Condition and Health Monitoring in Power Electronics

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Abstract

Condition and health monitoring (C&HM) is an effective means of improving the availability and controlling the life-time cost of power electronic components, converters and systems. Many solutions have been developed, but their adoption in industrial applications is still scarce. This paper intends to the reasons for this by favouring Industrially-motivated research. Advanced C&HM techniques that open new possibilities for industrialisation are reviewed. Their potential, limitations and implementation are outlined and critically assessed with the goal of benefiting both industry applications and research.

A significant part of the paper is dedicated to C&HM for power devices and modules, responding to the general perception that they are the least reliable with topics such as prognostics-based qualification for power electronics to predict the future reliability of the products and remaining useful lifetime methods. In-situ methods for estimation of junction temperature and use of temperature sensitive electrical parameters are summarised within the framework of C&HM. The C&HM of other notoriously unreliable components, such as capacitors and batteries are also addressed.

1 Introduction

The research and development activities for C&HM in power electronics are steadily intensifying for applications in Power Electronics. Figure 1 from [1] indicates that papers published in this area have doubled over the past decade, with a recent accelerating trend.

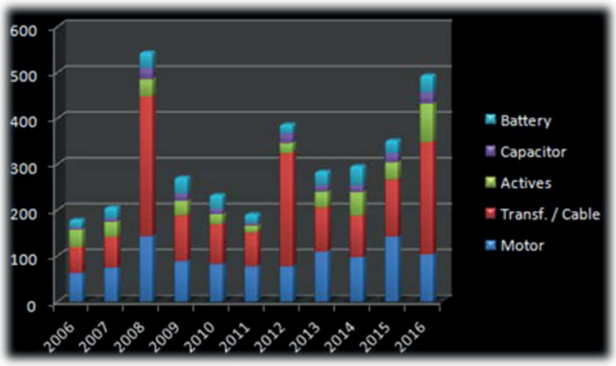

Figure 1: Number of published papers on C&HM in IEEE Xplore.

The number of products on the market is also richer. Most commercial offerings are for now based on Big Data approach [2,3,4] and systems are becoming connected to the internet, which gives a faster access to data on-line. However, products using a more deterministic approach are also seeing the day for applications [5,6]. It is likely that a fusion of the two approaches will be necessary as not all can be modelled accurately: taking into account all uncertainties combined with low development costs of the former and the reliability of the fault prediction of the latter.

The intensified market and research dynamics observed above indicate an increased interest in C&HM technologies, attributed to a widening electrification, both in generation and power usage, where applications become more mission-critical. Also the control of the grid transmission and distribution become more based on power electronic system. Transportation and renewable applications appear to be more inclined to invest in such technologies with the purpose to ensure a continuity of service and controlling the life-cycle costs.

A recent ECPE industry-wide study [7] indicates that the active components and the capacitors are the components that are most implicated in converter failures. Therefore, the C&HM Workshop spent a lot of the allocated time on these topics.

This paper intends to capture the findings and the main conclusions from the Workshop [1] and is organised as follows: Section 2 summarises the presentations covering various aspects of C&HM for power modules and active devices, Section 3 is concerned with energy storage devices, such as capacitors and batteries. Section 4 covers the presentations for user cases where wind applications had the most presenters. Section 5 summarises the outcomes of the workshop and proposes some perspectives for C&HM.

2 C&HM for Power Modules

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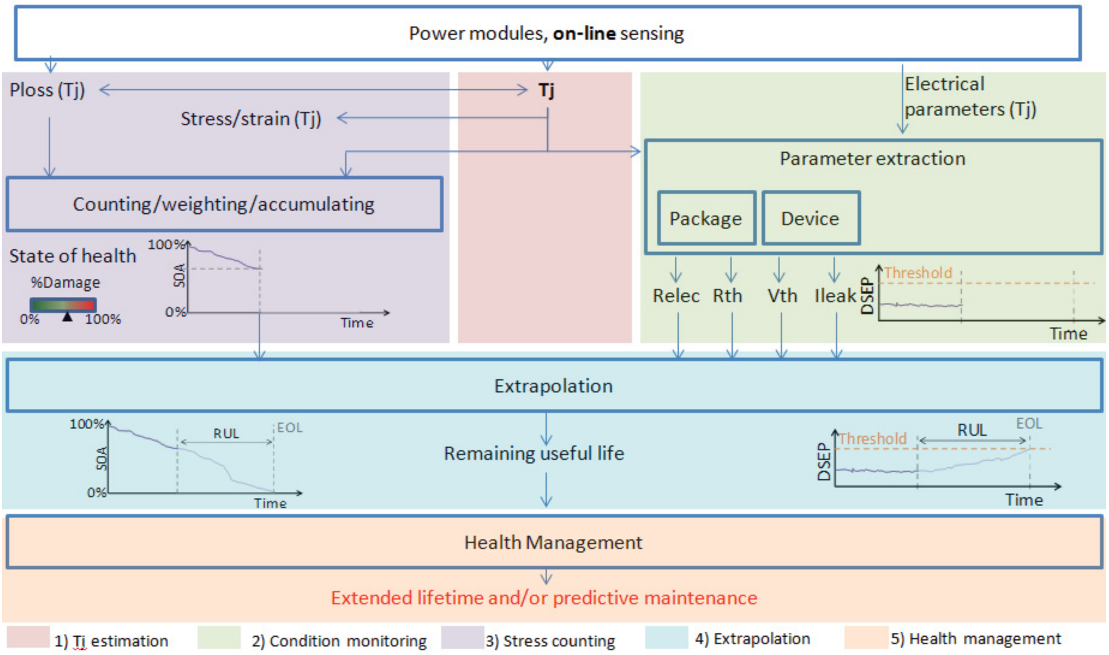

Figure 2: Condition and health monitoring of power semiconductors (RUL: remaining useful life; BOL: End of life; SOA: Safe operating area; DSEP: Damage Sensitive Electrical Parameter).[8]

This session opened with a review of Remaining useful Lifetime (RUL) estimation technologies for power semi-conductor devices [8]. It proposes a global view on RUL estimation that necessarily include condition monitoring technologies. It gave a brief overview of the most common failure mechanisms occurring in power modules. As packaging-related failures are mostly due to fatigue, precise junction temperature estimation is the prime means of calculating the incurred damage, so the paper summarises the most common techniques. Thermo-Sensitive Electrical Parameters (TSEP) appear to be more frequently investigated as some of the associated techniques permit on-line junction temperature measurement without interruption of the process – in fact the only realistic way of performing RUL.

The paper then moves on to enumerating various uses of DSEP and extrapolation techniques for RUL. It is pointed out that all damage models currently used are based on Palmgren-Miner Linear accumulation assumption, while increasing evidence suggest that it is not as widely applicable as previously thought. This could lead to significant errors in estimating RUL.

Finally, a common framework for RUL, Figure 2 was presented, where the RUL is targeting predictive and reasoned maintenance. An interesting use of the condition monitoring techniques was pointed out to be stress-steering, whereby the apparent module reliability can be notably improved.

The next presentation focused on condition monitoring and junction temperature estimation with an accent on industrialisation challenges [9]. From the point of view of universally applicable gate driver (the natural place to perform CM for power devices) the principal criteria for choosing a particular TSEP is the generality with respect to devices (IGBT/MOSFET/diode, Si/SiC). Thus, the used TSEP method is the on-state voltage, which also permits a non-interrupted power train operation. The main industrialisation challenges appear to be: low TSEP sensitivity, impact of PWM and mission profile, creepage distances, calibration, measurement circuit drift, ageing of the device since it is used as a sensor. The choice of well-balanced data architecture was also pointed to be pivotal for a successful product, where the computational burden is exported very early away from the driver to the control system with efficient data rates in the transmission.

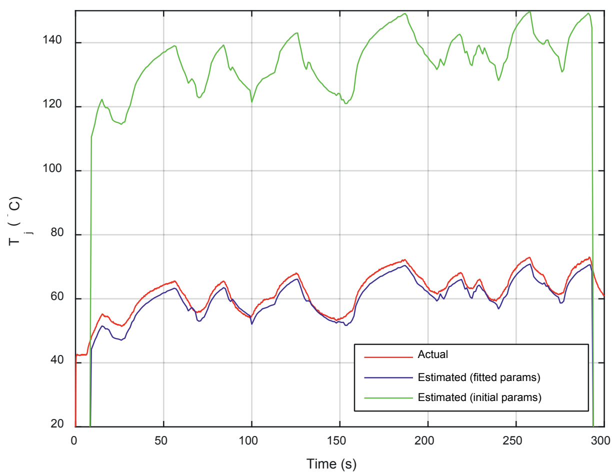

Figure 3: Estimated and measured junction temperature. [9]

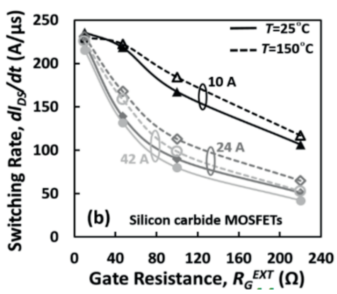

Figure 4: TSEP method for SiC MOSFET. [10]

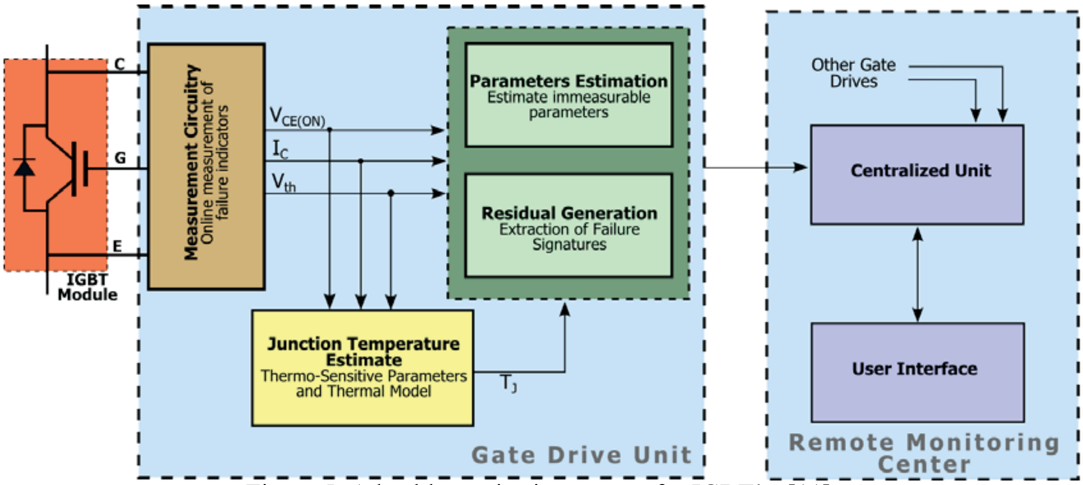

Figure 5: A health monitoring system for IGBT's. [11]

Calibration is the most critical process in any TSEP estimation and added difficulty is the device batch dispersion – given that, for the purposes of CM and RUL the junction temperature precision needs to be smaller than 3K. Some results were presented as shown in Figure 3 with an auto-calibration method that compensates for wire-bond degradation and could therefore potentially be used to monitor degradation.

The proposed gate driver with the integrated CM features is a significant step towards reasoned maintenance for applications for renewable power electronics and industrial inverters. However, high power applications (wind, traction etc.) employing multitude of parallel chips remain un-catered for due to the use on-state voltage method.

Continuing the theme of TSEP, a review of the thermal effects in power devices was presented [10]. Particular focus was the physical origin of various TSEPs, for various types of devices and materials. A special emphasise was given on SiC devices. For on-state voltage, the temperature dependency of the carrier mobility, drift currents and PN junction are of main concern. The combination of these phenomena with sometimes opposing temperature drifts explain the presence (or not) of Zero Temperature Coefficients (ZTC). ZTC should be avoided for Tj estimation (as a high sensitivity is necessary) or sought for/selected for damage estimation (where temperature-independent operating points are preferably used). ZTC operating points have also interesting design considerations when paralleling devices (or putting them in series), a subject covered in more details in CIPS2018.

Temperature estimation with SiC MOSFETs and Schottky diodes is more complicated than Si devices because of the lower sensitivity, the non-linearity, and the dependence on the built technology (trench or planar). The paper suggests, as shown in Figure 4, that the best TSEP would be Vth or di/dt, but in a practical implementation the gate driver should be slowed down (the method uses a diagnostic pulse), defeating the purpose of using fast-commutation SiC.

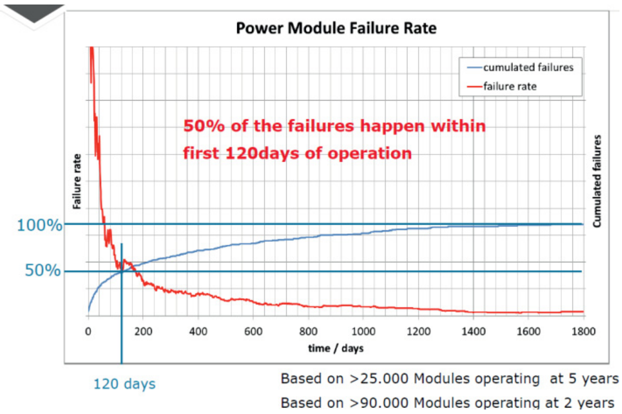

Figure 6: Registered power module failure rate over 5 years [12].

The following presentation [11] echoes the concern of implementing H&CM without service interruption and dwells on in-service health monitoring of insulated-gate-bipolar-transistors (IGBT) power modules.

Using a previously published method for measuring the on-state voltage, the paper proposes an $R_{CE(ON)}$ estimation employing a recursive least-squares algorithm based on a linear relationship between on-state voltage and IGBT current. A method employing the threshold voltage was suggested for estimating the junction temperature, though it was pointed out that the sensitivity is rather low (about 6 mV/K) and thus limited by the noise floor. Subsequently, a Kalman filter is incorporated that integrates the parameters of a Foster thermal model of packaging. This has the advantage of using the Kalman filter residual to estimate the thermal path degradation.

Using the above techniques, a health monitoring system was built for an IGBT module, with architecture shown in Figure 5. The online measurements can capture reliably a developing fault after the second or third wire bond lift-off, which is sufficient for early-warning faults. This also highlights the difficulties of using on-line measurements for RUL, where the needed precision would likely be an order of magnitude better.

The value of C&HM and the balance between investment and return has always been concerned in these methods. A paper [12] addressed such concerns by ex-

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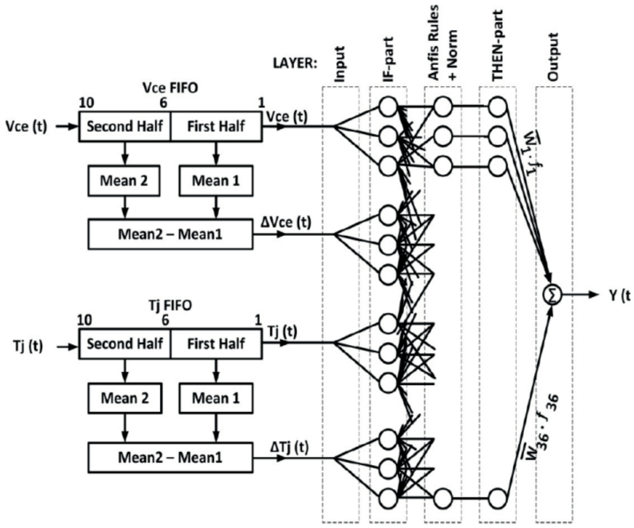

Figure 7: ANFIS-based H&CM of a power module using Vce and junction temperature [13].

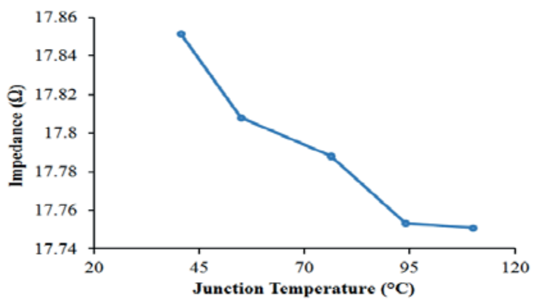

Figure 8: Junction temperature relation with the impedance of the power module [14].

pressing a critical view on condition monitoring of power semiconductors .

This paper argues that a great part of failures, for mature power electronic equipment designs, are actually early-life failures. This is based on root-cause analysis from field returns of modules operating for 2 to 5 years, as illustrated in Figure 6. According to the presenter, most failure causes are due to bad process (e.g., weak connections), converter manufacturing, shipment or installation of inverters, or failure of other components (e.g., gate drivers).

Nevertheless, the paper provides interesting suggestions regarding the use of condition monitoring to detect early-life failures and to improve the root-cause analysis. The $V_{CE(ON)}$ monitoring is difficult to justify from a module manufacturer point of view (high effort/cost, low accuracy), but the junction temperature would be very useful, provided that it is meaningful to be implemented, for both condition monitoring and functional robustness.

A big-data approach, using IOT was also presented for real-time health monitoring of power devices [13]. This presentation was done with aerospace as a main case study. It describes Prognostics and Health Management (PHM) and condition based maintenance as established technologies. The driver is safety and cost reduction. For companies such as Rolls Royce, maintenance is a large portion of the business with high added value attributed to

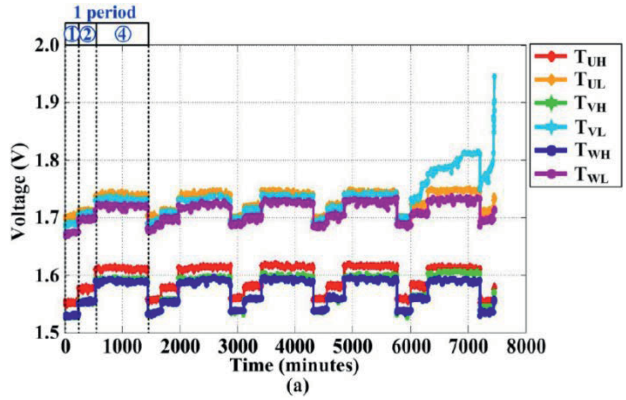

Figure 9: Mission profile loading of a power module [15].

prognostics technologies. The presentation highlights the importance and difficulty to generate a maintenance planning based on RUL estimation with uncertainties. They then presented a standard stress-counting method with a model generated from Finite Element Method (FEM) and a more exotic data-driven method using a mix of fuzzy logic and neural network to generate a damage model (ANFIS). The latter is shown in Figure 7 and it reduces the model prognostics error about 15 times for the chosen mission profile: the used data was generated from power cycling under identical conditions as the training data.

An important advantage of such an approach is the perception of lower cost, though this can be offset by the investment necessary to generate a large training data set. In a typical way, there is no distinction between different failure modes, so learning from the data on possible module improvements is not possible.

A number of unconventional techniques to determine the health of power semiconductor modules were presented [14]. The review covers a number of original methods to measure temperature or degradation. When a Kelvin connection is available, its resistance and inductance create steady-state and transient voltage drops that are useful for determining current, temperature, or degradation. In addition, other Kelvin connections can also facilitate access to important electrical measurement points. Unfortunately, only relatively low current modules have Kelvin connections and the added termination increases considerably the module cost. If the modules had one-Kelvin connection per die, this would be very convenient and allow a number of new condition monitoring techniques.

A family of sensors, directly placed on the power die, based on the resistive of SAW principle have been proposed for temperature or stress sensing, though they pose a fundamental problem of routing the power leads to the die (with the exception of current-mirror + diode embedded sensors, which occupy only a very limited real estate on the die surface).

A number of techniques using externally injected signals have recently been developed, since some of them can be implemented on-line. Most use the gate circuit for the injection and the TSEP detection since the signals involved have compatible magnitudes to that of the drive voltages.

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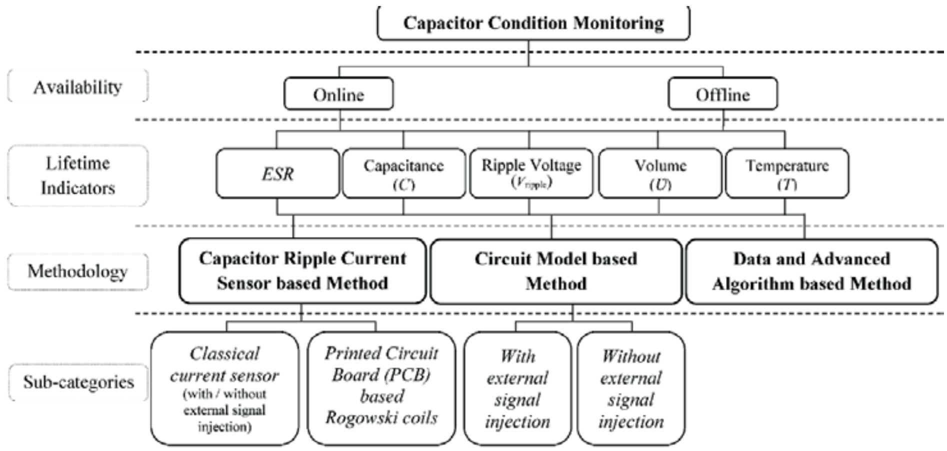


Figure 10: Overview of capacitor condition monitoring methods [16].

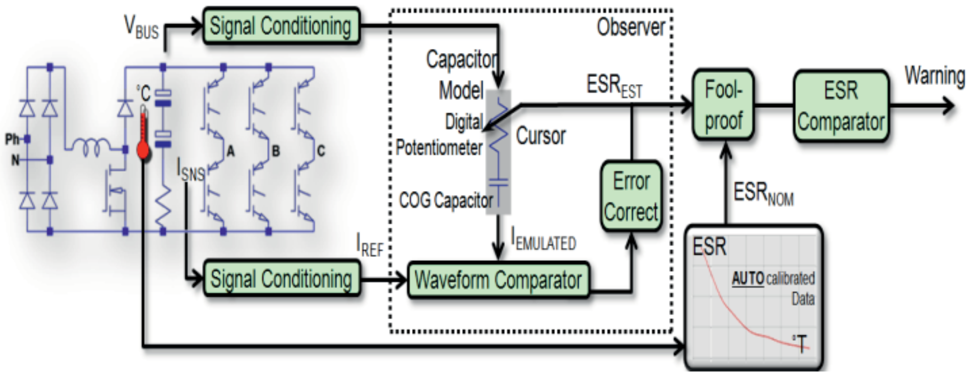


Figure 11: Capacitor condition monitoring in a three-phase inverter [17].

The use of in-situ / on-line CM hardware was demonstrated in [15]. A back-to-back configuration of PWM 3-phase converters was used to age power modules. The power cycling consists of a complex but controlled mission profile of repeatedly cycling through 3 different levels of stress, each for a fixed period of time as shown in Figure 9. Using curve-fitting of a statistical model for reliability versus heating times, the authors can predict reasonably well the occurrence of a wire-bond failure of the modules. Also, it is shown that the sequencing of stress types within a cycle has clear incidence on the overall module reliability. Notice that the power cycling is performed by commutating the modules at typical converter switching frequency, which is close to the real operation of the modules.

3 C&HM for Energy Storage Components

Capacitors, particularly electrolytic types, are often accused of causing converter failure. Batteries are even less robust in respect to the operating temperature though, as energy source, they are in the critical performance path.

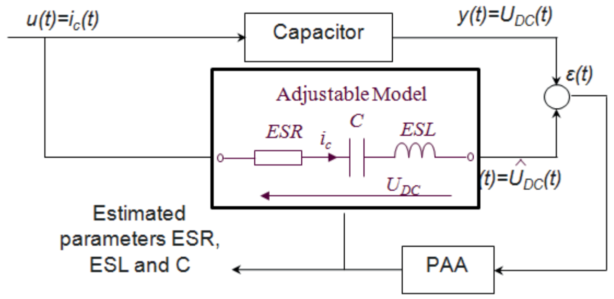
This session started with a review of condition monitoring for capacitors in power electronics applications [16]. Several techniques for condition monitoring and RUL estimation of capacitors are presented, with a classification shown in Figure 10. Most methods focus on estimating the equivalent series resistance, as it is prevalent for high voltage-class capacitors.

A number of methods concentrate on the current ripple estimation within the context of inverters, while using the information for the motor and rectifier currents – information readily available in these applications.

A purely data-driven method (neural network) is highlighted where only the voltage across the capacitor is monitored. The LF spectra of the voltage is used as an indicator of power (because of the diode input bridge) and the HF voltage is used as an indicator of capacitor and resistor (when knowing the power).

An observer-based condition monitoring of electrolytic capacitors was presented next [17]. It has a very practical approach to monitoring inverter-class electrolytic capacitors. The observer implementation permits condition monitoring without process interruption with consistent performance over time as it employs the naturally present switching frequencies. An auto-calibration operation was also demonstrated.

The judicious functional separation between analogue and digital electronics, enabled through the architecture shown in Figure 11, led to a very cost-efficient and reliable operation of the CM system. Other practical aspects, not commonly shown in other publications, were also discussed: setting the warning threshold, which for these applications appears to be motivated by voltage ripple amplitude, errors that might appear when connecting capacitors in series and in parallel, and the possibility of integrating the CM algorithm and circuit within a RUL system.



ESR			C		
Real (mΩ)	Estimated (mΩ)	Error (%)	Real (µF)	Estimated (µF)	Error (%)
1	1,2	20	120	125	<5

Figure 12: Adaptive algorithm for estimating the capacitance [18].

The following presentation was concerned with condition monitoring of metallised film capacitors [18]. It begins by describing the failure mechanisms for film capacitors. The three main stressors are moisture/oxygen, temperature and applied voltage. Their various combinations lead to different failure mechanisms, resulting in both capacitance reduction and ESR increase. The RUL estimation is probably made difficult by this large number of parameters. Two methods are discussed in the context of aerospace applications. The data-driven (neo fuzzy neural) approach was demonstrated to give a sufficient accuracy of identifying capacitance and ESR with 5% and 2% respectively. Note that for this application a 5% decrease in capacitance indicates the onset of a significant ageing. The algorithm relies on rich harmonic content of the current as it uses model parameter identification at a multitude of predefined frequencies. However, the associated acquisition front-end and the computational burden are relatively expensive.

Alternatively, a model-based (least mean square identification) was proposed, which is shown in Figure 12. This includes the parasitic inductance and adjusts the capacitance and the ESR in a second-order discrete transfer function. The voltage-to-current relationship is compared to the measured waveforms and the coefficients of the model are adjusted to reduce the mean-square error. Due to the more complex relationship between the coefficients, the model results in somewhat larger errors, but the cost is significantly lower and us thus the retained solution.

Estimating the state of lithium-ion batteries, which was the subject of the next papers [19,20], is challenging due to the complexity and the interplay of the involved chemical reactions, associated to the lack of direct access to relevant electrical parameters. Nevertheless, the relatively slow dynamics of a chemical system that a battery is, permit the use of sophisticated C&HM algorithms residing naturally in the dedicated battery management system. This appears to be one of the few applications where the necessity and the cost of the C&HM overhead are not being questioned.

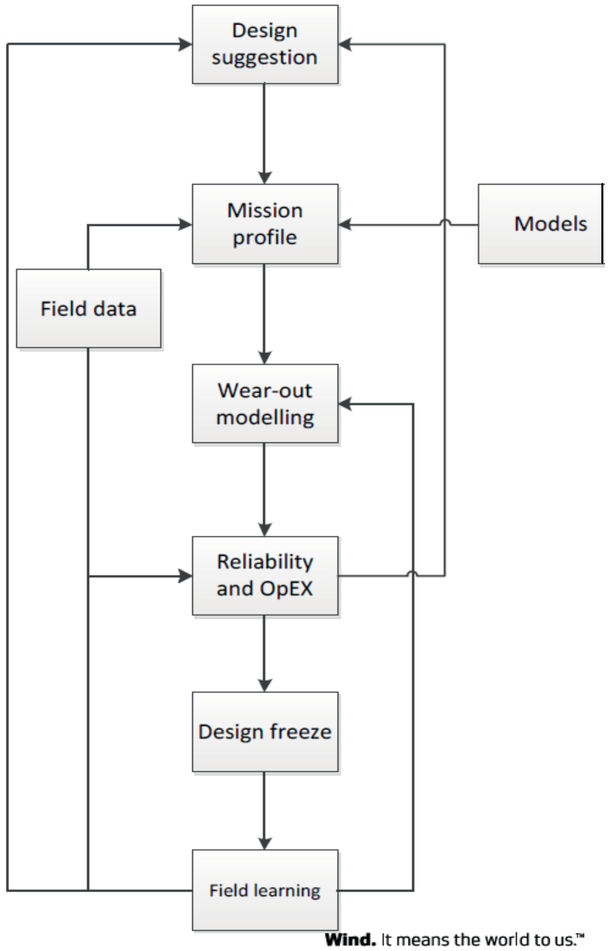


Figure 13: Field data used for improved design [21].

4 User cases: wind power

The first paper [21] in this group concerns the monitoring of electrical equipment in wind turbines. Condition monitoring is already used in wind turbines, but mostly for mechanical parts (based on information covering a park of about 10 thousand turbines), with dedicated Diagnostic Data Acquisition Unit. It provides valuable information for design updates and root cause analysis but is also used to optimise the maintenance and minimise the downtime. About fourth of the energy production loss is attributed to electrical aspects (cables, breakers, control, and power stacks), even though in total has been reduced steadily, and infant failures dominate. For maintenance intervention, the root cause of an elevated temperature value is an interesting information.

Field data logging is currently being used to improve the designs, as shown in Figure 13. This permits to correlate the data from the real mission profile to evolving aging precursors and feed the results into the following improved design process.

A platform and algorithms for model based monitoring of wind turbine components [22] were presented next. A dedicated open-ended platform was created that uses machine learning and data mining analysis. The model based monitoring is capable of detection anoma-

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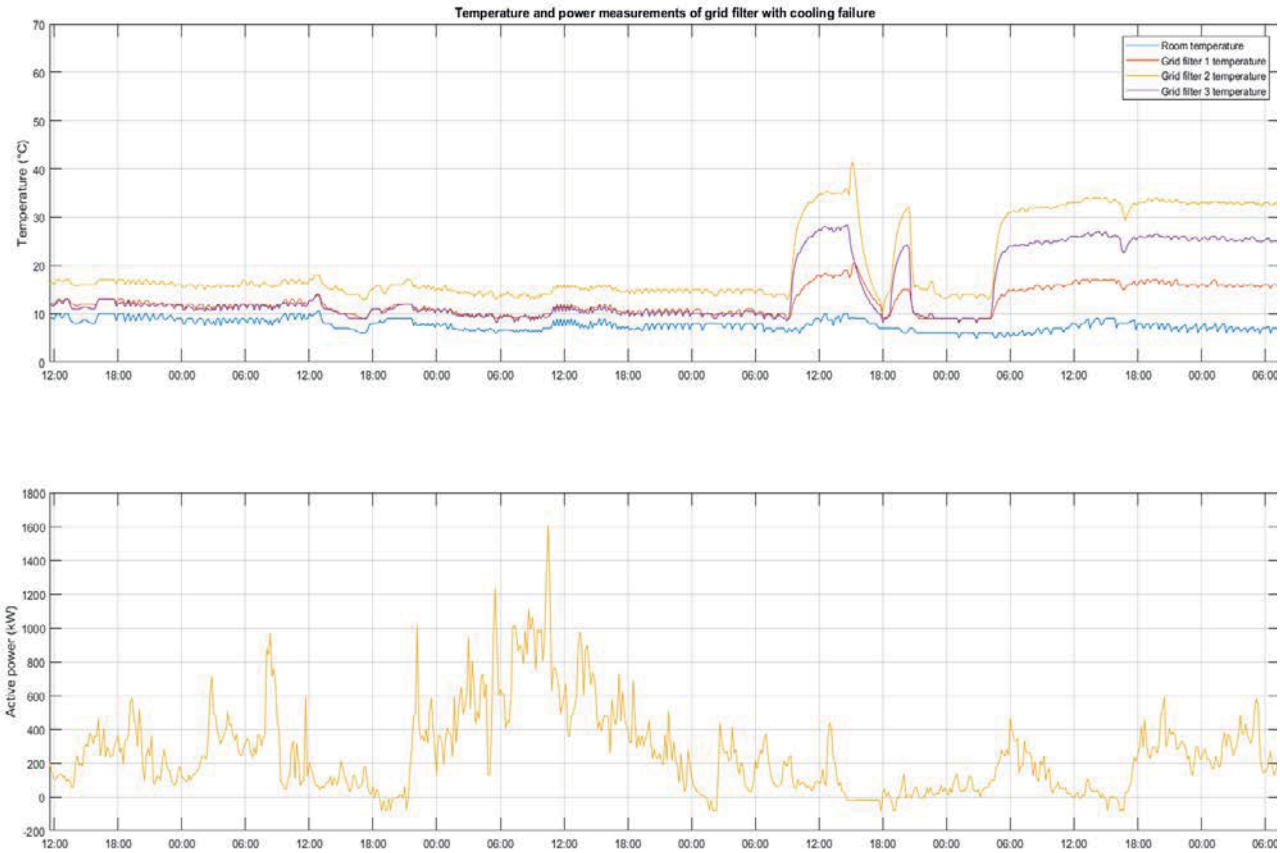

Figure 14: Measurement of the grid filter temperature in the case of cooling system failures [22].

lous operation even with the rudimentary information obtained from the available sensors with low sampling rate (every ten minutes), through careful fault cause analysis on a system level. Warning threshold are created from historical data and validated against other subsets of running turbines of the same type.

It would appear that deterioration of cooling systems takes place, an often overlooked issue, leading to other components to be aged in accelerated manner, and a response of such an event is shown in Figure 14. Analysing the data from system point of view therefore permits a predictive maintenance action, rather than reactive.

5 Perspectives and conclusion

There are numerous problems with the current product qualifications, with a trade-off between confidence levels and cost of testing, as pointed out in [23]. After a critical review of conventional qualification testing methodologies (standards-based qualification and physics-of-failure based qualification testing), the author moves on to propose qualification test approaches using data-driven diagnostic and prognostic techniques (DDDPT). These involve in-situ monitoring, feature extraction, feature selection, and classification of operating and environmental parameters to support anomaly detection, to identify the onset of degradation, and to predict health degradation trends.

It is suggested that using DDDPT, despite the effort necessary for generating data for training the machine learning blocks, could be a cost efficient approach to do qualification by extrapolating the created models.

Nevertheless the DDDPTs' lack of ability to identify appropriate parameters that will be useful for assessing impending failures necessitates a fusion prognostics-based qualification test methodology that combines the advantages of Physics-of-Failure and data-driven approaches to quickly and reliably qualify electronic assemblies, as shown in Figure 15. This renders the implementation of suitable in-situ condition monitoring methods to be imperative. In this scenario, the need to test until failure is avoided by predicting deviations from the baseline.

One recurrent topic discussed at the workshop was the return on investment for CM equipment. Though there is no clear break point, there was a consensus that the costs of maintenance are generally underestimated and that the initial investment of equipping the converters with C&HM hardware is largely paid-off, even before considering the avoidance of service discontinuity.

Depending on the application, there are different business models applied to C&HM. Generally, OEMs will engage maintenance responsibility (automotive applications for example) to absorb the initial cost and offset it through improved maintenance and subsequent reduction of lifecycle costs. Alternatively, C&HM costs can be transferred to the final user, when the latter can exploit the monitoring features, typically for services with strong requirements of non-interruption of service, public transportation or energy transport and generation as examples.

An interesting application of the hardware used for on-line continuous condition monitoring is stress steering and equalisation, for systems with built-in redundancy or parallelisation. In addition, such systems will experience a graceful deterioration through partial shedding, permitting

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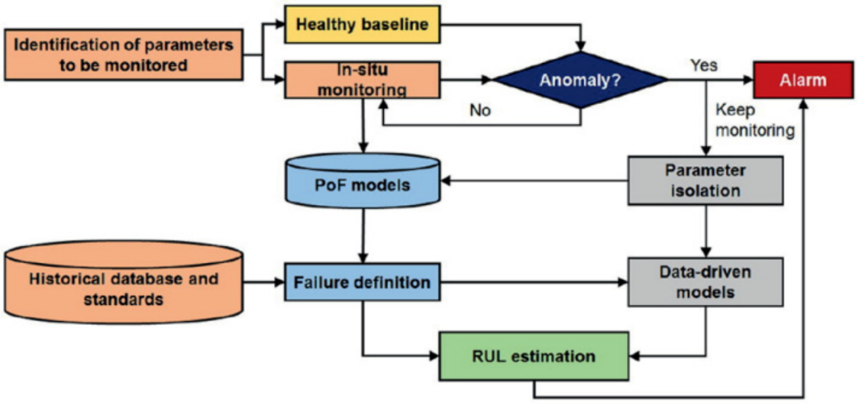

Figure 15: Qualification of products using both a data-driven and physics-of-failure approach [23].

the accomplishment of the initiated mission. The benefits in terms of life extension are still to be evaluated, but due to the low required computational burden, it is likely to be an additional argument for C&HM installations combined with more, better, and cheaper interconnections.

6 Acknowledgments

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