example could be one going from 1 [N] to 2 [N] and back again, and the other going from 20 [N] to 21 [N] and back.

Profile A and B in Figure 4.2 would be quantified equally, but for power devices the positive offset of the blue cycles does affect the experimental lifetime.

In reference [58], a number of test configurations are conducted experimentally. Here multiple tests are conducted with the same junction temperature range but with different junction temperature means. If the positive offset did not affect the lifetime, then e.g. test configurations I and V would have an identical number of cycles to failure. In reality, they differ by more than 92% as test configuration I fails the component in 24 kcycles (kilocycles or 1000 cycles) and configuration V manages to do the same in 315 kcycles. The test configurations are seen in Figure 4.3 and the paper [58] can be consulted to find more examples of the offset-dependent experimental lifetime results. Some implementations of Rainflow Counting and damage models take this into account and as a result, they are much more accurate [57]. Because of these factors, implementations like these are strongly recommended if the analysed stress profile contains cycles with varying positive offset.

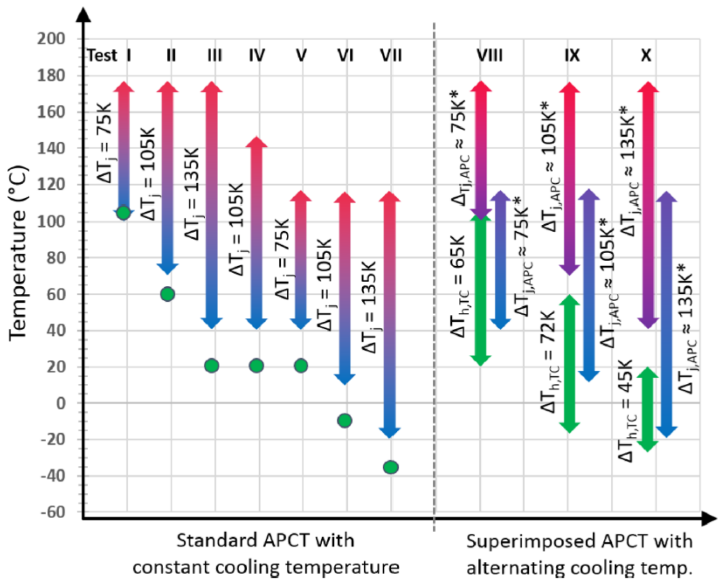

Fig. 4.3: Comparison of the loading of the different test conditions from reference [58]. ACPT is Acclerated Power Cycling Test.

Sequence

Another limitation of Rainflow Counting is that it does not take sequence into account. Profiles A, B and C in Figure 4.2 quantify as being equal according to Rainflow Counting. However, from fracture mechanics, it is known that cycles with a low amplitude can increase the size of a crack, but not initiate cracking themselves [59, 60, 61]. This means that experimentally, profile B would be more harmful than profile A, which is more harmful than profile C.

Sequence effects are ignored from damage calculation because of Miner's Rule. Miner's Rule/Palmgren-Miner's Rule/The Linear Damage Accumulation Rule states that the damage is equal to the sum of the ratio of counted cycles over number of cycles to failure for different loading amplitudes. The equation can be seen in Equation 4.1.

$$D = \sum_{i=1}^{kn} \frac{N_i}{N_{f,i}} \tag{4.1}$$

Where D is the accumulated damage, N_i is the numbers of cycles at the i_{th} stress amplitude, $N_{f,i}$ is the number of cycles to failure for the ith stress amplitude, and kn is the number of different stress amplitudes [62] and [63].

Miner's Rule [62] and [63] was originally formulated with crack initiation as the failure criterion, and not crack propagation beyond a certain threshold. Miner's Rule was formulated for mechanical systems where the system is defined as failed, once the first crack has been initiated. In power electronics, neither the first cracking in the bond-wires nor the solder layer cause failure of the component. Failure is not achieved until the cracks in those regions have grown to such a length that operation is compromised. This also means that Miner's Rule is not generally applicable. Within the mechanical reliability field, it is known that the Miner's Rule is inaccurate for damage calculation of variable loadings [64]. However, despite efforts to develop alternative methods, no single method has replaced it, as more advanced models taking more factors into account are more difficult to fit and use [64] and [65].

Research has shown that some regions exist where the inaccuracy of Miner's Rule is within reasonable limits for power electronics. However, these regions have not been fully mapped [66].

Stress Rate

Material characteristics are not constant and depend on conditions such as temperature and stress rate. Furthermore, some materials in a power module are anisotropic or may have residual stresses or even micro-cracks from the manufacturing process. Some of these effects can be modelled, but require more effort than simply applying a damage model (e.g. any of those in Table 4.1) to the counted cycles from Rainflow Counting as Rainflow Counting does not take stress rate into account.

Reference [41] investigates the effect of cycle duration on component lifetime. As the loading is semi-sinusoidal, the stress rates vary between the conducted loading conditions. Figure 4.4 shows a comparison of the temperature cycles of the loading condition, and it can be seen that the rate at which the junction temperature increases, is different from one condition to the next. According to the usual implementation of the Rainflow Counting Algorithm, the conditions would be counted as being equal as they have the same positive offset and range [50].

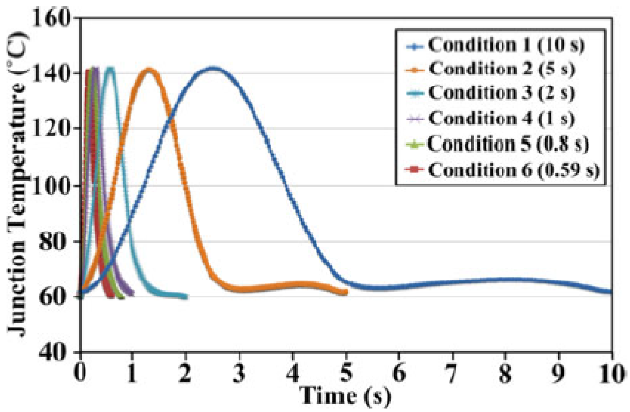

Fig. 4.4: Comparison of the loading of the different test conditions [41].

The loading conditions are summarized in Table 4.2, where it can be seen that the offsets and amplitudes of the thermal cycles are equal. However, despite the apparently equal stress of the different conditions, the experimental lifetime of the conditions are not equal [41]. This proves that another factor from the temperature swing amplitude and temperature offset affect the experimental lifetime.

Table 4.2: Test conditions and results from [41].

Condition	ΔT	T_{max}	t_{on}	N_f
1	80.8[°C]	142.7[°C]	10[s]	128900
2	80.6[°C]	142.8[°C]	5[s]	159900
3	82.0[°C]	142.3[°C]	2[s]	174000
4	81.6[°C]	142.3[°C]	1[s]	185810
5	81.8[°C]	143.3[°C]	0.8[s]	197500
6	80.8[°C]	142.4[°C]	0.59[s]	211201

4.2.2 The CIPS2008 Life Time Model

Rainflow Counting requires a damage model to enable an evaluation of the damage of a loading. A number of damage models were presented in Table 4.1, one such model is the CIPS2008 damage model. The CIPS2008 [57] damage model (AKA Bayerer damage model) is based on the empirical formulation of the older Coffin-Manson [54] damage model. The model is empirical and therefore is based on experimental lifetime results. The formulation of the model can be seen in Equation 4.2.

$$N_F = K\Delta T_j^{\beta_1} e^{\frac{\beta_2}{T_j+273}} t_{on}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6} \tag{4.2}$$

Where N_f is the number of cycles to failure, ΔT_j is the junction temperature range. T_j is the junction temperature, t_{on} is the thermal on-time, and I is the current in each bond-wire. V is the blocking voltage class of the DUT and D is the bond-wire diameter. Parameters K, β_1, β_2, β_3, β_4, β_5 and β_6 are experimental fitting parameters [57].

Damage models such as the CIPS2008 damage model have a number of advantages:

- Easily estimates the number of cycles to failure from in loading conditions.
- Uses multiple loading conditions (as opposed to just one).
- Based on experimental data.
- Based on statistics.

The model was defined for use with power electronic devices as opposed to e.g. the Coffin-Manson model. Which was defined for mechanical specimens [57] and [54]. This is advantageous as the mechanical structure of a power device is highly complex with a range of different materials. The complex interactions of structures and materials may lead to generally different relation between stress and damage for power electronics compared to mechanical specimens. A model defined for power electronics may be able to take those factors into account.

As the CIPS2008 model is based on the Coffin-Manson model it inherits the cycle-basis of the Coffin-Manson equation. This basis makes it straightforward to use for engineers and scientists familiar with a cycle-based concept from either experience with the Rainflow Counting algorithm or the Coffin-Manson lifetime model.

Compared to the Coffin-Manson model it offers the potential of higher accuracy as it has more loading terms and can take more varied loading conditions into account. This is directly related to the discussion of Section 4.2.1, where the limitations of Rainflow Counting were discussed. The CIPS2008 model was formulated on observations of experimental life tests of power electronic devices [57] and is therefore strongly related to the experimental results of accelerated lifetime tests.

4.2.3 Limitations of Current Lifetime Models

The foundation of the CIPS2008 model is, as mentioned in Section 4.2.2, the Coffin-Manson model [57]. This is where the first loading term of Equation 4.2 comes from. It is a power term like that in the Coffin-Manson model, which model was defined for lifetime predictions for samples subjected to plastic stress [54].

Samples subjected to force will deform. The amount of deformation depends on the amplitude of the applied force. At low force levels the subject will deform a little and will return to the original shape when the force has been removed, this is elastic deformation caused by elastic stress. A large amount of force will deform the subject so much that it will not return to the original shape once the force has been removed. This is plastic deformation caused by plastic stress [67].

As a result of the formulation for plastic stress ranges, the original formulation of the CIPS2008 model is only valid for temperature ranges over 40 K [68]. A newer formulation has been published in 2020 which extends the valid range down to +25 K [68]. Ideally, the damage model used is valid for all temperature swing ranges, as normal operation of most applications consist of varying temperature swing ranges and therefore the damage model used needs to be accurate for all ranges.

Most lifetime model characterisations are based on accelerated lifetime tests. Here the device is subjected to amplified loading conditions to fail the device within a reasonable amount of time. While a device may be designed to last for ten years, it is generally not profitable to test that device for ten years before putting it to market. Both because ten years of non-stop testing is expensive, but also because newer and better devices may have been developed and put to market in the meantime.

Non-optimal testing leads to a general problem that remains for empirical lifetime models characterised by experimental loading conditions in the plastic region, as these have not been characterised for elastic loads, and therefore may become inaccurate for elastic loading conditions [69].

4.2.4 DC and AC power cycling for damage model characterisation

Similar to the points of the previous sections, another factor in characterisation of empirical damage models for power devices is to characterise the devices with conditions that most closely match the conditions of the final application.

Many power devices are tested using DC power cycling, either active or passive. Passive power cycling refers to tests where the temperature of a device is cycled using an external source of heating. In active power cycling the device is heated using heat generated by the loss of that device. In active DC power cycling, the devices are alternately turned on and off with a set period and duty cycle [70] and [71]. In AC power cycling, the devices are heated using their own loss, but the devices are set up in, commonly, 1 or 3 phase topologies such that the active and reactive powers of the devices under test more closely match those of the final 1 or 3 phase operation of the application [72].

Based on the points of the previous sections, it should be advised that accelerated life test are conducted in way that most closely represents the actual application. Therefore, devices in AC applications should be tested using AC power cycling and devices in DC applications should be tested using DC power cycling [58].

Several examples of AC and DC cycling set-ups can be found in literature [73] and [74].

4.3 Stress, Damage and Degradation

Most lifetime or damage models only model the damage or consumed life, a dimensionless quantity going from 0 for a pristine device to 1 for a failed device [14]. These damage models can be linked to a degrading quantity with a non-linear degradation function. This is expressed in Equation 4.3.

$$1 - d = \left(1 - \frac{N}{N_f}\right)^k \tag{4.3}$$

Where d is degradation, N is the number of cycles already passed, N_f is the number of cycles to failure and k is the degradation shape parameter. The non-linear relation between damage and degradation with different values of k can be seen in Figure 4.5.

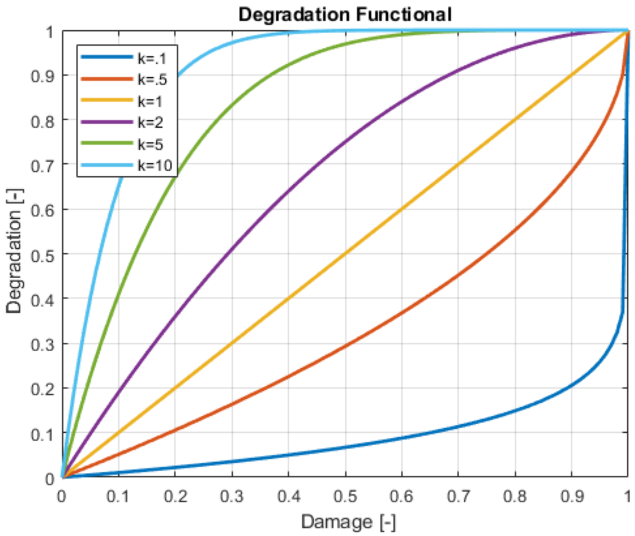

Fig. 4.5: A comparison of the non-linear coupling of damage and degradation for different shape parameter values. k=1 results in a linear coupling of degradation to damage, k>1 is for wear-in effects, and k<1 is for wear-out degradation [75].

The functional of Equation 4.3 links the damage (D or $\frac{N}{N_f}$) as in the lifetime already consumed, to the degradation (d) which is the relative crack length in the component. For bond-wires, this functional can be used to link the crack length to the calculated damage, and show the wire resistance over life. For the solder layer, this equation can link the crack length with the damage. This enables the modelling of the evolution of thermal resistance of the solder layer. This will result in a feedback loop where an increase of thermal resistance will increase the temperature swing. This will cause more damage and degrade the thermal interface further, increasing the thermal resistance and raising the temperature swing even more. This effect will be modelled in Chapter 5.

An example workflow for calculation of the crack length induced by a cycle with temperature swing ΔT_{ex} could be:

Calculation of the damage of the temperature swing using the temperature modified Coffin-Manson damage model:

$$D_{ex} = A(\Delta T_{ex})^B \tag{4.4}$$

Where D_{ex} is the damage of the example temperature swing and A and B are fitting parameters.

Damage summation with any previously accumulated damage:

$$D_{acc} = D_{prev} + D_{ex} \tag{4.5}$$

Where D_{acc} is the total accumulated damage, and D_{prev} is the damage before the example temperature swing.

Hereafter the degradation is found using the rearranged non-linear degradation function:

$$d = 1 - (1 - D_{acc})^k \tag{4.6}$$

Where d is the degradation and k is the shape parameter.

The degradation d is dimensionless, goes from 0 to 1, and represents a crack or fault propagating through a component. Recollecting Equation 2.1 in Chapter 2 shows how the resistance of the solder layer in a power module evolves with accumulating damage:

$$R = \frac{\rho T}{\pi(r - rd)^2} \tag{4.7}$$

Where R is the resistance, ρ is the resistivity, T is thickness and r is the radius.

4.4 Impact of Degradation on System Behaviour

The degradation of multiple bond-wires on an IGBT in a power module was investigated in [76] and [77]. 3D multi-physics finite element analysis was used to evaluate the stresses and strains in the bond-wires during operation. This work was conducted to help meet the objectives of Section 1.3.2 in Chapter 1 and investigate methods of introducing degradation effects into device and system modelling. The goal was to investigate the impact of degradation on the microscopic behaviour of the bond-wires during operation and see how this interacts with the sequence of bond-wire lift-offs.

The papers focuses on multi-bond-wire chips which have an added challenge as when a bond-wire starts to degrade, the electrical resistance increases. This leads to reduced current in that specific bond-wire and increases the losses in the other bond-wires.

4.4.1 Method

A 3D finite element model was built based on the geometry of a real power module. Then, an electro-thermo-mechanical multi-physics model was setup to simulate the operation of a power device [76] and [77]. The simulation workflow is seen in Figure 4.6.

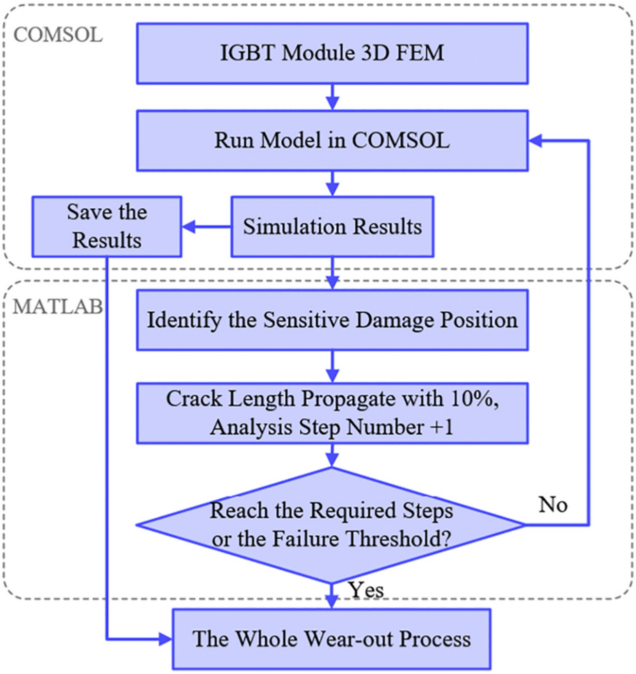

Fig. 4.6: The simulation plan of [77] applying both COMSOL and MATLAB. COMSOL was used for FEM simulation and MATLAB was used for data analysis and control of the simulation algorithm. The geometry is simulated in each iteration of the algorithm and is changed based on the simulation results.

The procedure in Figure 4.6 is as follows: The multi-physics simulation was performed and the results were saved. The stresses throughout the geometry were analysed to determine which bond-wire foot was the most highly stressed. An artificial crack was then slightly propagated in this bond-wire foot, and the whole process was repeated until the entire device failed. The crack length was propagated in increments of 10 % relative to the bond foot length to expedite the simulation process of the potentially 40 consecutive 3D multi-physics FEM simulations. This was the strategy to show the interactions between degrading bond-wires on top of a power device [76] and [77].

4.4.2 Results

Figure 4.7 shows the bond-wire lengths throughout the simulation steps where it can be seen that of the four wires, the middle two wires are subjected to the most stress and subsequently, fails first. As the center of the chip is also the area with the highest temperature, it is expected that the bond-wire feet closest to the highest temperature area are subjected to the highest stress and therefore fails first.

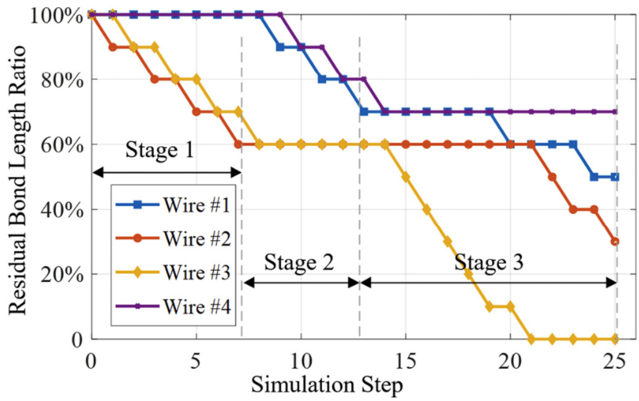

Fig. 4.7: Residual bond length ratio in the four bond-wires [77].

In Figure 4.7, it can also be seen that wires degrade in pairs in stages 1 and 2 as indicated in the figure. The middle bond-wires (2 and 3) degrade faster, but share the stress almost equally as a pair. The outer bond-wires (1 and 4) also share their stress almost equally, but as they are further from the centre, they suffer comparatively less damage. This shows that as one bond-wire degrades, the others will take more of the shared current. This will increase the stress on the other devices, evening out the stress of the devices somewhat.

4.5 Summary

To cover the topics given in the introduction of multi-timescale phenomena into reliability analysis (Objective 1 in Section 1.3.2 in Chapter 1), this chapter has analysed both damage and degradation timescale modelling of power electronics devices. First cycle-based damage modelling was discussed, with special focus on the advantages and disadvantages of the current state of the art methods, especially the limitations of the Rainflow Counting method. The state of the art models are easy to implement and widely used, but may lead to inaccurate results if the analysed stress profile contain temperature swings less than 25 Kelvin, if the stress profile contain temperature swings of varying amplitude or if the temperature swings have varying stress rate.

Degradation timescale modelling was presented, along with ways to model the interaction of damage and degradation. Some approaches to investigate the impact of degradation were also presented. 3D multi-physics modelling was used to investigate the effect of degrading bond-wires on power module operation. An artificial crack was introduced into the module, and the sequence with which the bond-wires failed was simulated, giving insight into the damage and degradation feedback loop needed to be used. The damage and degradation were linked using the non-linear degradation functional which can be fitted to represent linear degradation effects, but also both wear-in and wear-out degradation effects.

The models and interactions developed in this chapter will be combined with the developed models from Chapter 3, in a combined system and degradation model in Chapter 5.

Contributions of this Project

[75] **Fogsgaard, M. B., Bahman, Y. Zhang, A. S., Iannuzzo, F., & Blaabjerg, F.** (2022). Lifetime Analysis of Two Commercial PV Converters using Multi-Year Degradation Modelling. *e-Prime*, Vol 5, [100205]. https://doi.org/10.1016/j.prime.2023.100205 (2023).

This paper presents a multi-timescale system modelling method with integrated degradation effects. The paper investigates the lifetime impact of a degrading solder and the positive feedback mechanism associated with it.

[76] **Jiang , M., Fu, G., Ceccarelli, L., Du, H., Fogsgaard, M. B., Bahman, A. S., Yang, Y., & Iannuzzo, F.** (2019). Finite Element Modeling of IGBT Modules to Explore the Correlation between Electric Parameters and Damage in Bond Wires. *Proceedings of 2019 IEEE Energy Conversion Congress and Exposition (ECCE) (s. 839-844). [8912236] IEEE Press. IEEE Energy Conversion Congress and Exposition* https://doi.org/10.1109/ECCE.2019.8912236

This and the next paper presents an investigation into the degradation behaviour and current sharing of multiple bond-wires on the same power chip.

[77] **Jiang, M., Fu, G., Fogsgaard, M. B., Bahman, A. S., Yang, Y., & Iannuzzo, F.** (2019). Wear-out evolution analysis of multiple-bond-wires power modules based on thermo-electro-mechanical FEM simulation. *Microelectronics Reliability*, 100-101, [113472]. https://doi.org/10.1016/j.microrel.2019.113472

[73] **Zhang, K., Fogsgaard, M. B., & Iannuzzo, F.** (2022). Intelligent DC- and AC Power-Cycling Platform for Power Electronic Components. *2022 IEEE Applied Power Electronics Conference and Exposition (APEC) (s. 307-311). IEEE. I*

E E E Applied Power Electronics Conference and Exposition. Conference Proceedings
https://doi.org/10.1109/APEC43599.2022.9773518

This paper presents an advanced and flexible power cycling set-up capable of performing both AC and DC power cycling.

Chapter 5

Case Studies For Multi-Timescale Modelling

This chapter will present the work performed in [75] to answer the research question presented in Chapter 1. The method is based on the developments of previous publications, and combines previously presented models and tools to meet both objectives in Section 1.3.2 in Chapter 1: Simplification and speed-up of simulation and introduction of multi-timescale effects into reliability analysis.

In a study case the developed models and methodologies will be applied to two commercial PV generator systems to demonstrate the ability of the method to model their operation and wear-out. First the methodology will be presented, along with the work conducted to characterize the modelling. Next the two systems are introduced, and the analysis results will be presented.

5.1 Background

System simulation with degradation is similar to the simulation approaches used in previous chapters, such as in Section 3.3.1 in Chapter 3. The first couple of steps of the method are similar to the common lifetime prediction workflow with mission profile input, thermal simulation, Rainflow Counting, damage model and linear damage accumulation rule. In this analysis the mission profile simplification methodology described in Section 3.3.2 in Chapter 3 is used as an enabler for this analysis as it can be configured to reduce the simulation by up to 96% [44]. These steps calculate the damage inflicted upon the analysed devices during the analysed period.

The degradation is included by linking it to the calculated damage using the degradation functional (Equation 4.3) from Chapter 4. The degrading parameter can be linked to the degradation via Equation 4.7 from Chapter 4. Instead of performing the simulation one year at a time, the simulation is performed for one section at a time. The damage of each section is evaluated and the evolution of the degrading parameter is calculated. The next section is simulated using the updated parameter. The simulation is repeated with increasingly degraded parameters until device/system failure. The yearly mission profile input is repeated if the simulation lasts more than one year worth of simulated time [75]. This workflow enables system simulation with parameter degradation inclusion. This simulation is then able to model the positive feedback effect from solder layer degradation. This is when the solder layer degradation leads to increased temperature swing amplitude, leading to increased damage and degradation.

The methodology enables a parameter evolution-based lifetime prediction. Normally, in lifetime prediction, failure is achieved when the dimensionless damage quantity reaches 1. Using the presented method, failure can be defined to be the degradation of certain parameters beyond set thresholds, e.g. the thermal resistance or Vce reaches 120% of the original value. This is exactly how lifetime is defined experimentally for most applications, and it makes the simulation more representative of the physical behaviour of an actual system [74]. The overall workflow can be seen in Figure 5.1.

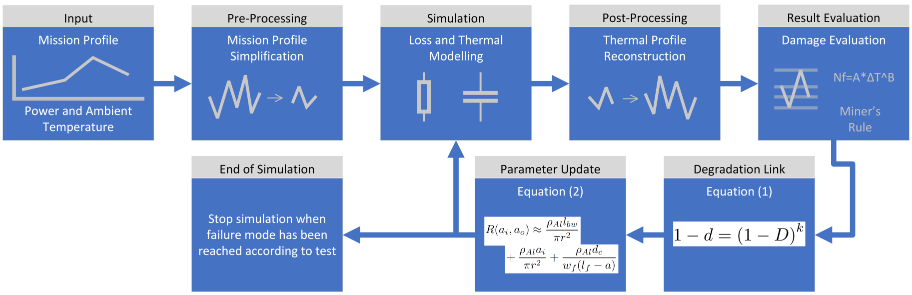

Fig. 5.1: The overall workflow for multi-year reliability analysis taking parameter degradation into account [75].

5.1.1 Characterisation of parameter based degradation modelling

As for conventional damage modelling approaches, this modelling approach requires empirical fitting based on experimental results. The modelling is primarily characterised using number of cycles to failure and the stressors of the chosen damage model, just as conventional damage modelling [70, 71, 72, 58, 73, 74]. Only one additional parameter is needed for characterisation, namely the evolution of the degrading parameter that is to be modelled [75].

First, a guideline damage model is fitted from the test conditions and the recorded number of cycles to failure. Then an optimization case is set-up with damage, wear-out and error equations:

$$D^i = \frac{N^i - N^{i-1}}{A(\Delta T_j^{i-1})^B e^{\left(\frac{C}{T_{mean}^{i-1}+273}\right)}} \tag{5.1}$$

Where D^i is the damage of the current step, N^i-N^{i-1} is the number of cycles from the previous to this step. A,B and C are fitting parameters, ΔT_j^{i-1} and T_{mean}^{i-1} are temperature swing and mean resulting from the degradation calculated the last step. Figure 5.2 illustrates how the degradation is increased from one simulation step to the next.

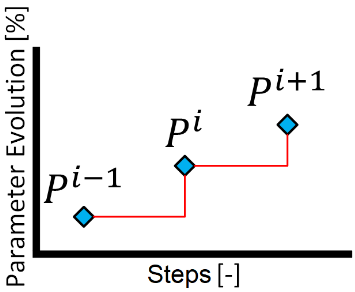

Fig. 5.2: Degradation points P^{i-1}, P^i and P^{i+1}. The parameter(s) and the degradation is considered to be constant between the steps and are updated when a new point is reached [75].

$$d^i = 1 - \left(1 - \sum_{j=1}^{i} D^j\right)^k \tag{5.2}$$

Where d^i is the degradation of the current step, k is the crack shape parameter, and D^j is the damage of the jth step.

$$RMSE = \sqrt{(d_{fitted} - d_{experiment})^2} \tag{5.3}$$

Where RMSE is the root mean square error calculated from the fitted degradation curve and the experimental degradation curve. d_{fitted} is the fitted degradation curve and $d_{experiment}$ is the experimental degradation curve.

Using Equations 5.1 to 5.3, the fitting parameters A, B, C and k can be found using optimization. The entire process, including power cycling and logged quantities can be seen in Figure 5.3.

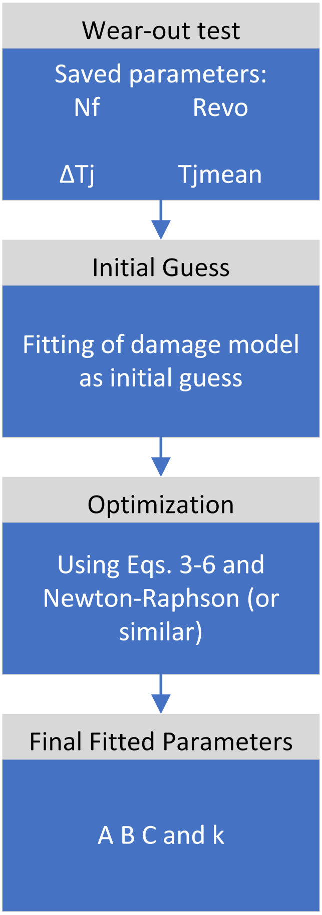

Fig. 5.3: The workflow used to determine the degradation model using power cycling testing [75]. N_f is the number of cycles to failure, R_{evo} is the resistance which evolution is the focus of the test. ΔT_j is the temperature swing, and T_{jmean} is the junction temperature mean.

To demonstrate the ability of the characterisation methodology to find the proper values af A, B, C and k, reference degradation curves were synthesized based on the experimental results [58]. The reference curves were subjected to the characterisation process and fitted curves were produced as a result. The fitted curves were able to match the reference curves well. The reference and fitted curves can be seen in Figure 5.4.

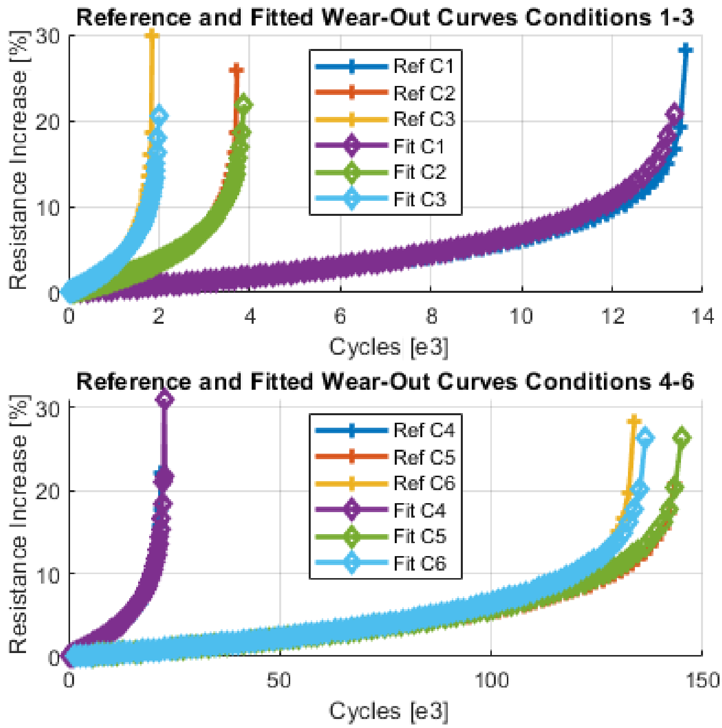

Fig. 5.4: Simulated reference and fitted degradation curves for six loading conditions from reference [58] as seen in [75]. The different operating conditions can be found in detail in [58].

Experimental wear-out data was also used to test the characterisation process. Experimental evolution of the temperature swing amplitude for a DC power cycling test of an IGBT was also characterised. The FS25R12KT3 [78] module was attached to a fixed temperature cooling plate and stressed with 44.3 A current pulses for 5 seconds on and off time. The wear-out curve was characterised successfully using the same method as before. The RMSE of the fitted curve was 0.9201. The reference and fitted curves can be seen in Figure 5.5 [75].

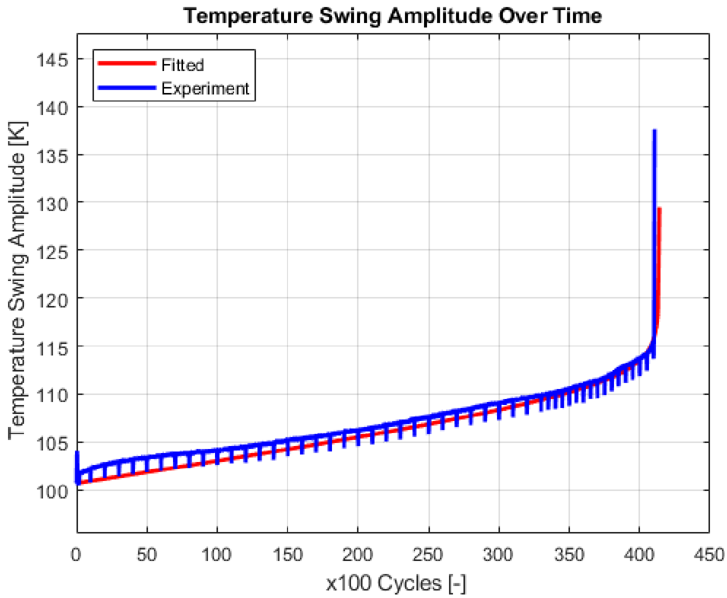

Fig. 5.5: Experimentally determined temperature evolution [75].

5.2 System 1: Microinverter

An Impedance-source-based PV microinverter from UBIK Solutions will be analysed as the first system in this chapter [79]. The system is a two-stage grid-connected PV generator consisting of a Front-end Quasi-Z-Source Series Resonant DC-DC Converter and a single phase grid-tied inverter. The system itself and the operation can be found in detail in references [80] and [81]. The schematic of the system can be seen in Figure 5.6.

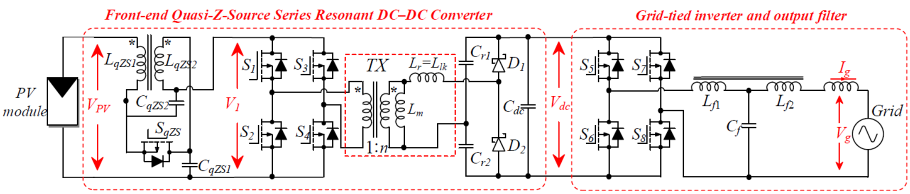

Fig. 5.6: The entire PV generator system of system 1 [80].

The system has previously been subjected to a reliability analysis documented in [82]. The analysis of [82] was very thorough, but did not take degradation into account which this analysis will. As mentioned in Section 5.1 the degradation is an important phenomenon to include as the degradation can cause a positive feedback loop which can affect the lifetime of the system negatively.

In this work, the inverter switches (S_5-S_8) will be the focal-point of the reliability analysis. These are SCT2120AF MOSFETs from ROHM Semiconductor and the electrical parameters can be found in the datasheet [83].

The thermal parameters for the junction to case are found from the datasheet [83] and the thermal parameters for the case to ambient can be extracted from the previous analysis [82]. The thermal network parameters can be seen in Table 5.1.

Table 5.1: Thermal parameters from [83] and [82] in a four level Foster network form [75].

Level	Resistance	Capacitance
Junction-Case RC pair 1	0.04197 [K/W]	0.001471 [J/K]
Junction-Case RC pair 2	0.2677 [K/W]	0.06857 [J/K]
Junction-Case RC pair 3	0.3778 [K/W]	0.006633 [J/K]
Case-Ambient	1.759 [K/W]	2774 [J/K]

The damage model used for the bond-wires is the same as in [82]:

$$N_f = \alpha \Delta T_j^{-m} \tag{5.4}$$

The solder layer degradation damage model for the solder layer and the model parameters used in this analysis will be found in literature. The equation can be seen in Equation 5.5 from [15].

$$N_f = A \Delta T_j^B e^{\left(\frac{C}{T_{mean}+273}\right)} \tag{5.5}$$

Where N_f is the number of cycles to failure, ΔT_j is the temperature swing, T_{mean} is the mean temperature. A, B and C are model parameters with the values of $A = 97.2231$, $B = -3.1292$ and $C = 7.1667e + 03$ [15]. The shape parameter refers to the non-linear coupling between damage and degradation, as shown in Figure 4.5 in Chapter 4. This parameter was extracted from the experimental results of [15]. Damage and degradation models from literature are used as the parameters for those models were found using multiple experimental test conditions, whereas the experimental results shown in Figure 5.5 were found using only a single test condition.

A lifetime prediction for system 1 was achieved using the workflow of Figure 5.1. The simulation was conducted for each section of the mission profile. After each section has been modelled, the inflicted damage was summed and the thermal resistance of the solder layer was updated based on the accumulated damage. The simulation was repeated until the device's failure. In Figure 5.7, the junction temperature profile, solder damage and thermal resistance over time can be seen for different locations.

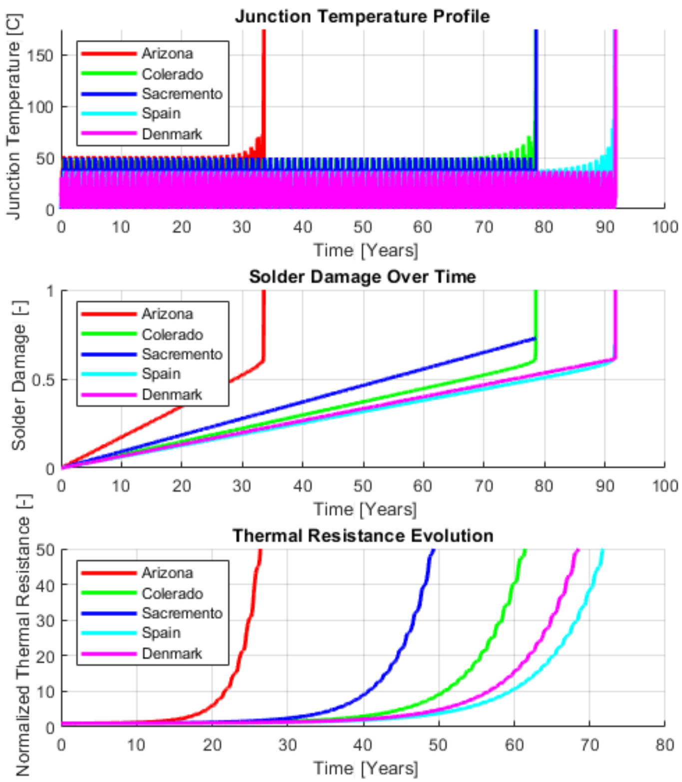

Fig. 5.7: The damage and degradation evolution of the UBIK system [75].

In the first graph of Figure 5.7, long periods of normal operation can be seen for most of the converter's lifetime. In the periods of normal operation, the solder damage will increase linearly, as seen in Figure 5.7. As the solder damage increases, so will the interface degrade, causing an increase in thermal resistance. The impact of the increase in thermal resistance can be seen in the junction temperature profile as an increase of maximum temperature. As the solder layer resistance in this application is a relatively small part of the total thermal resistance, the impact is not seen until the thermal resistance has increased to 40-60 times the original value. Once the resistance has started to increase exponentially, the temperature swing will as well and so will the damage[31].

Linearly projected lifetimes of the UBIK system without degradation were found by extrapolating the initial damage rates of Figure 5.7. The feedback mechanism was found to be a major lifetime-limiting factor and to reduce the lifetime by 20-60+ years depending on the mission profile. The projected and predicted lifetimes can be seen in Figure 5.8.

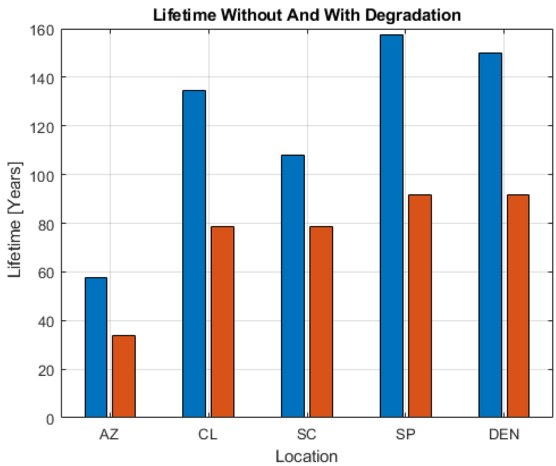

Fig. 5.8: The linearly projected (blue) and non-linear lifetime (red) [75].

5.3 System 2: 3-phase 15 kW NPC Inverter

The second system is a 15kW Danfoss TLX PRO+ [84] with three parallel input boost converters and an NPC inverter as seen in Figure 5.9. Some specifications of this system were unknown, but has been specified using specifications from other systems. This system will provide a more traditional point of comparison to the results of system 1 as it represents actively cooled systems.

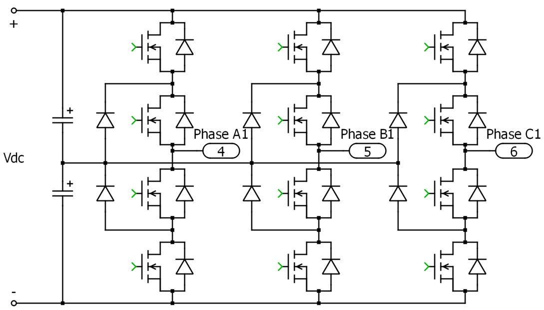

Fig. 5.9: The NPC inverter system of the 15 kW Danfoss TLX PRO+. An L-filter, three parallel boost converters and the auxiliary systems are not shown [75].

The thermal network from case to ambient was extracted from a 3D finite element modelling as in [85]. The chips were considered to be similar to those from [35]. The total thermal network of the system can be found in Table 5.2.

Table 5.2: Stand-in thermal parameters of the Danfoss system in Foster network form [75]. The junction to case resistances and capacitances are from literature [35], the case to ambient parameters are estimated using 3D FEM based on the real geometry.

Level	Resistance	Capacitance
Junction-Case RC 1	0.0324 [K/W]	0.3086 [J/K]
Junction-Case RC 2	0.1782 [K/W]	0.1122 [J/K]
Junction-Case RC 3	0.1728 [K/W]	0.2894 [J/K]
Junction-Case RC 4	0.1566 [K/W]	0.6386 [J/K]
Case-Ambient RC 1	0.0202 [K/W]	138.4 [J/K]
Case-Ambient RC 2	0.0191 [K/W]	865 [J/K]
Case-Ambient RC 3	0.0416 [K/W]	61.7 [J/K]

The bond-wire damage model used for the system 2 is the damage model presented in [57] and used in [35]. The parameters can be found in [35], and the equation is as follows:

$$N_f = A(\Delta T_j)^{\beta_1} \cdot e^{\frac{\beta_2}{T_{j,min}+273}} t_{on}^{\beta_3} I_B^{\beta_4} V_C^{\beta_5} D^{\beta_6} \tag{5.6}$$

The stressors and fitting parameters of Equation 5.6 was presented in detail in Section 4.2.2 in Chapter 4.

In Figure 5.10, the evolution of junction temperature, solder damage and thermal resistance evolution of the system 2 can be seen. Since the internal structure is unknown, the thermal conditions for all inverter devices can only be assumed to be identical. Therefore the following analysis is based on the damage of a single device.

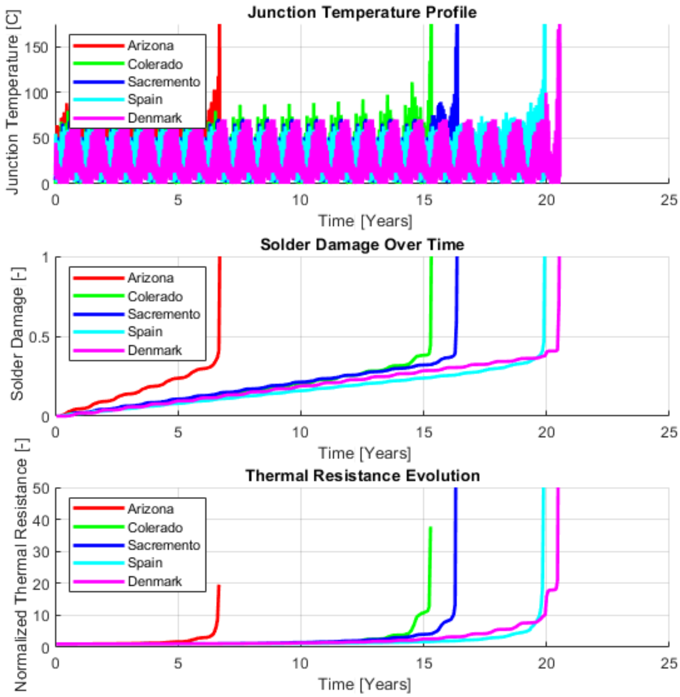

Fig. 5.10: The damage and degradation evolution of the Danfoss system [75].

The thermal feedback is also seen for this system. The temperature swing causes a linearly increasing damage, which degrades the thermal interface and causes an increase in the thermal resistance. At a certain level of damage, this resistance starts to increase the temperature swing, thereby increasing damage and resistance, increasing the temperature swing even more.

In Figure 5.11 the lifetime predictions with and without taking degradation into account can be seen.

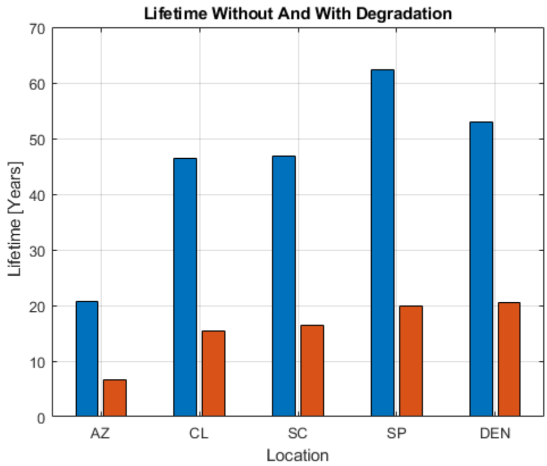

Fig. 5.11: The linear damage lifetime prediction (blue) and non-linear degrading lifetime prediction (red) of system 2 at five different locations [75].

5.3.1 Comparison of Degradation Shape Parameters from Literature

To compare the impact of the degradation shape parameter (as introduced in Chapter 4) on parameter evolution, five different values for thermal resistance and degradation shape were compared using the Arizona mission profile and system 2. The parameters can be seen in Table 5.3.

Table 5.3: Degradation parameters for different components in different applications from literature showing some of the different possible values for the parameters. a and b are Coffin-Manson damage model parameters and k is the degradation shape parameter [75].

Parameter	a	b	k	
Case 1	0.02979	1.000111	4.278	[86]
Case 2	0.0002544	0.9877	3.902	[87]
Case 3	0.01764	1.08498	0.8485	[87]
Case 4	0.000512	1.035	5.622	[15]
Case 5	0.1851	0.6749	0.06	[75]

The results of the simulation sweep of 5 cases can be seen in Figure 5.12. Simulations are performed for different cases of degradation shape values giving thermal resistance evolution trends. Figure 5.12 show that the behaviour of the degrading parameter is essential to fit correctly as the damage model for parameters will cause a positive feedback loop. The figure also shows that the impact of the degradation modelling vary with the degradation behaviour, for some combinations, the impact is minor and for others the degradation is a major factor in device lifetime.

The simulations of Figure 5.12 are based on the geometry of system 2.

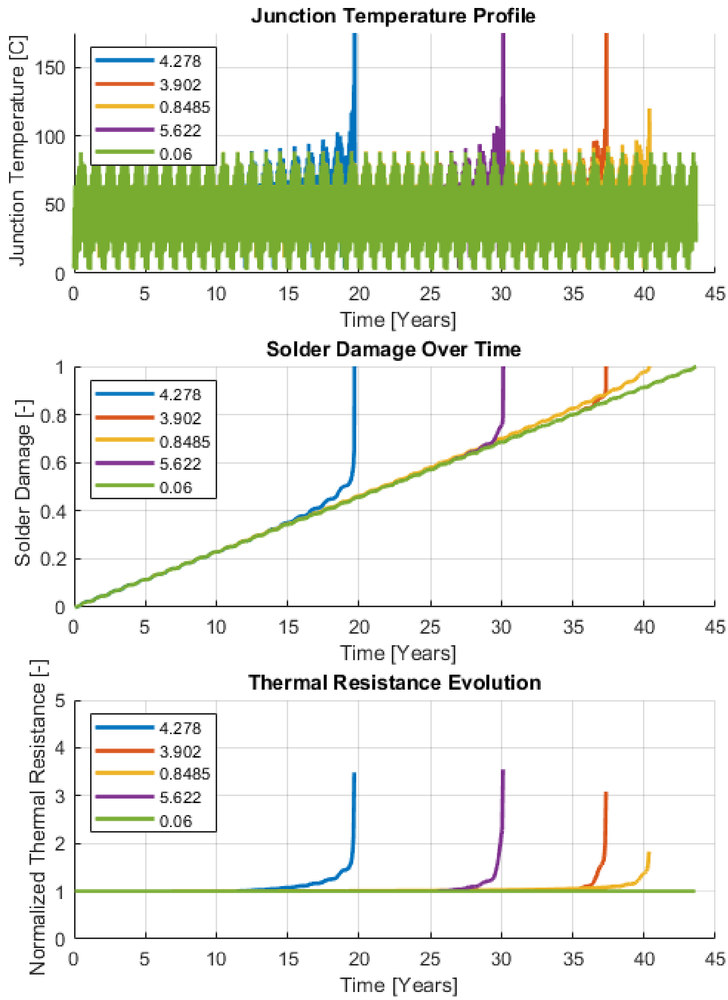

Fig. 5.12: Temperature swing, damage and thermal resistance evolution of different parameter cases [75].

Figure 5.12 shows the results of the different degradation parameter cases from Table 5.3. Figure 5.13 show the impact of k variation with case 1 parameters and for the Arizona mission profile. The higher the k is, the earlier the degradation will propagate, and the earlier the positive feedback effect will be activated. As a result, the simulated lifetimes are inversely related to the amplitude of k.

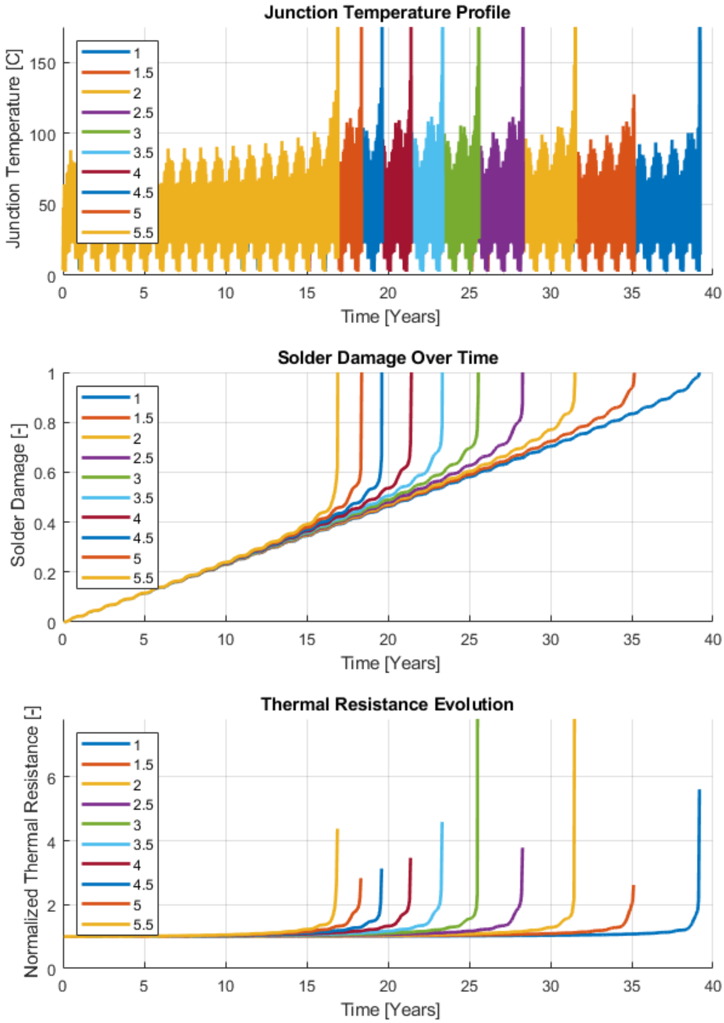

Fig. 5.13: Temperature swing, damage and thermal resistance evolutions of different values of k for system 2 using the Arizona mission profile [75].

5.4 Summary

In this chapter, the final developments to meet the research objectives of Section 1.3.2 in Chapter 1 were presented. In Chapter 4, the method to perform multi-timescale degradation modelling was developed, meeting the objective of introducing multi-timescale phenomena into reliability modelling. This work was based on the mission profile simplification method developed in Chapter 3 which provided the solution to meet the objective of simplifying and speeding up lifetime modelling.

This chapter has presented a method to perform fast degradation modelling for power electronics as well as a method to determine the degradation behaviour equations. Two case studies with degradation modelling were conducted to demonstrate the method. Finally, the impact of degradation behaviour was investigated through sweeps of the degradation behavioural parameters.

Contributions of this Project

[75] **Fogsgaard, M. B., Bahman, Y. Zhang, A. S., Iannuzzo, F., & Blaabjerg, F.** (2022). Lifetime Analysis of Two Commercial PV Converters using Multi-Year Degradation Modelling. *e-Prime*, Vol 5, [100205]. https://doi.org/10.1016/j.prime.2023.100205 (2023).

This paper presents a multi-timescale modelling approach developed to answer the research question in Chapter 1. The modelling methodology integrates system modelling with degradation effects and is enabled by the simplification method presented in Chapter 3.

Chapter 6

Conclusion

This chapter summarises the main contributions of the PhD Thesis, concludes the thesis and offers perspectives on future work defined on this work. The efforts of the PhD project will be evaluated to answer the research question.

6.1 Summary

This section contains a summary of the work of the thesis. The main findings and developments are highlighted using bold text.

Device Timescale Modelling

Chapter 2 presents an **overview of the physics and couplings needed for power electronic device modelling**. Maps for the electro-thermal and damage and degradation modelling are included and are used as the basis for the modelling in the thesis.

Additionally, in Chapter 2 a multi-physics finite element model was used as a digital twin for a power module exposed to power cycling with varying loading conditions. **The chapter, presents an alternative approach to evaluating the loading a power device experiences during power cycling** and during operation. The loading evaluated using this method can be directly used to predict experimental lifetime, and was found to more accurately predict the results of an experimental power cycling test than the reference methodology.

These results also show that **there may be more accurate loading terms**

than the temperature swing commonly used in the literature. Based on the data in this chapter, the thermal energy flux during cycling is a quantity worth exploring in future work.

System Timescale Modelling

Chapter 3 proposes a novel methodology to analyse mission profiles. **This methodology seeks to categorise the mission profile into events.** These events are temporally limited, and, unlike counted cycles, contain temporal information about the dynamics in the system during the event. The events may be used as binning to target different event categories with different modelling complexities, such that the events that are considered to be the most harmful, are modelled with the highest modelling detail, while the less influential events are modelled in a faster and more simple way.

Multiple methods with which the mission profile can be categorised into events have been studied. In the initial work, the event types are defined manually and sorted using an algorithm. Subsequent efforts presented work to **use artificial intelligence methods to categorise a mission profile into events**. The length of an event is also open for future work, as a fixed length is more well-defined, but varying length events may be more useful when representing a mission profile with events. These are however more complex to analyse and to categorise.

Chapter 3 presents a **PV mission profile simplification methodology for profiles from arid climates**. The method employs a novel process to synthesize representative days that make up a representative profile which can be simulated much faster than the original profile. The method also includes a reconstruction phase where the results from the simulation of the representative profile are extracted to produce a yearlong junction temperature profile for damage modelling. The method is useful for performing analyses in a shorter time frame, enabling simulation sweeps e.g. to find optimal designs or simulation of more complex models.

While the simplification method was intended for arid climates, it proved to be inaccurate with profiles containing clouds. The chapter also presents a **general methodology for solving the cloud-dependent accuracy issue**. Using a "Zero-order model", where representative days are chosen from the mission profile to form a representative profile. The general methodology has the advantages of the previous, climate dependent, methodology, both being useful to speed up the simulation and as an enabler for doing simulations of more complex models.

Damage and Degradation Timescale Modelling

The **impact of degradation was studied** in Chapter 4. Multi-physics finite element modelling was used to see the effect of propagating bond-heel cracks on the behaviour of a multi-bond-wire power device.

One of the options that are enabled by the simplification method in Chapter 3 is the **addition of degradation modelling in mission profile modelling of power electronics**. The year, or a part of the year, can be simulated, and the damage can be calculated to the value of a parameter to represent degradation, within such a time frame that even if the process is repeated until failure, the whole simulation can still be performed practical time-frame. This process is presented in Chapter 5.

6.2 Main Contributions in the Thesis

A mission profile simplification method was found to reduce simulation time As defined in the research question, and further specified in the project objectives, the simplification and speed-up of mission profile modelling is an important enabler for multi-timescale modelling. A method for this was presented in Chapter 3 for PV converters in arid climates.

The simplification methodology was improved to remove climate dependence The research question was not defined for a single climate, therefore the climate dependent method in Chapter 3 was improved upon to develop a climate independent method.

An FEM-based alternative to conventional damage modelling was found Alternatives to the conventional damage modelling methodology were explored in Chapter 2 and Chapter 3. The first investigation was of a new procedure for empirical damage model fitting, which was found to offer novel stressors for use in new damage models.

An alternative to the cycle-based damage modelling was studied to become event-based damage modelling In Chapter 3, an event-based loading modelling method, which, if expanded upon, could form the basis of a new damage modelling paradigm.

Integration of degradation feedback into load modelling was developed First investigated in Section 2.3 and later in Section 4.4, methods to include degradation in system load modelling were sought. Finally, Section 3.3.1 and Section 3.3.2 enabled the method of Chapter 5, achieving multi-timescale modelling comprising of regular system modelling coupled with degradation modelling.

6.3 Future Work

The work of this thesis may lead to the following future work.

Experimental Verification of Representative Mission Profile The lifetime predictions of Section 3.3.2 and Section 3.3.1 should be tested experimentally. This should be done with AC power cycling with loading conditions designed to test the generality of the generated profile.

Investigation into using Thermal Energy Flux as Stressor Alternative to Temperature Swing In Section 2.4, the results suggested that the thermal energy flux may be a more accurate stress quantity than the temperature swing. This should be investigated experimentally, and if found to be true, modelling methodologies should be adapted to use the thermal energy flux instead of the temperature swing.

Adaptation of Simplification Method for Other Applications The simplification methods of Section 3.3.1 and Section 3.3.2 were developed specifically for PV generator systems. Similar simplification methodologies may be devised for other applications such as automotive, wind-power etc.

Multi-timescale Modelling of Larger and Connected Systems More and more system are installed in configurations with a large amount of parallel and linked systems. The developed models with fast computation times in this thesis may be used as the basis for a methodology for modelling large systems comprising multiple converters.

Experimental Characterization of Degradation Shape Parameter The degradation shape parameter links the damage and degradation of a component or interface, and in this thesis it is considered constant. Efforts to validate that assumption experimentally would be very beneficial, both to more precisely find the range of the k value, but also to test for loading, temperature or other dependencies of the value.

Chapter 7

Complete Bibliography

References

[1] Hitachi Energy. Power electronics: Revolutionizing the worlds future energy systems. [Online]. Available: https://www.hitachienergy.com/news/perspectives/2021/08/power-electronics-revolutionizing-the-world-s-future-energy-systems

[2] B. K. Bose, "Global warming: Energy, environmental pollution, and the impact of power electronics," *IEEE Industrial Electronics Magazine*, vol. 4, no. 1, pp. 6–17, 2010.

[3] J. Falck, C. Felgemacher, A. Rojko, M. Liserre, and P. Zacharias, "Reliability of power electronic systems: An industry perspective," *IEEE Industrial Electronics Magazine*, vol. 12, no. 2, pp. 24–35, 2018.

[4] A. Energy. Reliable power electronic based power system. AAU Energy. [Online]. Available: https://www.repeps.et.aau.dk/

[5] P. D. T. O'Connor and A. Kleyner, *Practical Reliability Engineering, Fifth Edition*. John Wiley and Sons, Ltd, 2011, iSBN 9780470979822.

[6] K. Ma, H. Wang, and F. Blaabjerg, "New approaches to reliability assessment: Using physics-of-failure for prediction and design in power electronics systems," *I E E E Power Electronics Magazine*, vol. 3, no. 4, pp. 28–41, dec 2016.

[7] M. Musallam, C. Yin, C. Bailey, and M. Johnson, "Mission profile-based reliability design and real-time life consumption estimation in power

electronics," *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2601–2613, may 2015.

[8] A. Sangwongwanich, Y. Yang, D. Sera, and F. Blaabjerg, "Lifetime evaluation of grid-connected pv inverters considering panel degradation rates and installation sites," *IEEE Transactions on Power Electronics*, vol. 33, pp. 1125–1236, feb 2018.

[9] D. Zhou, H. Wang, and F. Blaabjerg, "Mission profile based system-level reliability analysis of dc/dc converters for a backup power application," *IEEE Transactions on Power Electronics*, vol. 33, pp. 8030–8039, sep 2018.

[10] K. Ma, U. M. Choi, and F. Blaabjerg, "Prediction and validation of wear-out reliability metrics for power semiconductor devices with mission profiles in motor drive application," *IEEE Transactions on Power Electronics*, vol. 33, pp. 9843–9853, nov 2018.

[11] T. Dragicevic, P. Wheeler, and F. Blaabjerg, "Artificial Intelligence Aided Automated Design for Reliability of Power Electronic Systems," *IEEE Transactions on Power Electronics*, vol. 34, no. 8, pp. 7161–7171, aug 2019.

[12] S. V. Dhople, A. Davoudi, A. D. Domínguez-García, and P. L. Chapman, "A unified approach to reliability assessment of multiphase dc-dc converters in photovoltaic energy conversion systems," *IEEE Transactions on Power Electronics*, vol. 27, pp. 739–751, 2012.

[13] R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*. Springer New York, NY, 2001, iSBN 978-1-4757-0559-1.

[14] A. Hanif, Y. Yu, D. Devoto, and F. Khan, "A Comprehensive Review Toward the State-of-the-Art in Failure and Lifetime Predictions of Power Electronic Devices," *IEEE Transactions on Power Electronics*, vol. 34, no. 5, pp. 4729–4746, 2019.

[15] B. Gao, F. Yang, M. Chen, Y. Chen, W. Lai, and C. Liu, "Thermal lifetime estimation method of igbt module considering solder fatigue damage feedback loop," *Microelectronics Reliability*, vol. 82, pp. 51–61, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S002627141730611X

[16] S. Peyghami, H. Wang, P. Davari, and F. Blaabjerg, "Mission-Profile-Based System-Level Reliability Analysis in DC Microgrids," *IEEE Transactions on Industry Applications*, vol. 55, no. 5, pp. 5055–5067, sep 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8727971/

[17] V. N. Le, L. Benabou, Q. B. Tao, and V. Etgens, "Modeling of intergranular thermal fatigue cracking of a lead-free solder joint in a power electronic module," *International Journal of Solids and Structures*, vol. 106-107, pp. 1–12, 2017.

[18] L. Yang, P. A. Agyakwa, and C. M. Johnson, "Physics-of-Failure Lifetime Prediction Models for Wire Bond Interconnects in Power Electronic Modules," *IEEE Transactions on Device and Materials Reliability*, vol. 13, mar 2013.

[19] ——, "Calibration of a Novel Microstructural Damage Model for Wire Bonds," *IEEE Transactions on Device and Materials Reliability*, vol. 14, dec 2014.

[20] W. Heinz and G. Dehm, "Grain resolved orientation changes and texture evolution in a thermally strained al film on si substrate," *Surface and Coatings Technology*, vol. 206, pp. 1850–1854, dec 2011.

[21] R. Ruffilli, M. Berkani, P. Dupuy, S. Lefebvre, Y. Weber, and M. Legros, "In-depth investigation of metallization aging in power mosfets," *Microelectronics Reliability*, vol. 55, pp. 1966–1970, aug 2015.

[22] H. Wang and F. Blaabjerg, "Reliability of capacitors for dc-link applications — an overview," in *2013 IEEE Energy Conversion Congress and Exposition*, 2013, pp. 1866–1873.

[23] Y. Yang, K. Ma, H. Wang, and F. Blaabjerg, "Mission profile translation to capacitor stresses in grid-connected photovoltaic systems," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2014, pp. 5479–5486.

[24] ——, "Instantaneous thermal modeling of the dc-link capacitor in photovoltaic systems," in *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2015, pp. 2733–2739.

[25] K. Ma and F. Blaabjerg, "Multi-timescale modelling for the loading behaviours of power electronics converter," in *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, sep 2015, pp. 5749–5756. [Online]. Available: http://ieeexplore.ieee.org/document/7310467/

[26] X. Wang and F. Blaabjerg, "Harmonic Stability in Power Electronic-Based Power Systems: Concept, Modeling, and Analysis," *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2858–2870, 2019.

[27] A. S. Bahman, K. Ma, and F. Blaabjerg, "A Lumped Thermal Model Including Thermal Coupling and Thermal Boundary Conditions for High Power IGBT Modules," *IEEE Transactions on Power Electronics*, vol. 33, no. 3, pp. 2518–2530, 2018.

[28] ——, "Thermal impedance model of high power IGBT modules considering heat coupling effects," *Proceedings - 2014 International Power Electronics and Application Conference and Exposition, IEEE PEAC 2014*, pp. 1382–1387, 2014.

[29] L. Ceccarelli, A. S. Bahman, F. Iannuzzo, and F. Blaabjerg, "A fast electro-thermal co-simulation modeling approach for SiC power MOSFETs," *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, pp. 966–973, 2017.

[30] K. B. Pedersen and K. Pedersen, "Dynamic modeling method of electro-thermo-mechanical degradation in igbt modules," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 975–986, 2016.

[31] H. Luo, N. Baker, F. Iannuzzo, and F. Blaabjerg, "Die degradation effect on aging rate in accelerated cycling tests of sic power mosfet modules," *Microelectronics Reliability*, vol. 76-77, pp. 415–419, sep 2017.

[32] L. Ceccarelli, R. M. Kotecha, A. S. Bahman, F. Iannuzzo, and H. A. Mantooth, "Mission-Profile-Based Lifetime Prediction for a SiC mosfet Power Module Using a Multi-Step Condition-Mapping Simulation Strategy," *IEEE Transactions on Power Electronics*, vol. 34, no. 10, pp. 9698–9708, oct 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8616890/

[33] A. S. Bahman, K. Ma, P. Ghimire, F. Iannuzzo, and F. Blaabjerg, "A 3-d-lumped thermal network model for long-term load profiles analysis in high-power igbt modules," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, pp. 1050–1063, sep 2016.

[34] B. Liu, F. Xiao, Y. Luo, Y. Huang, and Y. Xiong, "A Multi-timescale Prediction Model of IGBT Junction Temperature," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 3, pp. 1593–1603, sep 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8580550/

[35] A. Sangwongwanich, H. Wang, and F. Blaabjerg, "Reduced-order thermal modeling for photovoltaic inverters considering mission profile dynamics reduced-order thermal modeling for photovoltaic inverters considering mission profile dynamics," *IEEE Open Journal of Power Electronics*, vol. 1, pp. 407–419, sep 2020.

[36] M. Fogsgaard, P. Reigosa, F. Iannuzzo, and M. Hartmann, "Mechanistic power module degradation modelling concept with feedback," in *EPE'20 ECCE Europe*, sep 2020, pp. P.1–P.7.

[37] Y. Zhang, E. Deng, Z. Zhao, J. Chen, Y. Zhao, J. Guo, and X. Cui, "Sequential v-ce(t) method for the accurate measurement of junction temperature distribution within press-pack igbts," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 3735–3743, 2021.

[38] N. Baker, *An Electrical Method for Junction Temperature Measurement of Power Semiconductor Switches*. Aalborg Universitetsforlag, 2016, iSBN 9788771125481.

[39] M. Piton, B. Chauchat, and J. Servière, "Implementation of direct chip junction temperature measurement in high power igbt module in operation — railway traction converter," *Microelectronics and reliability*, vol. 88-90, pp. 1305–1310, 2018.

[40] M. B. Fogsgaard and F. Iannuzzo, "Fem-aided damage model calibration method for experimental results," *Microelectronics Reliability*, vol. 114, 2020.

[41] U.-M. Choi, F. Blaabjerg, and S. Jørgensen, "Study on effect of junction temperature swing duration on lifetime of transfer molded power igbt modules," *IEEE Transactions on Power Electronics*, vol. 32, no. 8, pp. 6434–6443, 2017.

[42] M. Fogsgaard and F. Iannuzzo, "Introducing the lego mission profile analysis methodology," in *CIPS 2020; 11th International Conference on Integrated Power Electronics Systems*. VDE Verlag GMBH, may 2020, pp. 455–459.

[43] M. Fogsgaard, A. Bahman, F. Iannuzzo, and F. Blaabjerg, "Pv mission profile simplification method for power devices subjected to arid climates," *Microelectronics Reliability*, vol. 126, oct 2021.

[44] M. B. Fogsgaard, A. S. Bahman, F. Iannuzzo, and F. Blaabjerg, "Mission profile simplification method for reliability analysis of pv converters," *Microelectronics Reliability*, p. 114651, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0026271422001755

[45] L. Ceccarelli, R. Kotecha, F. Iannuzzo, and A. Mantooth, "Fast electro-thermal simulation strategy for sic mosfets based on power loss mapping," *Proceedings - 2018 IEEE International Power Electronics and Application Conference and Exposition, PEAC 2018*, pp. 1–6, 2018.

[46] A. S. Bahman, F. Iannuzzo, and F. Blaabjerg, "Mission-profile-based stress analysis of bond-wires in sic power modules," *Microelectronics Reliability*, vol. 64, pp. 419–424, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.microrel.2016.07.102

[47] M. Fogsgaard, J. Bitsch Nørgaard, and F. Iannuzzo, "Artificial intelligence-based approach for damage estimation of power igbts from real mission profiles," in *PCIM Europe digital days 2020*. VDE Verlag GMBH, jul 2020, pp. 985–989.

[48] J. Seckback, P. Rampelotto, and R. Gordon, *Model ecosystems in extreme environments*, 2019, iSBN 0-12-812742-2.

[49] M. Kjaer, Y. Yang, H. Wang, and F. Blaabjerg, "Long-term climate impact on igbt lifetime," in *2020 22nd European Conference on Power Electronics and Applications, EPE 2020 ECCE Europe*, ser. 2020 22nd European Conference on Power Electronics and Applications, EPE 2020 ECCE Europe. United States: IEEE, sep 2020, pp. 1–10.

[50] Y.-L. Lee, M. E. Barkey, and H.-T. Kang, *Metal Fatigue Analysis Handbook*. Elsevier, 2012, iSBN 978-0-12-385204-5.

[51] S. Kadry and A. El Hami, *Numerical Methods for Reliability and Safety Assessment*. Springer International Publishing, 2015, iSBN 978-3-319-07167-1.

[52] S. D. Downing and D. F. Socie, "Simple rainflow counting algorithms," *International Journal of Fatigue*, vol. 4, pp. 31–40, 1982.

[53] H. Lu, C. Bailey, and C. Yin, "Design for reliability of power electronics modules," *Microelectronics Reliability*, vol. 49, pp. 1250–1255, sep 2009.

[54] S. S. Manson, "Behavior of Materials Under Conditions of Thermal Stress," *NASA*, jan 1954. [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=19930092197

[55] M. Junghänel, J. Schmidt, R.and Strobel, and U. Scheuermann, "Investigation on isolated failure mechanisms in active power cycle testing," *PCIM Europe 2015*, pp. 1–8, May 2015.

[56] J. Bielen, J.-J. Gommans, and F. Theunis, "Prediction of high cycle fatigue in aluminum bond wires: A physics of failure approach combining experiments and multi-physics simulations," in *7th. Int. Conf. on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems*. IEEE, 2006, pp. 1–7. [Online]. Available: http://ieeexplore.ieee.org/document/1644022/

[57] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, and M. Feller, "Model for power cycling lifetime of IGBT modules - various factors influencing lifetime," *5th International Conference on Integrated Power Systems (CIPS)*, pp. 1–6, 2008.

[58] A. Otto, S. Rzepka, and B. Wunderle, "Investigation of active power cycling combined with passive thermal cycles on discrete power electronic devices," *ASME 2018 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems*, 2019.

[59] B. E. Powell, T. Duggan, and R. Jeal, "The influence of minor cycles on low cycle fatigue crack propagation," *International Journal of Fatigue*, vol. 4, pp. 4–14, 1982.

[60] B. Nie, Z. Zhao, Y. Ouyang, D. Chen, H. Chen, H. Sun, and S. Liu, "Effect of low cycle fatigue predamage on very high cycle fatigue behavior of tc21 titanium alloy," *Materials*, vol. 10, no. 12, 2017. [Online]. Available: https://www.mdpi.com/1996-1944/10/12/1384

[61] P. A. Agyakwa, L. Yang, E. Arjmand, M. R. Corfield, and C. M. Johnson, "Damage evolution in al wire bonds subjected to a junction temperature fluctuation of 30 k," *Journal of Electronic Materials*, vol. 45, pp. 3659–3672, 2016.

[62] A. Palmgren, "Lifetime of roller bearings," *Zeitschrift des Vereines Deutscher Ingenieure*, vol. 68, pp. 339–341, 1924.

[63] M. A. Miner, "Cumulative damage in fatigue," *Journal of Electronic Packaging*, vol. 12, pp. 159–164, 1945.

[64] I. Milne, R. O. Ritchie, and B. Karihaloo, *Comprehensive Structural Integrity*. Elsevier Science, 2003, iSBN 978-0-08-043749-1.

[65] P. Huffman and S. Beckman, "A non-linear damage accumulation fatigue model for predicting strain life at variable amplitude loadings based on constant amplitude fatigue data," *International Journal of Fatigue*, vol. 48, pp. 165–169, 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142112312003155

[66] G. Zeng, C. Herold, T. Methfessel, M. Sch¨afer, O. Schilling, and J. Lutz, "Experimental investigation of linear cumulative damage theory with power cycling test," *IEEE Transactions on Power Electronics*, vol. 34, no. 5, pp. 4722–4728, 2019.

[67] M. Pfeifer, "Chapter 6 - degradation and reliability of materials," in *Materials Enabled Designs*, M. Pfeifer, Ed. Boston: Butterworth-Heinemann, 2009, pp. 161–187. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780750682879000069

[68] J. Lutz, C. Schwabe, G. Zeng, and L. Hein, "Validity of power cycling lifetime models for modules and extension to low temperature swings," *2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe)*, pp. P.1–P.9, 2020.

[69] K. Ravi Chandran, "A universal functional for the physical description of fatigue crack growth in high-cycle and low-cycle fatigue conditions and in various specimen geometries," *International Journal of Fatigue*, vol. 102, pp. 261–269, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142112317300543

[70] Z. Sun, L. Benabou, and P. Dahoo, "Prediction of thermo-mechanical fatigue for solder joints in power electronics modules under passive temperature cycling," *Engineering fracture mechanics*, vol. 107, pp. 48–60, 2013.

[71] M. Brincker, K. B. Pedersen, P. K. Kristensen, and V. Popok, "Comparative study of al metallization degradation in power diodes under passive and active thermal cycling," 2018.

[72] U. min Choi, I. Trintis, F. Blaabjerg, S. Jørgensen, and M. Svarre, "Advanced power cycling test for power module with on-line on-state vce measurement," in *Proceedings of the 30th Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2015*, ser. I E E E Applied Power Electronics Conference and Exposition. Conference Proceedings. IEEE Press, mar 2015, pp. 2919 – 2924, 30th Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2015, IEEE APEC 2015 ; Conference date: 15-03-2015 Through 19-03-2015.

[73] K. Zhang, M. Fogsgaard, and F. Iannuzzo, "Intelligent dc- and ac power-cycling platform for power electronic components," mar 2022, applied Power Electronics Conference 2022, APEC 2022. [Online]. Available: https://apec-conf.org/

[74] U. Choi, "Studies on igbt module to improve the reliability of power electronic systems," Skjernvej 4A, 9220 Aalborg Ø, DK, 2016.

[75] M. B. Fogsgaard, Y. Zhang, A. S. Bahman, F. Iannuzzo, and F. Blaabjerg, "Lifetime analysis of two commercial pv converters using multi-year degradation modelling," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 5, p. 100205, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2772671123001006

[76] M. Jiang, G. Fu, L. Ceccarelli, H. Du, M. Fogsgaard, A. Bahman, Y. Yang, and F. Iannuzzo, "Finite element modeling of igbt modules to explore the correlation between electric parameters and damage in bond wires," in *Proceedings of 2019 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE Press, sep 2019, pp. 839–844.

[77] M. Jiang, G. Fu, M. Fogsgaard, A. Bahman, Y. Yang, and F. Iannuzzo, "Wear-out evolution analysis of multiple-bond-wires power modules

based on thermo-electro-mechanical fem simulation," *Microelectronics Reliability*, vol. 100-101, sep 2019.

[78] Infineon. Fs25r12kt3: 1200 v, 25 a sixpack igbt module. Infineon. [Online]. Available: https://www.infineon.com/cms/en/product/power/igbt/igbt-modules/fs25r12kt3/

[79] S. I. Foundation. Ubik s350 optiverter. Solar Impulse Foundation. [Online]. Available: https://solarimpulse.com/solutions-explorer/ubik-s350-optiverter

[80] Y. Shen, H. Wang, Z. Shen, Y. Yang, and F. Blaabjerg, "A 1-MHz Series Resonant DC–DC Converter With a Dual-Mode Rectifier for PV Microinverters," *IEEE Transactions on Power Electronics*, vol. 34, no. 7, pp. 6544–6564, 2019.

[81] D. Vinnikov, A. Chub, E. Liivik, and I. Roasto, "High-performance quasi-z-source series resonant dc–dc converter for photovoltaic module-level power electronics applications," *IEEE Transactions on Power Electronics*, vol. 32, no. 5, pp. 3634–3650, 2017.

[82] Y. Shen, A. Chub, H. Wang, D. Vinnikov, E. Liivik, and F. Blaabjerg, "Wear-out failure analysis of an impedance-source pv microinverter based on system-level electrothermal modeling," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3914–3927, 2019.

[83] R. Semiconductor. SCT2120AF. ROHM Semiconductor. [Online]. Available: https://eu.mouser.com/datasheet/2/348/sct2120af_e-1871870.pdf

[84] Danfoss. TLX-inverterserien, Fra 6-15 kW, trefasede invertere uden transformator. [Online]. Available: https://co2pro.dk/wp-content/uploads/2018/03/Danfoss_TLX_datablad_DK.pdf

[85] COMSOL Multiphysics. Heat sink. [Online]. Available: https://www.comsol.com/model/heat-sink-8574

[86] Y. Jia, Y. Huang, F. Xiao, H. Deng, Y. Duan, and F. Iannuzzo, "Impact of solder degradation on vce of igbt module: Experiments and modeling," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 4, pp. 4536–4545, 2022.

[87] W. Lai, M. Chen, L. Ran, S. Xu, N. Jiang, X. Wang, O. Alatise, and P. Mawby, "Experimental Investigation on the Effects of Narrow Junction Temperature Cycles on Die-Attach Solder Layer in an IGBT Module," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1431–1441, 2017.

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-627-0

AALBORG UNIVERSITY PRESS