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Increasing the Reliability of Wind Turbines Using Condition Monitoring of Semiconductor Devices: a Review

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Abstract: The majority of electrical failures in wind turbines occur in the semiconductor devices of either the grid or generator converters. This is due to temperature swings affecting the layers of IGBTs in different ways; these effects are aggravated by the variation of wind speed. In order to increase reliability and decrease the maintenance costs of wind turbines, several condition monitoring methods for semiconductor devices have been proposed in the technical literature. The implementation of accurate on-line condition monitoring mainly relies on on-line tracking of the temperature variation of components. The maximum temperature stress is observed at the junction terminal of the devices, which cannot be easily measured. Additionally, it is difficult to track the exact dynamic of temperature due to the slow response of sensors. Thus, several methods have been presented in the technical literature to estimate the junction temperature from the monitoring of electrical parameters. Each method has merits and disadvantages in terms of accuracy and complexity, as failure mechanisms have their own effects on the variation of junction temperature and some or all of the electrical parameters. Therefore, detection algorithms have to determine whether the temperature variation estimated by the variation of electrical parameters is due to a real failure or whether it is caused by normal converter operations. This paper comparatively reviews the condition monitoring methods presented in the technical literature and gives directions on the future steps that should be addressed by research in this area.

1. Introduction

The use of renewable power sources has increased significantly over the last two decades. Among renewable sources, wind power generation technology has improved considerably and today represents a valid integration to traditional fossil fuels. The electrical power generation of wind turbines (WTs) is intermittent and dependent on wind conditions. Therefore, the power converters of WTs are subjected to temperature cycles that are not easily predictable and, hence, the ageing phenomena of the semiconductor devices of these converters are still not completely understood. Other factors like variable environmental conditions, mechanical vibrations and electrical loadings are likely to add additional stress on the electrical system. The principal causes of failure of wind turbines arise in the power conversion system (17.5%), the control system (12.9%) and the generator (5.5%) [1]. Downtime of the electrical system is also ranked first [2]. A study on 350 WTs has shown that the highest rate of failure is for power modules (32%), followed by rotor module (24%), control system (15%), nacelle (12%), drive train (8%), auxiliary system (6%) and structure (3%) [3] as shown in Fig. 1. This leads to the conclusion that avoiding unplanned halts and failures of the electrical system of WTs highly depends on the reliability of power converters [4]. Therefore, a frequent maintenance routine is required to avoid unplanned halts and loss of power generation. Additionally, failure rates increase with the power of wind turbines and, then, the power processed by the IGBTs. Previous studies indicate that the annual failure rate of a 1.5 MW WT built in 2004 was 3.5% higher than that of a 225 kW WT built in 1993 [5].

An accurate prediction of imminent faults would then be extremely beneficial for the WT industry. Condition monitoring (CM) refers to the real-time process of monitoring the operations and characteristics of systems so as to predict upcoming faults [6].When a critical or potentially critical condition is detected, an appropriate action can be taken to avoid further deterioration or breakdown of the monitored system, with significant reduction of failure costs. In order to estimate defects, a range of sensors and data analysis methods can be used and applied to the different parts of a WT [7].

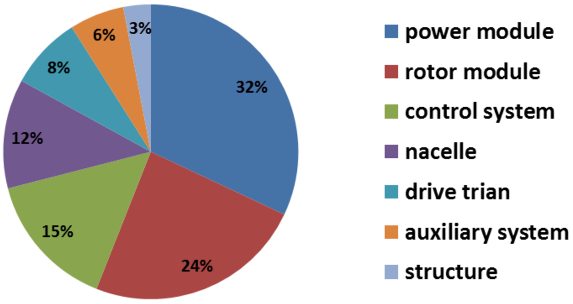

Fig.1. *Percentage of failure of the different parts of a WT*

A condition monitoring system (CMS) has two principal parts to identify the degradation of the monitored system. The first part diagnoses the faults and tries to identify their original root cause. The second part undertakes a prognosis of the health condition of the system, in which the health level of each component is assessed.

Maintenance costs of WTs are often high due to the remote locations of the turbines, ranging from €100,000 to €300,000 for 2-3 MW offshore WTs and from €200,000 to €720,000 for larger offshore WTs [8]. However, the typical cost of a CMS is about €10,000 per year per turbine, which is mainly related to the employment of people and maintenance of the CMS itself [9].

CM of the electrical system of a WT can be applied to power electronics devices and electrical generators. Effective CMSs should operate on-line and require an adequate knowledge of failure mechanisms and physical factors underpinning the failures. Physical external factors such as dust, humidity, vibrations, insects and wind conditions such as wind gusts and turbulence [10] contribute to some extent to various failure mechanisms. The analysis of the technical literature on CM methods has evidenced the lack of an in-depth comparison between the proposed methods. This paper addresses this gap by critically comparing the CM systems available in the technical literature and linking them to the specific failure modes of IGBTs. The principal limitations of current CM methods are analysed with particular attention to the assumptions on the characteristics of semiconductor devices. The CM methods use different types of sensors, models and numerical algorithms and, hence, different schemes and resources to estimate the state of health of IGBTs and predict faults [11], [12].The in-depth comparison is herein undertaken on the basis of the accuracy, complexity and cost effectiveness of the methods. Moreover, the effect of the wind condition on the accuracy of the condition monitoring system is carefully discussed in the final section. The results of the comparison are represented in the final tables giving indications on the suitability of the CMS and failure indicators for the power converters of WTs and their impact on the estimation of the lifetime of devices.

2. Failure mechanisms of IGBT modules

IGBT modules are widely used for WTs as switching devices, because of their high efficiency and capability of handling high currents. It is the multi-layer structure of these modules with different materials that provides a high mechanical stability, electrical insulation and good thermal conductivity [13]. However, each of the layers is made up of different thermal expansion coefficient materials, which can in turn cause thermal stresses due to several extinctions and constrictions during the power cycling of IGBT [14], [15].

The degradation of IGBT modules is a natural phenomenon during normal operations, which can be exacerbated in the application of WTs because the variation in wind conditions imposes different thermal loading and different temperature cycling [16]. Thermal cycling and thermo-mechanical fatigue in multi-layer structures causes thermo-mechanical stresses. In IGBT modules, thermo-mechanical stresses are due to temperature swings, the variable rate of power dissipation and the mismatch between the thermal expansion coefficients between different layers, especially between the semiconductor die, made of silicon, and the bond wire, made of aluminium, as well as solder joints, made of a ceramic substrate, and base plate, made of copper [17].

Thermo-mechanical stresses lead to a number of failure mechanisms that can be categorised according to Fig. 2. Among these faults, bond wire lift-off (BWLO) [18], solder fatigue (SF) [19] and aluminium corrosion (ALC) [20] are found in the majority of cases of IGBT modules for WT applications [21].

In terms of BWLO, the bonded area is where the bond wire foot is connected to the chip metallisation. The most fragile part of the bond wire is its heel, due to the sheer stresses between the wire and the chip pad. Heel crack can lead to the disconnection of the wire bonds and, with the extension of the crack, to a full BWLO. The root causes of wire failures are temperature swings, average temperature level and temperature variations. In terms of SF, both temperature swings and different thermal expansion coefficients of the materials cause shear stresses and consequently fatigue [22]. The intensity of stresses has a direct implication on the time of occurrence of fatigue. A small initial crack in the solder attached to the die can start even from a small and short temperature cycle. The root causes of SF are temperature swings, humidity, average temperature level and temperature variations and, hence, very similar to those of BWLO. In terms of ALC, IGBTs are not sealed against humidity and their silicone gel is not impermeable to moisture [23]. Thus, especially in offshore WTs, an increase of humidity causes an increase of the electric field at the edge terminals of the IGBTs and leads to the corrosion of solder joints [24]. Another destructive effect of moisture is the expansion of small cracks due to the surge of pressure inside the module during soldering [25]. The root causes of corrosion are average temperature levels and current density.

Each type of failure has a significant effect on a subset of electrical parameters of the IGBT module. These parameters, called Thermal Sensitive Electrical Parameters (TSEPs), can be considered as detectors of early faults of IGBT modules. The challenge of this approach is that the variation of an individual parameter can be considered the symptom of a failure, whereas the opposite variation of the same parameter can be referred to another type of fault. This causes problems with the discrimination between healthy operations and actual degradation of IGBTs. For instance, the collector emitter voltage, $V_{CE,on}$, increases when BWLO occurs, but decreases when SF around die attach occurs [19], [26]. Hence, when several types of degradation occur simultaneously, the accuracy of the CMS diminishes and the state of health of the IGBT modules cannot be correctly estimated. The main failure mechanisms are summarized in Table 1. “See Appendix” and their indicators are compared in terms of accuracy, linearity and sensitivity.

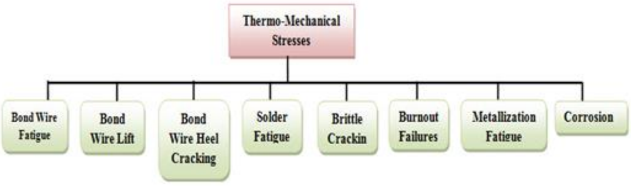

Fig. 2. *Thermal stresses cause failure in IGBT modules*

3. Review of current degradation indicators of IGBT modules

The different failure mechanisms can be detected by looking at specific parameters, but often research papers have shown that the variation of a specific parameter can be the symptom of multiple causes. Therefore, it is quite difficult to classify the methods of failure detection. In this paper, an attempt has been made to group together different methods used for failure detection and compare them on the basis of specific performance criteria. Table 1 “See Appendix” represents a comparison of different failure detectors in terms of accuracy, linearity and sensitivity. The most recommended detector has been scored with the maximum number in each column.

3.1 Methods to detect BWLO

Direct measurement of T_j is mainly considered as a BWLO detector. A resistor, operating as a temperature sensor, is connected in parallel to the bond wires [27].When BWLO occurs, the impedance of the sensor resistor becomes comparable with that of the bond wires and it draws a much higher current. The fault is then detected by the significant temperature variation of the sensor resistor. This method provides accurate real-time monitoring of BWLO, since T_j is directly measured. However, it requires a suitable modification of the die, the bond wires and the heatsinks to accommodate the extra sensor resistor. To detect and observe BWLO, an optical fibre [28], infrared (IR) camera [29], or infrared sensors [30] can be used, which then avoids significant modifications of the device. However, methods based on IR cameras are not sufficiently accurate, as the camera only scans the surface of IGBTs.

L. Chen et al. [31] have demonstrated that accuracy can be improved by using an IR camera together with laser scanning, as the laser provides an internal view of the module. However, the synchronisation between the IR camera and laser scanning requires a large number of samples, which makes this method unsuitable for on-line measurements. Direct methods are not very popular, as they normally have low resolution, high implementation costs and often need to access the inside of the module or remove the module from the converter. Additionally, these methods are not sensitive to small variations of the temperature due to the tolerance of either the sensors or the cameras. For these reasons the application of direct detection of failure mechanisms is mainly adopted only for the experimental verification of other methods. Another method which has been investigated for the detection of BWLO is an estimation based failure detector. This method starts from thermo-mechanical and electro-thermal modelling of the IGBT module, since the variation of the temperature as the root cause of failure is caused by either mechanical or electrical stresses on the IGBT structure. However, the estimation based method (electro-thermal modelling) cannot be applied to the detection of BWLO as it does not detect the occurrence failure in its early steps. In fact, BWLO only affects the current distribution from the die to the bond wires. Due to the small cross-sectional area, these wires do not contribute to the heat transfer of the device and, hence, their degradation does not produce significant modifications of the temperature distribution. As a result, the only way to detect BWLO is to monitor thermal sensitive electrical parameters (TSEPs) with a minor role played by thermal modelling.

The methods based on TSEPs use several parameters, including on-state collector emitter voltage ($V_{CE\text{-on}}$), on-state resistance (R_{on}), threshold-gate emitter voltage ($V_{GE\text{-}th}$), and the on-state to off-state time (t_{off}).

The voltage $V_{CE\text{-}on}$ is widely used to detect early BWLO, when less than half of the bond wires have lifted off. Ghimire et al. [32] demonstrated with FEM simulations and experiments that $V_{CE\text{-}on}$ is linearly increasing with T_j [33]. However, an increase of $V_{CE\text{-}on}$ does not necessarily imply an increase of T_j, as $V_{CE\text{-}on}$ is affected by other parameters not directly related to BWLO. An example is given by the increase of $V_{GE,th}$, which can be considered as the early failure detection of gate oxide degradation. Consequently, an increase of T_j due to gate oxide degradation would cause a reduction of $V_{CE\text{-}on}$. Therefore, CM methods based on $V_{CE\text{-}on}$ can accurately predict BWLO only if the estimated T_j is verified in healthy mode from at least one other method which is not oriented to BWLO. An alternative method is based on an in-situ circuit connected to the power converter that measures both I_C and $V_{CE\text{-}on}$ in real time, as proposed in [34] and [35]. The two measurements give the power losses that are used to estimate the temperature T_j and, hence, infer the health condition of the bond wires. However, the additional electrical circuit adds relatively high complexity and implementation costs and increases the physical dimensions of the converter. L. Zhou et al. [36] remarked that monitoring $V_{GE,th}$ is not recommended to detect BWLO in the initial step. They modelled the gate of the IGBT by its collector-gate capacitance and parasitic common inductance to evaluate the variation of the gate-emitter voltage during the turn-on of the IGBT. When early and partial lift-off occurs, there is no significant change of the gate-emitter voltage because the variation of the total parasitic inductance of the gate circuit is not noticeable. Z. Wang et al. [37] applied $V_{CE\text{-}on}$ as an indicator of BWLO. A 10 to 20% variation of $V_{CE\text{-}on}$ could be the symptom of early BWLO.

N. Baker et al. [38] applied I_G and $V_{CE,on}$ as the early failure detector. The current I_G has been calculated from the measurement of the voltage across the gate external resistance and the value of the gate resistance. The results showed that BWLO causes an increase of I_G and a decrease of $V_{CE,on}$. However, the effect of other failures such as gate oxide on the variation of I_G has not yet been considered. D. Barlini et al. [39] and P.Xue et al. [40] used both static and switching characteristics of IGBTs to detect the failure mechanism. The derivative of I_C and V_{GE} are measured through a double pulse method in order to increase the accuracy of measurement [41]. However, variation of V_{CE} should be evaluated in the proposed method as it directly affects the level of I_C. In other words, if current I_C is applied to detect BWLO, it should be uncoupled with the variation of T_j as it can be originated by non-failure reasons. In order to uncouple the variation of T_j with BWLO, independent failure detector can be applied. Another problem of the proposed method is several sampling rates and measurements have to be done to reduce parasitic noise. A problematic issue of the method based on a TSEPs failure detector is measurement error due to parasitic noises generated. S. Zhou [42] has demonstrated that the effect of noise can be removed by relevance vector machines.

3.2 Methods to detect SF

D. Barlini et al. [39] and J. Lehmann et al. [43] employ an in-situ circuit to evaluate the variation of $V_{GE,th}$. They showed that an increase in $V_{GE,th}$ can be caused by thermal stresses of IGBTs. This variation is due to the surge of the capacitance across the gate and the emitter, which is in turn due to trapped electrons in the gate oxide. The accuracy of this method has been experimentally proved by Scanning Acoustic Microscopy (SAM). However, this method does not work for on-line condition monitoring as it needs the exact time when the IGBT turns on to measure $V_{GE,th}$, which is not accurate .Acoustic microscopy has the main advantage that no modifications of the IGBT chip are required [44], as this significantly affects the temperature distribution of the module.

With reference to thermo-mechanical models, M. Ciappa et al. [45] provided the stress-strain profile of IGBTs using the fundamental thermomechanical equation, describing the creep mechanism due to cyclic loads. The creep of solder is modelled by a 3-D finite element thermal model in two ways, mechanical and thermal. This is due to the fact that temperature swings also produce creep plastic deformations. The health level of the solder layer can be deduced from the analysis of the total deformation energy given by the model. The downside of this method is the required accuracy of the 3-D model of the IGBT module, which leads to a high computational complexity. Although this method provides an accurate description of T_j evolution, it is not applicable to time-dependent temperature variations such as those connected to SF. With reference to the electro-thermal model, C. Yun et al. [46] and T. Kojima et al. [47] used experimental data and infrared thermography techniques to calibrate a static 3-D finite element thermal model of both converter and heatsink, with an improvement of accuracy against simple models based only on heat transfer theory.

C. Yun et al. [46] used a 3-D model to determine the temperature distribution across the IGBT layers and then the thermal impedance based on an equivalent R-C circuital model of the system. The response of the circuit is fast and shows the thermal variation of IGBT layers simultaneously. However, the method still depends on the development of complicated computational 3-D models. Conversely, A. Bahman et.al [48] and S. Madhusoodhanan [49] used a compact R-C model of each IGBT layer to define its thermal characteristics and then its thermal impedance with associated power losses. The Finite Element Method (FEM) model of each layer is then used to calculate the thermal distribution of the entire module. Different heat resistances show the presence of cracks on the solder layers of the IGBT. SF affects the thermal coupling between the die and the contact pad. If there are voids between the layers the effectiveness of heat transfer from the die to the heatsink is reduced, increasing the thermal impedance. However, the drawback is the high computational time due to FEM.

L. Fratelli et al. [50] and V. Sankaran et al. [51] proposed the estimation of T_j by means of the calculation of the junction-to-case thermal resistance ($R_{j\text{-}c,th}$). It has been revealed that this resistance can increase up to 20% in the presence of solder fatigue. These methods are applicable even for faults occurring in the time frame of microseconds, such as short circuits, because they do not rely on any external measurement of electrical and thermal quantities.

D. Xiang et al. [52] have shown that T_c and $R_{j\text{-}c,th}$ are both SF indicators. A thermal pad is used to emulate the present of SF. The resistance $R_{j\text{-}c,th}$ was increased artificially by adding a thermal pad to the IGBT module. The T_c and I_c were measured to calculate the differences in power losses with and without the added thermal pad. In the presence of SF, an increase of almost 20% in $R_{j\text{-}c,th}$ and an increase of 2% in almost T_c were observed. Simulation results also confirmed an increase of almost 3.7 ºC in T_c in the present of SF. However, using this method it is not clear whether the observed variations originated from SF degradation, or from the heatsink degradation, since the rise in T_c due to SF increases the heatsink temperature.

F. X. Che et al. [53] revealed that the variation of V_{GE} can be used as an SF indicator, since SF causes also wear-out of gate drivers. As V_{GE} is not constant during the switching, it is essential to ensure a consistent sampling of V_{GE} to ensure the accuracy.

Of the method. However, as V_{GE} is influenced by other factors and not only SF, the root cause cannot be distinguished. This can in turn diminish the accuracy of CMSs in case of multi-failures.

D. Xiang et al. [54] have proposed monitoring the variation of the case temperature (T_c) to estimate the variation of the thermal impedance from the case to the heat sink. They used this method mainly for the detection of SF, as this fault directly increases the thermal impedance and, hence, T_C, roughly instantaneously. D. C. Katsis et al. [55] revealed that a 10% increase of $R_{j\text{-}c,th}$ can be a symptom of crack existence, as temperature distribution on the case-base plate becomes imbalanced. The maximum stresses appear close to the crack tips, because of concentration of stresses. A longer crack also leads to faster expansion and the relation between stress cycling and $R_{j\text{-}c,th}$ is exponential. However, the method did not consider the effect of other failures and the health condition of thermal grease on the variation of $R_{j\text{-}c,th}$. D. Xiang et al. [56] have revealed that IGBT degradation can change the odd current harmonics of the inverter. This is because the switching time and $V_{CE\text{-}on}$ of a degenerated IGBT changes compared to a healthy one. A 5% decrease in the 5th harmonic has been observed when SF occurred A. E Ginart et al. [57] revealed that IGBT degradation can change the odd current harmonics of the inverter. This is because the switching time and $V_{CE\text{-}on}$ of a degenerated IGBT changes compared to a healthy one. A 5% decrease in the 5th harmonic has been observed when SF occurred.

3.3 Methods to detect gate oxide degradation

Ageing causes gate oxide degradation [58], which results in a variation of the gate to emitter capacitor (due to electron trap) and consequently an increase of $V_{GE,th}$ and a decrease of $V_{CE,on}$ [59]. Therefore, an increase of $V_{GE,th}$ can be seen as a symptom of gate-oxide degradation. An increase of $V_{GE,th}$ is only caused by gate oxide degradation. Consequently, an increase of T_j due to gate oxide degradation would cause a reduction of $V_{CE\text{-}on}$.

H. Lue et al. [60] have used switching parameters to estimate T_j, considering that there is a linear relation between T_j and both t_{on} and t_{off}. The negative aspect of this method is that an increase of t_{on} and t_{off} can also be caused by a degradation of the gate characteristics and the voltage V_{GE}. X. Perpiñà et al. [61] suggested that the progressive degradation of the gate driver of IGBTs should be taken into account when using this method. Thus, high resolution, high speed sampling and a noise immune system for each IGBT and gate driver are required to provide an accurate measurement of the switching times.

H. Kuhn et al. [62] studied the sensitivity and linearity of $t_{d,on}$ and its first derivative against T_j, which has been estimated from V_{CE}, V_{GE} and I_C waveforms. Ageing causes gate oxide degradation [63], resulting in a variation of the gate to emitter capacitor due to electron trap and, consequently, an increase of $V_{GE,th}$ and a decrement of $V_{CE\text{-}on}$ [64]. Therefore, an increment of $V_{GE,th}$ can be counted as a symptom of gate-oxide degradation. However, the proposed failure indictor cannot be applied for CM in practice correlated with the occurring failure to avoid loss of accuracy in the CMSs.

3.4 Methods to detect corrosion

IGBTs are not sealed against humidity and their silicone gel is not impermeable from moisture [65]. Thus, particularly in the application of offshore WTs, an increase in humidity causes an increase in the electric field at the edge terminals of the IGBT and leads to corrosion of the solder joints [59]. Another destructive effect of moisture is generating cracks due to a surge of pressure inside the module during soldering (heating up module) [58]. The root causes of corrosion are mean temperature and current density. C. Zorn et al. [64] have proved that a sudden increase in leakage current shows the presence of corrosion and, hence, a decrease in avalanched voltage. However, the result is just valid for the subjected IGBT as the material used in the structure of the IGBT is important and plays a role in the percentage of humidity effectiveness of the electrical performance of the module [66] .In this case, K. Takashi et al. [66] revealed that enhancing waterproof silicone gel and passive materials (weaken of surface charges) can significantly improve the resistance of the module against humidity. C. Zorn et al. [65] also found that a simple acceleration test (standard temperature- humidity bias (THB) test [69]) is not sufficient enough to examine the degradation behaviour of the IGBT in humid conditions; 50% or 90% of the nominal voltage of the collector emitter is suggested to observe the degradation of blocking capability. However, applying a higher voltage causes self-heating of the IGBT and evaporation of humidity, which slows down the failure related to the humidity. On the other hand, applying a higher voltage leads to thermal stresses in the module. ALC reduces the effective cross section and leads to an increase in electrical resistance [23]. H. Wang et al. [70] have applied $V_{CE,on}$ as an indicator of ALC. It revealed that a 10% increase in $V_{CE,on}$ is the symptom of ALC.

4. Discussion of CM methods

Methods based on estimation of T_j are preferred to those based on the direct measurement of T_j, as they do not require modifications of the internal structure of IGBTs. The improvement of models and algorithms for the analysis of indirect measurements is now bringing the indirect methods to the same level of accuracy of their direct counterparts, even when a fast detection of T_j is required.

On the other hand, TSEPs-based methods have drawbacks in terms of practical implementation and reliability. This is because, particularly for wind power generation, IGBTs operate with variable vibrations, ambient temperatures, loads, switching frequencies and duty cycles. Since these conditions are not easily predictable, conflicting information is collected by the measurements and this may result in a false alarm from the CM system. The efficacy of TSEPs methods can be improved by repeated tests, albeit this is time-consuming. Moreover, TSEPs methods invariably require accurate real-time sensors, which are normally expensive.

Table 2 “See Appendix” summarises the main characteristics of the CM methods described in the previous section and gives indications of their main field of application, their advantages and implementation difficulties and cost.

The methods based on FE thermal modelling require specialised software, which can be expensive. The commissioning phase of FE modelling is also time-consuming, due to necessary of defining and applying accurate meshing of the system and initialization of the variables. Additionally, the pre-calculation of power losses, achieved by thermal modelling of FE analysis, is required for a large number of operating conditions of the IGBT. With reference to implementation, these methods require the measurement of power losses of the converter, which may require additional dedicated sensors.

The methods based converter output quantities and on RC modelling of the different layers of IGBTs require circuital software, which is simpler, but the pre-calculation of power losses and the measurement of actual power losses is needed in a way similar to FE thermal modelling.

Sensor based methods require expensive temperature sensors, such as IR cameras, which require an accurate initial calibration. Additionally, they are difficult to implement as the sensors should be placed inside the IGBT modules. The positive aspect is the absence of pre-calculations and the limited need of computational capabilities.

The TSEP-based methods require additional sensors, but they are on average cheaper than IR cameras as they measure only electrical quantities. Additionally, fast signal processors are required as electrical quantities are sampled at the same rate of the switching frequency of the converter. The commissioning phase requires a pre-calibration of the relation between TSEPs and the junction temperature.

From the analysis of the. Table 1 and Table 2 “See Appendix”, it is possible to highlight that determination of the exact root cause of failure mechanisms are still the main issue of all current CMSs. This is because multi-fault mechanisms can interfere with each other and give misleading information to the CMSs. Additionally, there is not a comprehensive applicable CM algorithm for different types of IGBTs and this requires a new calibration every time that a new IGBT module is used, increasing significantly the cost of the CMSs.

A clear area of development to overcome this problem is the monitoring of a combination of different variables and the development of suitable algorithms analysing the simultaneous variation and the cross-correlation of these variables to find the most probable root cause. An additional problem specific for the CMS of wind turbines is the sudden and repetitive load variations that cause a continuous change of the thermal distribution across the IGBT modules and, hence, additional difficulties in the detection of the specific degradation mechanism. An interesting example for wind turbines is the discrimination between early BWLO and SF. If the variables monitored are $V_{GE,th}$, R_{CE} and T_C, an increase of R_{CE}, while T_C and $V_{GE,th}$ are almost constant, is a likely symptom of early BWLO. Instead, an increase of T_C and $V_{GE,th}$ without significant variation of R_{CE} would be a symptom of SF. For this successful implementation of this method, it is then essential a pre-calibration to understand the sensitivity of each variable for the chosen fault mechanism and their level of correlation, as well as a characterisation of these sensitivities for different load conditions. It can be anticipated that these algorithms require a significant computational effort, due to the non-linear relations between the failure detectors and the actual ageing of IGBT. Algorithms based on artificial intelligence, bee colonies or neural networks could be used to tackle this problem as they are particularly when the mathematical relationships between causes and effects are not well known or are expressed in a complex way.

5. Conclusions

Condition monitoring of wind turbines can be a very effective way to reduce costs related to maintenance and to limit unexpected interruptions of the power generation. The electrical systems of a wind turbine, especially the power converters, are subjected to the largest proportion of failures; hence, condition monitoring would be determinant to improving the reliability of wind turbines. From this review it is clear that there is a complex correlation between the variation of IGBT parameters and failure mechanisms and, therefore, an effective CM algorithm has to consider at the same time the presence of the most common failures. The main issue of the state of the art condition monitoring systems is the trade-off between accuracy, complexity and implementation costs, especially for on-line monitoring. This paper has reviewed the main methods used to detect faults and the degradation of IGBT modules used in the converters of wind turbines to highlight the main areas of research and the future trends.

Although several condition monitoring methods have been proposed so far, undesired false alarms can be considered as a huge challenge. This is because all degradation mechanisms of IGBTs have an impact on the module’s junction temperature T_j. Consequently, all TSEPs as failure detectors can be impressed by the variation of T_j. However, T_j can be varied by un-related failure phenomenon such as wind condition in the application of wind turbines. Therefore, it is necessary to uncouple the temperature variations originated by failure mechanisms with those varied by the unrelated-failure phenomenon. In this case, two different values are achieved for a specific TSEP in each moment. Any discrimination between two different values represents the presence of a failure mechanism. In the application of wind turbines, wind speed variations can cause errors in reading the health status of IGBT. This is due to different load cycling and consequently thermal fluctuation of IGBT. This can be considered as unrelated-failure phenomenon in the application of wind turbines. Future condition monitoring systems are expected to overcome the limitations of the current methods by combining several methods together and using cross-correlation techniques to discriminate different degradation mechanisms.

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8. Appendices

Table.1 Failure mechanisms of IGBTs and their indicators

Failure	Failure Indicators	Accuracy	Linearity	On-line	Sensitivity	Symptom	Ref
BWLO	$V_{CE,on}$	3	3	4	6	+10%,+20%	[32]
	I_C	5	3	4	6	Increase	[70]
	T_C	2	4	5	4	+10%	[41] [71]
	5th current harmonic	6	1	6	5		[42]
	$I_{leakage,GE}$	1	2	1	1		[57]
	$V_{GE,th}$	3	3	2	2	+11%	[61]
	V_{GE}	2	3	3	2	Decrease	[39] [72]
	I_G	4	3	2	2		[65] [38]
	I_{sc}	7	4	5	6	-4.5%	[29] [63]
	R_{CE}	7	3	4	6	+15%	[51]
	$R_{j\text{-}c,th}$	3	3	5	3	+10%	[50] [73]
SF	$R_{j\text{-}c,th}$	3	2	3	4	+20%	[51]
	5th current harmonic	2	1	3	1	-3 to-5.5%	[56]
	$V_{GE,th}$	1	2	1	2	+11%	[39]
	T_C	4	3	4	4	+1.57ºC	[54]
	$V_{CE,on}$	1	2	2	3	-17%	[37]
Gate Oxide	$V_{GE,th}$	2	2	2	2	+11%	[61]
	$I_{GE,leakage}$	3	1	1	2	+Sharp	[64] [65]
	$V_{CE,on}$	1	2	3	1	-13%	[60]
Corrosion	$V_{CE,on}$	1	2	1	2	+10%	[55] [64]
	$I_{GE,leakage}$	2	1	2	1	+Sharp	[58] [23]

Table 2 Comparison of IGBT CM methods

Techniques	Failure mechanism	Requirements	Perceived advantages	Perceived limitations	Identification / Indicator	implementation	Ref
Modelling	Thermal fatigue	-FEM software -Time consuming	-Accurate prediction of temperature - No additional sensor	-Computational cost - time consuming	-Thermal model	-Pre-calculation	[32] [49] [73]
	-Thermal model -Gate driver	- Thermos electrical modelling -Time consuming	-Easy measurement -No additional sensor	-Accuracy of thermal model -Distinguishing the type of fault and the unhealthy part	-Heatsink modelling	-Pre-calculation	[46]
Sensor-Based	-Bond wire lift-off - Solder fatigue	-IR-Camera	-Reliable and accurate	-Required modification in IGBT module	-T_j (+10%)	-Pre-calibration	[27]
TSEP-Based	-Bond wire lift-off	-Embedded measurement circuit - Additional sensors -Fast sampling processor	-Distinguish of fully lift --off -Applicable within the operation of system	-Influenced by both IGBT and driver -in accurate in parallel IGBTs chips	-Gate current (decrease)	-Pre-calibration	[42] [29]
	-Solder fatigue -Short circuit -latch up -Wire bond degradation -Die attach degradation	-Embedded measurement circuit - Additional sensors	-Applicable within the operation of system	-Distinguishing type of fault and unhealthy part -Capture of small variation in fast switching	-$V_{CE,on}$ (+5%,10%,20%)	-Pre-calibration	[51] [65]
	-Gate degradation -Short circuit - latch up - Wire bond degradation	-Embedded measurement circuit - Additional sensors - Fast sampling processor	-Indicator of gate oxide degradation	-Applicable in off -line mode of system -Required modification in IGBT module	$V_{GE,th}$ (+11%)	-Additional sensor -Pre-calibration	[61]
	-Solder fatigue and cracking	-Electro thermal and thermos electrical modelling		-Time consuming	R_{th} (+20%)	-Pre-calculation	[51]
Converter Output	-Solder fatigue	-Embedded measurement circuit to amplify harmonic -Fast sampling processor -	-No additional sensor	-Distinguishing type of fault and unhealthy part -Complicated algorithm	-Current harmonics amplitude	-Pre and post calculation	[56] [42]
	-Thermal increase -Power losses of converters	-Embedded measurement circuit -Fast sampling processor	-No additional sensor -Estimation of T_j	-Accuracy depend on power loss estimation - Distinguishing type of fault and unhealthy part	-Control of converter efficiency	-Pre and post calculation	[56]