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Exploring the Causes of Power-Converter Failure in Wind Turbines based on Comprehensive Field-Data and Damage Analysis

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Abstract: Power converters are among the most frequently failing components of wind turbines. Despite their massive economic impact, the actual causes and mechanisms underlying these failures have remained in the dark for many years. In view of this situation, a large consortium of three research institutes and 16 companies, including wind-turbine and component manufacturers, operators and maintenance-service providers has joined forces to identify the main causes and driving factors of the power-converter failures in wind turbines to create a basis for effective remedial measures. The present paper summarizes and discusses the results of this research initiative, which have been achieved through the evaluation of converter-specific failure and operating data of a large and diverse worldwide wind-turbine fleet, field measurements as well as post-mortem investigation of returned converter components. A key conclusion of the work is that the thermal-cycling induced fatigue of bond-chip contacts and die-attach solder, which is a known issue in other fields of power-electronics applications and which has been widely assumed to be the principle damage mechanisms also in wind turbines, is no relevant contributor to the observed converter failures in this application. Instead, the results indicate that environmental factors such as humidity and contamination but also design and quality issues as well as human errors play an important part in the incidence of these failures.

Keywords: reliability; power electronics; power converter; wind power; root-cause analysis; post-mortem analysis; field data

1. Introduction

Power-electronic converters are key components in variable-speed wind turbines (WTs). At the same time, they are among the most frequently failing components of WTs. This has been shown by numerous system-level studies evaluating the reliability of wind turbines in different parts of the world. According to the RELIAWIND study based on data from 373 WTs with a total of 1115 WT operating years from 2004–2010, the power converter ranks second with regard to both the failure rate and the resulting downtime [1,2]. A study evaluating >5800 failures in wind farms in China during 2010–2012 identified the frequency converter as the by far most frequently failing component [3]. Recent system-level reliability data collected within the SPARTA initiative during 2015–2016, which covers 1045 offshore WTs in the UK with 1219 WT operating years, ranks power converter failures fourth, with an average of 1.3 failures per WT and year [4].

1.1. State of Research on Power-Converter Reliability in Wind Turbines

Although the issue of high converter unreliability in WTs has existed for more than two decades and is a relevant contributor to maintenance costs and downtime-related revenue losses, it has to date still not been solved. The main reason is that the causes and mechanisms underlying the frequent failures have remained largely unclear. For a long time, the scientific literature related to power-converter reliability in the wind application has focused almost exclusively on the failure mechanisms known from other power-electronics applications: the fatigue of bond-wire contacts and die-attach solder under the long-term impact of temperature cycles due to power cycling and the thermomechanical stress resulting from this (see e.g., [5–8]). Assuming that the same mechanisms were the dominant life-limiting ones also in power converters in the wind application, the empirical lifetime models available for these "classical" failure mechanisms were widely applied, e.g., for reliability simulations and work on remaining-life estimation (see e.g., [9–19]). In this body of work, a particular focus on the generator-side converter in WTs with doubly-fed induction generator (DFIG) and in WTs with low-speed permanent-magnet synchronous generator (PMSG) is found. As these converters are loaded with low-frequency currents on the generator side and are therefore subject to large temperature cycles [20], they were expected to be particularly prone to failure.

A wider focus going beyond the above-mentioned fatigue-related damage mechanisms is found, e.g., in [21–25]. However, a recently published survey has made clear that temperature cycles due to power cycling are still perceived as most critical stressor for power converters in wind turbines [26].

1.2. Previous Work of the Authors

An initial field-experience based study of some of the authors (project CONFAIL, see [27,28]) raised for the first time the question of whether thermal-cycling induced fatigue was in fact the cause of the power-converter failures observed in wind turbines. However, as this study was focused on only two WT models, it was too limited to allow drawing any conclusions for the wind application in general. In view of this, a large consortium of three research institutes and 16 companies, including wind-turbine and component manufacturers, operators and maintenance-service providers, joined forces under the lead of Fraunhofer IWES in a research cluster, the Fraunhofer Innovation Cluster on Power Electronics for Renewables. Using again a field-experience based approach, the research carried out within this cluster has built on an exploratory analysis of comprehensive converter-failure and operating data, which was provided by the project partners, as well as on field measurements and the post-mortem analysis of power-converter components returned from the field. This has been complemented by comprehensive modelling and simulation work for investigating potentially critical effects resulting from the dynamic interaction of the electrical, mechanical and structural wind-turbine components under the influence of stochastic wind fields and grid conditions [29–31]. The results of all these different approaches have been evaluated in an interdisciplinary team in close collaboration with the project partners, with the main objective to identify the relevant factors and mechanisms leading to converter failure in wind turbines in order to create a sound basis for the development of effective countermeasures.

Thanks to the project partners, field data from more than 2700 horizontal-axis, variable-speed WTs of a wide variety of manufacturers, types and operating ages operating at onshore and offshore sites on four different continents could be collected and evaluated. With almost 7400 WT operating years covered, the to the authors' knowledge most comprehensive and up-to-date cross-manufacturer collection of converter-specific failure and operating data worldwide could be established in this way.

Previous publications of the authors based on this data collection are [32–36]. The most relevant findings, which constitute important background information for the present paper, are summarized in the following. For details about the analysis methodology underlying these results, the reader is referred to the respective publications.

On average, 0.48 a^{-1} failures of the main power-converter system occurred per WT in the considered worldwide turbine fleet. With a mean failure rate of 0.16 a^{-1} failures per WT, the largest share of this is accounted for by the core components of the converters denoted "phase module" [35]. This phase-module component category includes the power semiconductor modules with their gate-driver boards, the DC-link capacitors and busbars. As the phase-module categories were identified to be not only the weak point in the converter system with respect to failure frequency but also the main driver of repair cost and downtime [32], the focus of all subsequent field-data analysis has been on examining the phase-module failures and identifying factors influencing these.

A failure-rate comparison between WTs commissioned from 1997 to 2015 has revealed that their average phase-module failure rates have not decreased over successive WT generations [35]. This has made clear that the high power-converter unreliability is a problem not limited to old turbine fleets but is also a critical issue in contemporary WTs. To understand and counteract the causes of converter failure is therefore a challenge of unchanged relevance.

A comparison of the average phase-module failure rates in WTs with different generator-converter concepts and of different manufacturers has revealed major differences between these. The group of WTs with electrically excited synchronous generator (EESG) and full power converter was found to have the on average lowest failure rate, while that of WTs with squirrel-cage induction generator and full power converter (IG + FPC) showed the highest. The group of WTs with doubly-fed induction generator (DFIG) and partially rated converter, which is particularly well represented in the evaluated database, ranked between the other two groups [35]. However, it is important to note that this comparison has not taken into consideration the diverse wind regimes (and with that the load conditions) the WTs in the different groups have been operating in.

In search of spatial or temporal failure patterns, a strong seasonal variation of phase-module failure rates was discovered in WT fleets in India and Scandinavia. In Scandinavia, this pattern was found in WT fleets of three different manufacturers. The observation that periods with increased phase-module failure rates coincided with periods of high ambient absolute humidity suggested that moisture and condensation are factors with a relevant influence on converter failure in wind turbines [35].

An investigation of the operating point preceding phase-module failures showed that the frequency of these failures was highest in and around full-load operation, i.e., during operation close to, at or above the rated power of the wind turbine. This observation was made for turbines of different generator-converter concepts and manufacturers and suggested that high electrical loads are a trigger for converter failures [35].

Weibull analysis applied to WTs with known converter-component age revealed a pronounced infant-mortality behavior (shape factor $b < 1$), i.e., failure rates decreasing with the age of the phase modules [33,36]. Wear-out failure behavior with increasing failure rates, which would have been typical of fatigue-driven failure mechanisms, was not found in any of the analyzed WT fleets.

Finally, the comprehensive field data was utilized to statistically investigate the effect of different design factors on phase-module reliability. These included the power-converter position inside the turbine (nacelle, tower base or distributed), the converter cooling concept (liquid- vs. air-cooled), the rated power of the converter, its DC-link voltage level and the earthing system (earthed system "terre neutre" TN vs. system "isolé terre" IT, in which all active parts are insulated from earth). Low DC-link voltages, liquid cooling and IT systems were found to have a significant positive effect on reliability [36].

1.3. Contribution and Outline of the Present Paper

The present paper seeks to provide the state of knowledge with respect to the failure causes and relevant influencing factors that has been achieved within the Innovation Cluster. Following an introduction of the analysis methods (Section 2), it complements the previously published field-data analysis results summarized above with deepened statistical analyses and presents the findings of comprehensive damage assessments of defect power-converter components carried out at the involved research institutes and their industrial partners (Section 3). Taking into account the full picture of results obtained, it provides an in-depth discussion of the mechanisms and factors identified to be relevant (or irrelevant) for converter failure in wind turbines (Section 4). The paper closes with a summary of the main conclusions as well as an outlook to future work (Section 5).

2. Investigated Systems and Analysis Methods

2.1. Studied Wind-Turbine Systems

The converters in the investigated horizontal-axis WTs, which are illustrated in Figure 1, are low-voltage two-level IGBT-based voltage source converters in back-to-back configuration. Although the first WT models with medium-voltage converters are encountered on the market since several years ago, the aforementioned technology is still by far prevailing in the field. The converter systems of the EESG-based WTs differ from that of the other WT groups in two ways: the AC-DC conversion on the generator side is performed by a diode- or thyristor-based rectifier in these WTs. In addition, they contain a unit for the electrical excitation of the generator and, in some WT types, a voltage step-up unit in the DC link. In our analyses, these components are considered as parts of the power-converter system.

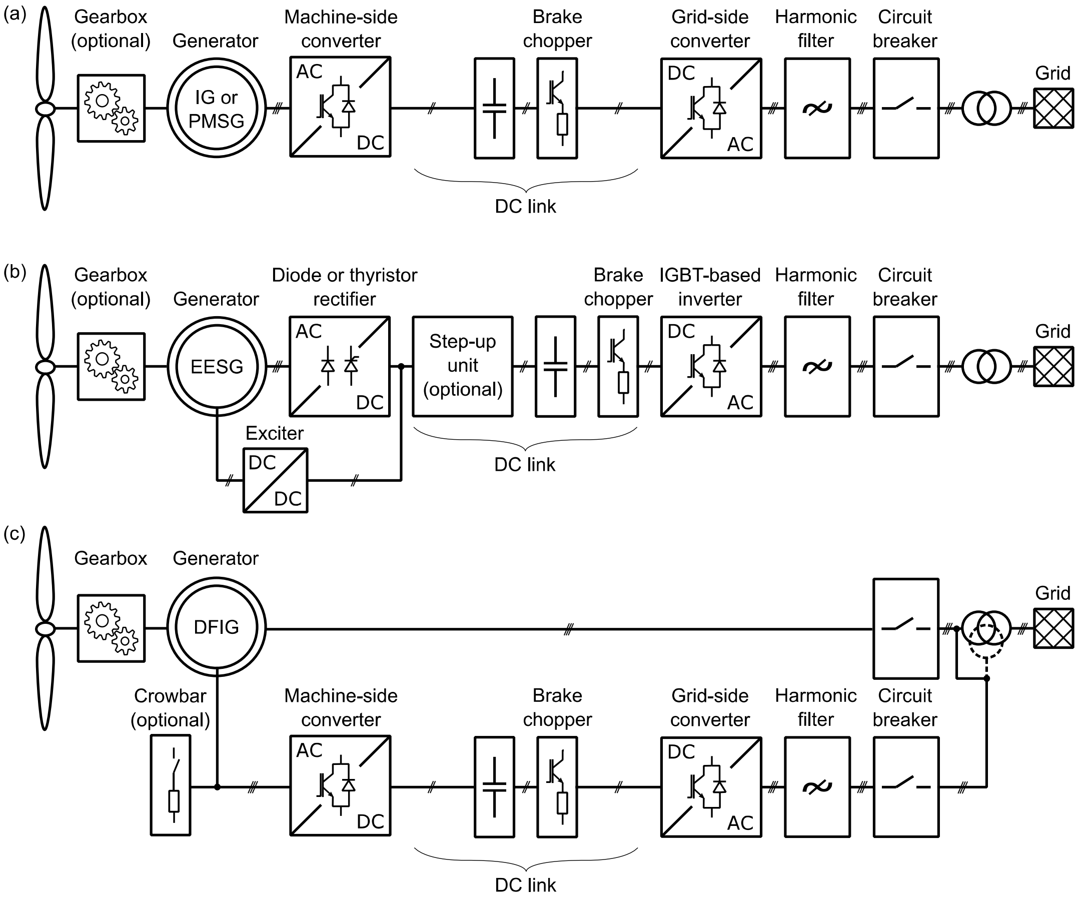


Figure 1. Schemes of the investigated WT systems with (**a**) induction generator (IG) or permanent-magnet synchronous generator (PMSG) and full power converter, (**b**) electrically excited synchronous generator (EESG) and full power converter, and (**c**) doubly-fed induction generator (DFIG) with partially rated converter.

2.2. Field-Data Analysis

The comprehensive power-converter failure data, which has been provided by the project partners and evaluated at Fraunhofer IWES, is summarized in Table 1. In addition, 10 min-aggregated SCADA data and SCADA status-logs have been available for analysis from more than half of the considered WTs. While the evaluated raw data as well as the exact WT types studied cannot be disclosed for confidentiality reasons, Table 1 characterizes the investigated turbine fleet with respect to the generator-converter concepts, manufacturers, range of rated power and time of commissioning of the WTs.

Table 1. Converter-specific failure dataset compiled and evaluated within the Innovation Cluster.

Number of WTs with a main converter	2734
Converter failure data from years	2003–2017
Total number of evaluated WT operating years	7399
Evaluated dataset covers WTs of the manufacturers	DeWind, Enercon, Fuhrländer, Gamesa, General Electric, Kenersys, Nordex, Senvion, Suzlon, Siemens, Vestas
Rated power of WTs	500–3600 kW
Year of commissioning of the WTs	1997–2015 (unknown for 114 WT)
WTs located on continents	Europe, Asia, North America, South America
Generator-converter concepts of WTs	• Doubly-fed induction generator (DFIG) with partially rated converter • Electrically excited synchronous generator (EESG) with full power converter • Induction generator with full power converter (IG + FPC) • Permanent-magnet synchronous generator (PMSG) with full power converter (only single WTs)

Based on failure descriptions and information on used spare parts from the maintenance records, the power-converter failures have been classified according to the following component categories:

- phase module (including IGBT modules and corresponding driver boards, DC-link capacitors and busbars)
- power-converter control board
- cooling system
- main circuit breaker
- grid-coupling contactor
- other power-converter components (e.g., electrical filter components, fuses, relays, . . .)

The field-data analyses presented in this paper are based on average failure rates. This is a common measure for describing the reliability of a component or system, which is suitable also for cases with lacking information about the age. Note that in the present work, only faults requiring on-site repair and the consumption of spare parts or other material are considered as failures, while issues remedied by means of cleaning or retightening of components or by a remote reset of the turbine are not included in the analysis. The average failure rate of a component is calculated according to the following equation:

$$f = \frac{\sum_{i=1}^{I} N_i}{\sum_{i=1}^{I} X_i \cdot T_i} = \frac{N}{T} \tag{1}$$

Herein, N_i denotes the number of failure events of the component in the time interval i, X_i is the total number of turbines evaluated in this time interval, and T_i describes the duration of the time interval. Accordingly, N denotes the overall number of failure events of the component of interest and T is the total number of evaluated wind-turbine operating years, which must include both the failed and the non-failed turbines.

As introduced in detail in [35], we provide confidence intervals for failure-rate values in order to quantify the uncertainty these are afflicted with. For the given case of time-censored data, the confidence intervals are estimated according to

$$\left[\frac{\chi^2(\frac{\alpha}{2}, 2N)}{2T}, \frac{\chi^2(1-\frac{\alpha}{2}, 2N+2)}{2T}\right] \tag{2}$$

provided in [37]. Herein, $\chi^2(\alpha/2,2N)$ is the $(\alpha/2)$-quantile of the χ^2-distribution with $2N$ degrees of freedom. In the present paper, the average failure rates are presented with the 90% confidence intervals ($\alpha = 0.1$).

In order to characterize the load regime of the analyzed wind turbines, their capacity factor CF is used. It is defined as the mean active power fed to the grid divided by the WT rated power.

$$CF = \frac{P_{mean}}{P_{rated}}, \tag{3}$$

which is equivalent to the ratio of the actual electrical energy output over a certain period of time to the potential energy output over the same period that would result from continuous operation at rated power. The capacity factor is calculated using the 10min-averaged SCADA data of the WTs. Only integer multiples of 1-year-periods are included in the calculation of CF in order to avoid a bias due to seasonal wind-speed variations.

2.3. Post-Mortem Analysis of Returned Power-Converter Components

As part of the Innovation Cluster, the project partners provided failed converter components from in total three different wind-turbine types. These have been investigated at Fraunhofer ISIT and IWES with regard to the damage appearance in order to obtain indications of the failure modes and causes.

After preparatory work including the disassembly, the removal of the silicone gel covering the power semiconductors or the production of metallographic micro-sections, the following laboratory-analytical methods have been applied:

- visual inspection
- optical microscopy
- X-ray transmission
- scanning acoustic microscopy (SAM)
- scanning electron microscopy (SEM)
- diagnostic measurements for defect localization
- manual pull-testing of bond contacts

The post-mortem analyses of in total 18 converter components carried out at Fraunhofer ISIT and IWES using the aforementioned methods are complemented with findings from the damage analysis of a large number of returned converter components, which were shared with the Fraunhofer IWES not only by project partners, but also by converter/module manufacturers outside the Innovation Cluster consortium.

3. Results

3.1. Results of the Field-Data Analysis

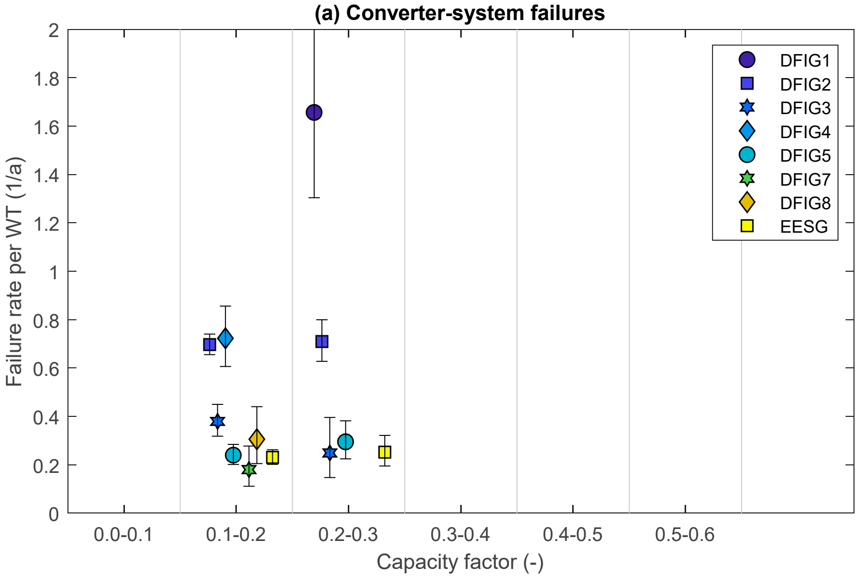
3.1.1. Converter Failure Rates vs. Wind-Turbine Capacity Factors

The field-data compiled and evaluated in the Innovation Cluster covers WTs with different generator-converter concepts, of a multitude of manufacturers and at sites with a variety of wind regimes. The latter has not been taken into consideration in our previous presentations and comparisons of converter failure rates. This raises the question if certain groups of WTs (such as e.g., the EESG-based WTs in our dataset) exhibit particularly low converter failure rates mainly due to the fact that they might rarely be operating at full load. Taking into consideration the different capacity factors of the investigated turbines adds therefore an important piece to the picture.

The following analysis seeks to answer the question if there is a systematic difference in converter failure rates between turbines operating at low capacity factors and such operating at high capacity factors. For this purpose, all WTs with at least one year of SCADA data for calculating the capacity factor are grouped by manufacturer and their average capacity factor (clustered in bins of 10%). Average converter-system and phase-module failure rates are calculated for each of these groups.

Figure 2 presents these failure rates over the capacity-factor ranges for turbines of different generator-converter concepts and manufacturers. Only failure rates calculated based on data from at least 30 WT operating years are included in the diagrams in order to avoid values afflicted with a very large uncertainty.

(a) Converter-system failures



(b) Phase-module failures

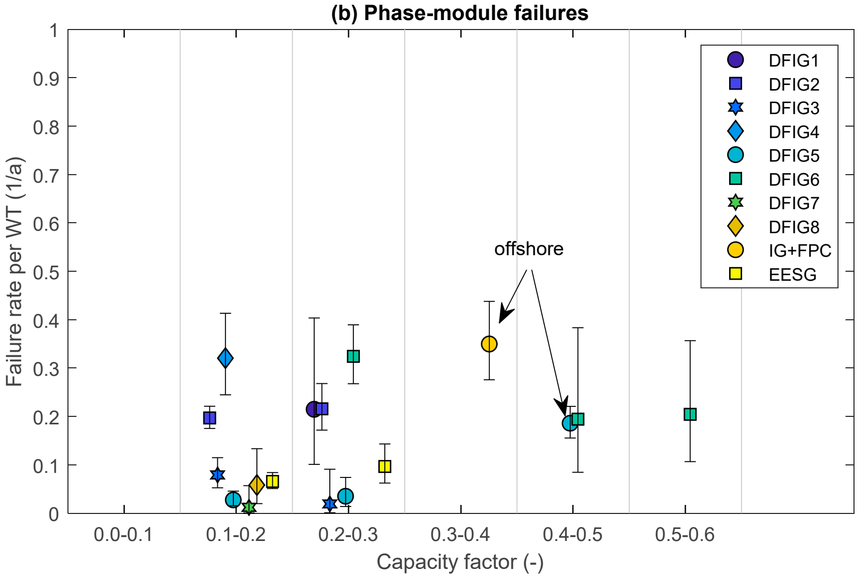


Figure 2. Average failure rates of the overall power-converter system (**a**) and the phase-module components (**b**) over WT capacity factors for turbines of different generator-converter concepts and manufacturers.

As Figure 2 shows, most WTs represented in the dataset operate at capacity factors between 10% and 30%. From WTs operating at higher capacity factors, only phase-module failure data has been available, so only these are found in Figure 2b. The less data a failure-rate value is based on, the larger is the confidence interval, which is directly related to the higher uncertainty.

Major differences with respect to the average failure rates can be observed among the WT groups of different manufacturers, with the overall converter failure rates ranging up to 1.66 a^{-1} per WT and the maximum phase-module failure rates reaching 0.35 a^{-1} per WT. The most relevant finding with respect to the guiding question raised above is that only in single cases (the group of EESG-based WTs and the group of DFIG-based WTs denoted DFIG5), the failure rate increases with the capacity factor. In other cases (namely the WT groups DFIG3 and DFIG6), the WTs operating at higher capacity factors experienced the lower phase-module failure rates.

In an overall view, for the majority of investigated WTs, the failure rates of both the phase modules and the complete converter system show no relevant correlation with the capacity factor and thus with the average electrical load of the WTs. Instead, the results underline that the manufacturer (and with that the WT and converter design) has a much stronger impact on the converter reliability than the generator-converter concept (DFIG, IG + FPC, EESG) or the capacity factor of a WT.

3.1.2. Seasonal Variation of Phase-module Failure Rates

As presented in [35], we observed a pronounced seasonal pattern in the phase-module failures in fleets in India and Scandinavia, with maximum failure rates occurring during periods with high absolute ambient humidity. This has been a strong indication that moisture and/or condensation play an important role in the incidence of converter failures. At the same time, it was surprising to find that at first sight no such pattern could be identified for the WT fleet in Germany. In view of the fact that the evaluated turbine fleets have liquid-cooled converters while air-cooled converters prevail in the German fleet, this observation raises the question if the cooling concept of the converter influences the system's susceptibility to humidity.

In the following, the analysis of the seasonal variation of phase-module failure rates is substantially extended and deepened: While the results presented in [35] have been limited to the monthly phase-module failure rates in India and Scandinavia, the following analysis includes the WT fleet in Germany. Furthermore, the analysis is deepened by differentiating between turbines with liquid-cooled vs. air-cooled converter systems and by taking into consideration the operating point of the WTs preceding the failures where this information is available.

Figure 3 shows the situation in the Indian fleet, which consists solely of onshore turbines with liquid-cooled converters. It displays the average phase-module failure rates along with the monthly average values of wind speed, ambient temperature, relative humidity and dew-point temperature throughout the year. The dew-point temperature, i.e., the temperature below which the airborne water vapor condenses to liquid water, is a function of the absolute humidity and hence determined by the ambient temperature and relative humidity.

The wind-speed information is based on WT SCADA data from the evaluated fleet. The monthly average values of temperature and humidity are derived from climate data from [38] by averaging over the regions of interest as well as over several years. The color scale in the bar chart of Figure 3 indicates in which load range (characterized by the 10min-average value of the WT active power P_{10min} normalized with the rated power P_{rated} of the WT) the turbine operated in the 10min-interval before the failure occurred. Please see [35] for a detailed description on how this value is determined. In case of the areas in grey color, no information about the operating point has been available.

Figure 3 clearly shows the temporal pattern in the phase-module failure behavior and the accumulation of failures during the months with highest absolute humidity in the ambient air. The large portion of failures without operating-point information limits the interpretation of the top diagram in Figure 3, but some indications can nevertheless be obtained: Only a small portion of the failures occurred at full-load operation of the WTs. In none of the cases, for which the operating point could be determined, the failure initiated in an "overload" situation with $P_{10min} > P_{rated}$. Instead, most failures occurred in low part-load operation. In this operating regime, the losses in the converter are low and with these also their heating effect, which promotes high relative humidity and the risk of condensation inside the converter cabinet. It is interesting to note that the occurrence of converter failures is not limited to periods in which the turbines feed active power to the grid, but that these occur also in zero-load situations (with $P_{10min} \leq 0$ kW), e.g., during idling or start of the turbines.

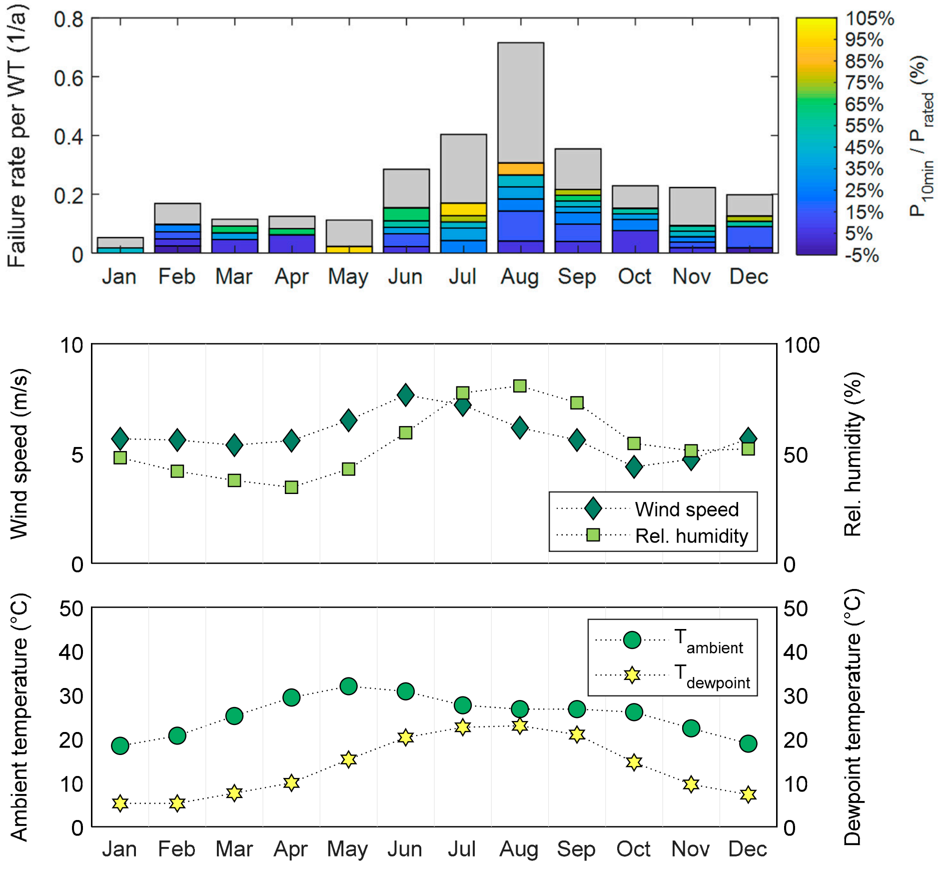


Figure 3. Seasonal variation of phase-module failure rates in WTs with liquid-cooled converters in India (based on data from 590 WT operating years) with corresponding monthly average wind-speed and climate data, including information of the operating point preceding the failures.

In analogy with the previous diagrams, Figure 4 presents the situation observed in the WT fleet in Scandinavia. It consists of WTs located in both onshore and offshore sites. As in the previous case, all considered WTs have liquid-cooled converters. Note that the wind-speed values are based solely on the SCADA data of the offshore WTs. As in the present analysis the focus is on the seasonal variation of the wind speed through the course of the year and not on the exact absolute values of the wind speed, this is considered an acceptable approximation. The monthly average values of temperature and humidity are calculated from climate data by [39,40] (data from [27]).

Figure 4 illustrates again the previously shown accumulation of phase-module failures during the months with highest absolute humidity. However, the evaluation of the operating point preceding failure provides interesting additional information: The portion of phase-module failures occurred during operation close to, at or above rated power is found to be much higher in this fleet. This is not surprising in strong-wind months such as December to January, but comes at first sight unexpected in the low-wind month August. Taking into consideration the strong influence of both ambient temperature and WT active power on the air temperature inside the converter cabinets revealed by field measurements in the Scandinavian fleet, the higher-load failures in August are likely attributable to overheating. Another interesting observation from Figure 4 is the increased occurrence of failures from zero- or low part-load operation during May to October, i.e., during the months with highest absolute ambient humidity or dew-point temperature, respectively.

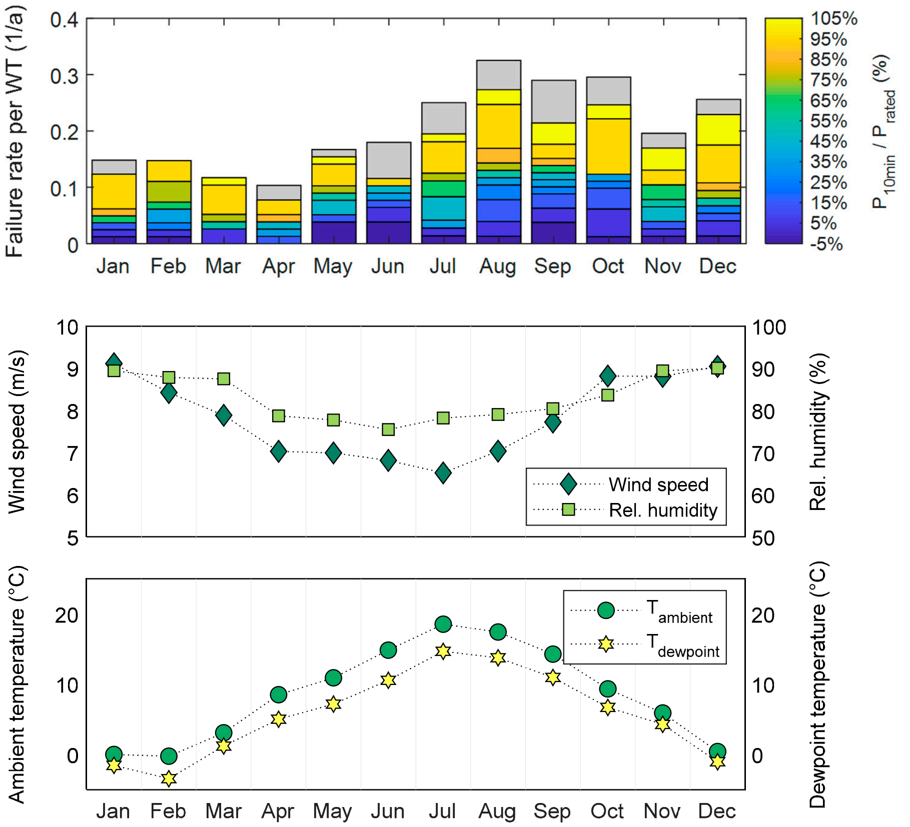


Figure 4. Seasonal variation of phase-module failure rates in WTs with liquid-cooled converters in Scandinavia (based on data from 933 WT operating years) with corresponding monthly average wind-speed and climate data, including information of the operating point preceding the failures.

Finally, Figure 5 presents the corresponding diagrams for the large WT fleet in Germany covered by the Innovation Cluster dataset. All evaluated WTs in Germany are located onshore. In contrast to the Indian and the Scandinavian fleets analyzed above, the German fleet includes both WTs with air-cooled and WTs with liquid-cooled converters. The seasonal variation of the phase-module failure rates is presented separately for these two cases in the upper two diagrams of Figure 5. The wind-speed information is based on WT SCADA data from the evaluated fleet. The climate data is derived from temperature and humidity data obtained from [41] by averaging over different regions in Germany and over several years.

In the interpretation of Figure 5, it should be noted that the number of phase-module failures in WTs with liquid-cooled converter is considerably lower than in the other cases. The scatter in the monthly failure rates, which is a result of the scarce underlying failure data and particularly visible in the large month-to-month variation during January-April, makes it harder to identify any seasonal pattern. In addition, operating-point information is available only for a part of the phase-module failures. Nevertheless, the figure allows the interesting observation that also in the German fleet increased average phase-module failure rates are encountered during June–October, but solely in WTs with liquid-cooled converter. Among the failures with information about the preceding operating point, failures from zero load or low part-load operation are clearly prevailing, especially during summer and autumn, i.e., the months with highest absolute humidity. This is in agreement with the observations in the Indian and Scandinavian fleets with liquid-cooled converters. It is worth recalling in this context that the dew-point temperatures included in Figures 3–5 are monthly average values.

Measurements undertaken inside WT converter cabinets in both Germany and Scandinavia have shown that dew-point temperatures larger than 20 °C occur inside the cabinets, i.e., values lying far above the monthly average values of the dew-point temperature shown in the diagrams above.

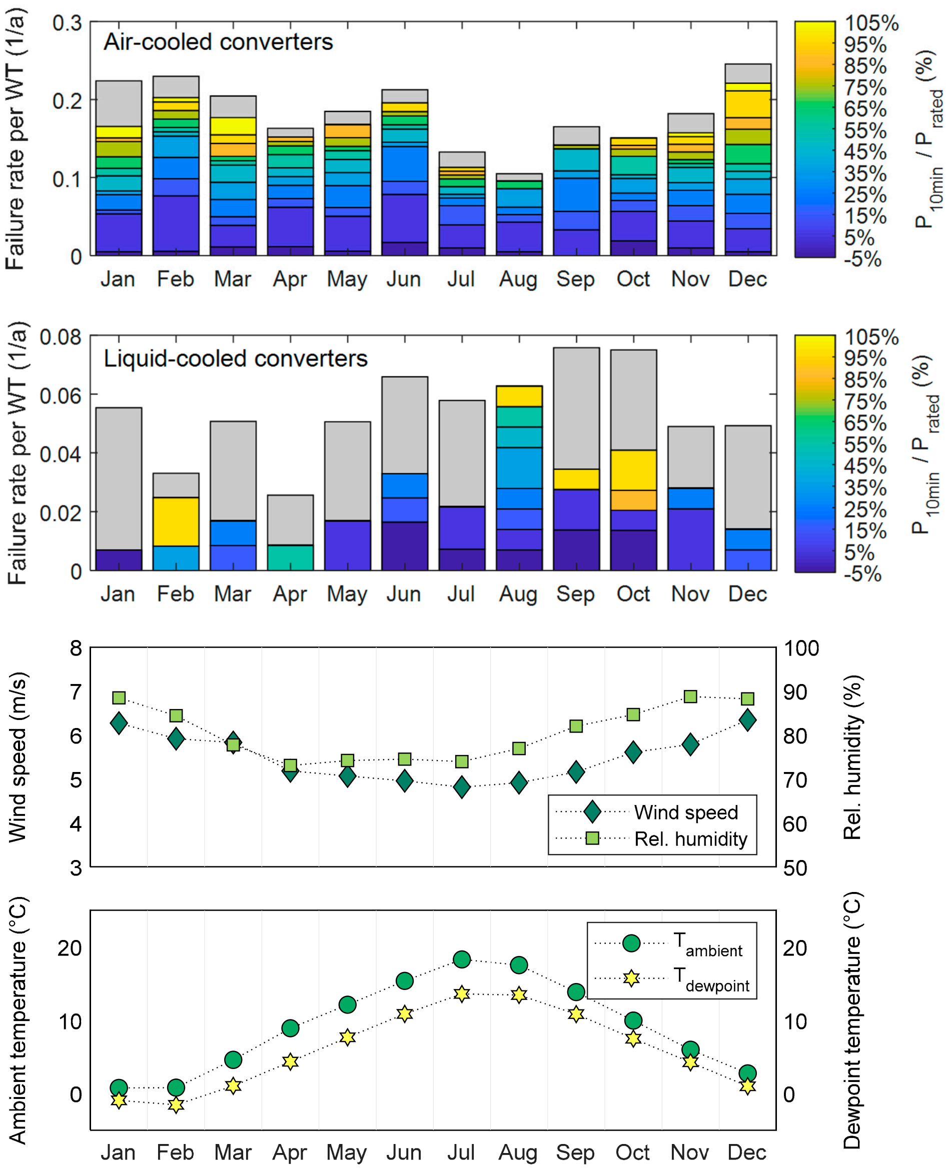


Figure 5. Seasonal variation of phase-module failure rates in WTs with air-cooled (upper diagram) and liquid-cooled (lower diagram) converters in Germany including information of the operating point preceding the failures (based on data from 2352 operating years of WTs with air-cooled converters and from 1604 operating years of WTs with liquid-cooled converters, respectively) with corresponding monthly average wind-speed and climate data.

In contrast to the previous cases, a reversed temporal failure pattern is observed in the German WT fleet with air-cooled converters: There are particularly few phase-module failures during summer and autumn. Instead, increased failure rates are observed during December to March, i.e., during the months with the on average highest wind speeds.

Another example of a pronounced seasonal accumulation of electrical-system failures can be found in the literature: In [42], failure statistics from a large wind farm with 1.5 MW turbines located in the Chinese Jiangsu province are presented, which are based on a total of 254 WT operating years. A comparison of the monthly failure rates reveals a massively increased failure rate in the electrical system during the months July and August. While this is related to high ambient temperatures in the paper, it can as likely be attributed to the by far highest absolute humidity (as visible in dew-point temperature data from this region obtainable e.g., from [38]) being present during these months.

The results presented in this section give further support to the hypothesis that high humidity (i.e., moisture and condensation) has a negative effect on phase-module reliability. Furthermore, in combination with the results presented in [42], they make clear that this effect is encountered in the most different parts and climate zones of the world. An important new finding has evolved from the separate analysis of WTs with liquid-cooled and air-cooled converters located in Germany. The different failure patterns observed in these two fleets suggest that the high susceptibility to humidity is an issue mainly related to WTs with liquid-cooled converters.

3.2. Results of the Post-Mortem Analysis of Defect Components

The project partners of the Innovation Cluster provided failed converter components from wind turbines of three different manufacturers. These have been examined with respect to the damage as well as indications of failure mechanisms and possible causes. In the following sections, the results are presented separately for each of the three WT types.

3.2.1. Analysis of IGBT Modules from a DFIG-based Turbine Type

The most comprehensive post-mortem analysis was performed on liquid-cooled IGBT modules (including driver boards) from a DFIG-based turbine type located in an offshore wind park. Modules of this type are very widely used in wind turbines. Ten of these modules were subjected to a detailed damage analysis at Fraunhofer ISIT. Among the ten investigated modules were five modules from the generator side and five modules from the grid side of the converter, all without externally visible signs of destruction. The modules were manufactured in the years 2006–2010 and failed during 2014–2015 so that it can be taken for granted that all of them experienced several years of operation in the field.

The most important result of this investigation is that in eight of the ten modules the failure could be attributed to low-side driver-board damage, which in turn was caused by the same defective transformers serving both for power supply and signal transmission. Figure 6a shows the position of these transformers on an X-ray transmission image of the driver board. Figure 6b provides an infrared image of the reactivated driver board, in which the right transformer is found to be defective. The X-ray CT images (reconstructed materials volume images by computer tomography) in Figure 6c,d clearly show the winding interruption causing the failure. In places like this, it came to the dissolution of the copper wire. Owing to voids in the insulating layer of the winding, as can be seen e.g., in the metallographic cross section in Figure 6f, copper in ionic form has diffused into the surrounding potting material until it has come to a complete interruption of the copper wire. The underlying mechanism is electrochemical migration under long-term exposure to moisture and an electric field as well as in the presence of chlorine. The speed of this migration process is also influenced by the temperature.

Another important result of the analysis is that no signs of bond-wire detachment or chip-solder damage were detected in the IGBT modules investigated. The bond contacts (Figure 7b) analyzed using micrographs and the solder layers analyzed by means of both scanning acoustic microscopy and micrographs (Figure 7c) were all intact and free of any signs of degradation. In this regard, the results confirm the post-mortem investigations on IGBT modules from the same wind farm carried out in the context of the pre-project CONFAIL [27,28], which also revealed no signs of classical fatigue damage.

The good condition of the contact points of bond wires and IGBTs or diodes has also been confirmed in another investigation. In this case, further five IGBT modules from the generator-side converter of the above-named DFIG-based wind turbines have been tested for bond-wire detachment. For this purpose, as shown in Figure 8a, each individual bond wire in these modules has been manually tensioned using a pointed tool until it was ruptured or unilaterally detached. If bond wires are ruptured without detaching from the chip, as shown in Figure 8b,c, this indicates a firm adhesion and thus a good condition of the bond contacts.

In one of the five manually tested modules (built in 2010), a single IGBT chip decomposed under the tensile stress of the pull test. In another of the five modules (built in 2006), the detachment of bond-wires not from the chip but from the adjacent track on the ceramic Direct Copper Bonding (DCB) substrate was observed. This concerned bond wires to a total of 11 IGBT chips, all of them current-loaded wires, i.e., no bond wires leading to the gate of the IGBTs. In none of the pull-tested modules, however, the bond wires lifted off the IGBTs or diodes, demonstrating the integrity of the contacts of bond wires and semiconductor chips.

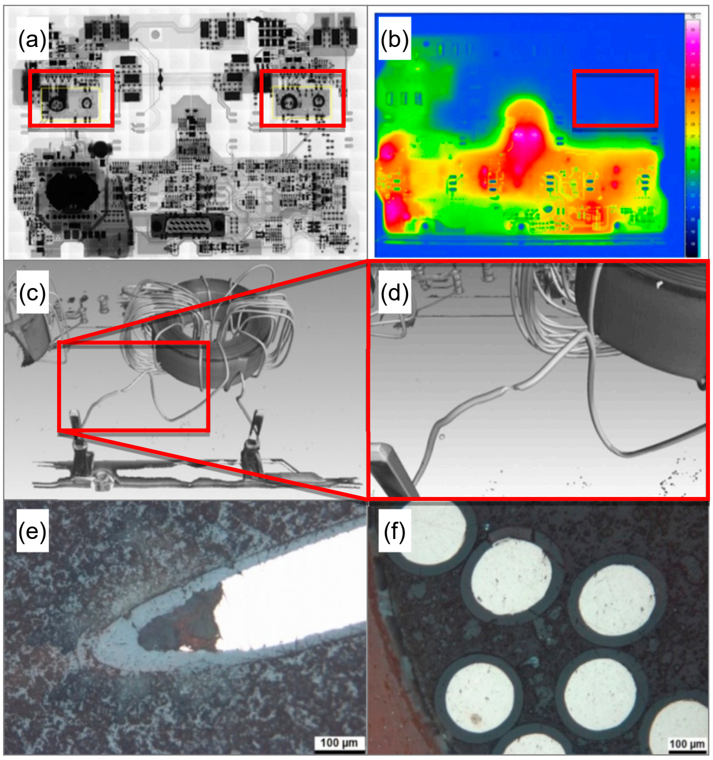


Figure 6. In eight out of ten analyzed modules, the failure could be attributed to transformers on the driver board, in which initial voids in the winding insulation have resulted in an interruption of the conducting wire. (**a**) X-ray transmission image and (**b**) infrared image of the driver board; (**c**,**d**) X-ray CT images of the interrupted winding; (**e**,**f**) metallographic cross sections of the winding.

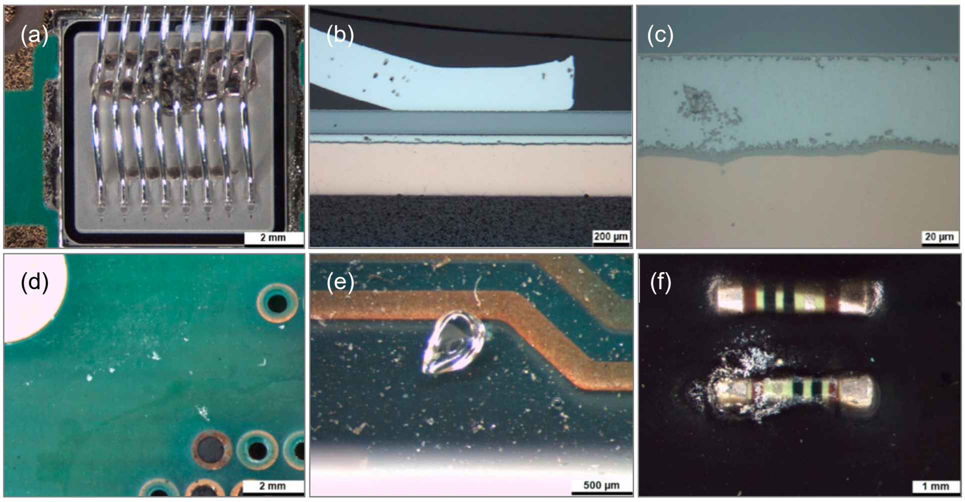


Figure 7. (**a**) Damaged diode in the power section of an IGBT module; (**b**) bond contact and (**c**) chip-solder layer without signs of fatigue damage; (**d**,**e**) contamination and (**f**) corrosion on driver boards of the investigated modules.

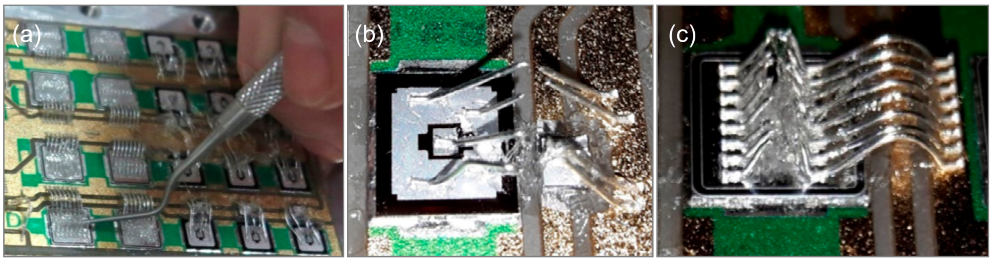


Figure 8. (**a**) Manual pull test of bond contacts; (**b**) IGBT and (**c**) diode after the pull test without bond-wire detachment.

3.2.2. Analysis of an IGBT Module from a Second DFIG-based Turbine Type

From another, again DFIG-based WT type of a different manufacturer, only a single IGBT module with complementary circuitry and driver board was available for the post-mortem analysis. This has undergone a detailed damage analysis at Fraunhofer ISIT. Information on the operating age of the module could not be obtained. Figure 9 shows the severely damaged IGBT module in the as-received state (left), after removing the top-mounted circuit board (center) and after chemical removal of the silicone gel (right).

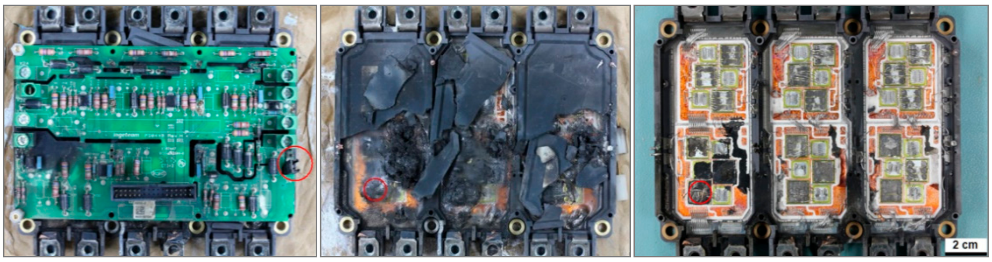


Figure 9. Destroyed IGBT module before (**left**) and after (**center**) removal of the circuit board as well as after removal of the silicone gel (**right**).

The power module shows traces of an explosive pressure build-up in its power section. This has destroyed the module covers and broken the adjacent circuit board. Escaping metal vapors or soot have led to flashovers at the supply-voltage terminals of the power module. All IGBTs and four of the freewheeling diodes have a short circuit (gate-collector-emitter or anode-cathode). The emitter-bond connections as well as the metallizations of the IGBTs and a number of copper surfaces passing through the module are destroyed due to overcurrent. The damage appearance indicates that the low-side IGBT, marked on the right in Figure 9, was destroyed first.

Overall, the damage is most likely the result of a short circuit in the power module, i.e., of a simultaneous on-state of low and high-side IGBTs. The trigger could have been an over-voltage from outside the module or the failure of the marked IGBT with the strongest destruction. A detected low-side defect on the driver board is, if the components originate from the same failure event, to be classified as consequential damage due to an over-voltage ingress from the power module.

In spite of the limited conclusiveness of the results obtained in this analysis of a single power module, the case is included here due to the fact that it is a typical example of the frequently encountered severely destructed power modules and illustrates the procedure and challenges related to the post-mortem analysis in such cases.

3.2.3. Analysis of a Generator-side Converter from a Turbine with PMSG

From a third type of wind turbine, an onshore plant with PMSG and full power converter, a generator-side converter was available for analysis. This had been manufactured in 2009 and gathered a maximum of 2.5 years in operation in the field. For damage analysis, it was disassembled and examined at Fraunhofer IWES.

Figure 10a shows the liquid-cooled partial converter consisting of three slide-in stacks with traces of soot on the left-hand side. In this case, signs of damage could be found neither on the IGBT modules, their driver boards nor the snubber or DC-link capacitors. Instead, the failure could be attributed to a short circuit at the DC-link busbar in the area of the screw connections, see Figure 10b. The created soot has penetrated far into the stack and in particular the DC busbar, as shown in Figure 10c.

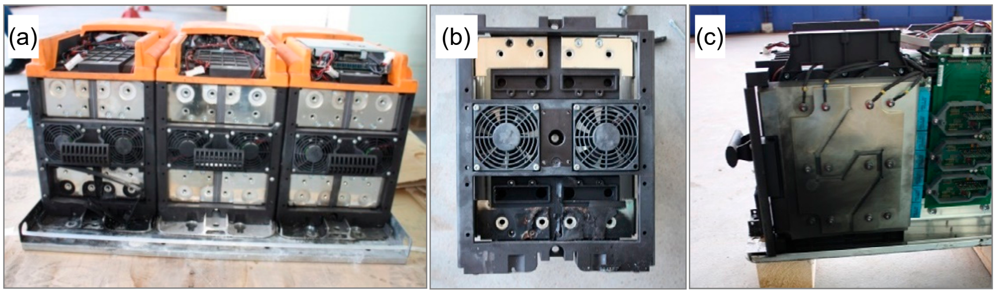


Figure 10. (**a**) Defective generator-side converter, (**b**) slide-in stack with short-circuit damage in the area of the connection to the DC-link busbar and (**c**) soot penetrated into the stack.

With a DC-side short circuit, this case provides another example of an issue repeatedly encountered in the field, as also the compilation of analysis results and experiences of power-converter and module manufacturers in the following section will show.

3.3. Results from Damage Analyses of Power-Converter and Power-Module Manufacturers

The post-mortem analysis of field returns is a proven method for determining the causes of failure. In view of the relatively few defect components investigated within the present project, however, the conclusiveness of the above described findings would have been limited. It is therefore very valuable that comprehensive results and insights from the damage analysis of an at least five-digit number of returned converter components from the wind application have been shared with Fraunhofer IWES by various converter and module manufacturers (not being limited to the members of the project consortium). The analyzed components include in particular a large number of IGBT modules with their driver boards. The most important findings, many of which are in good agreement across the companies involved, are summarized below.

Particularly noteworthy is the confirmation of the field-data and post-mortem analyses regarding the lack of fatigue failures known from other power-electronics applications: Several parties—each on the basis of post-mortem analysis of large component numbers—have stated that no "end-of-life" indications in the form of bond-wire detachment or chip-solder damage have been detected at all in field returns from wind parks.

Overall, the failures are distributed approximately equally between the IGBT module and the driver board, with driver-board failure predominating in case of single manufacturers. The failure of DC-link components plays a minor but still non-negligible role. With one-fifth to one-third, a significant part of the failures—especially of IGBT modules with explosion damage—remains unexplained. This is mainly due to the fact that the cause or origin of the failure can often no longer be determined in largely destructed modules. The actual causes of these failures, which in practice are typically categorized as electrical overstress (EOS) failure, remain in the dark.

On the part of the driver boards, the failures are spread over all types of components, especially diodes, fuses, resistors, capacitors, inductive wound components and integrated circuits (ICs). Weak batches with increased failure rates, the causes of which are attributable to processes at the component manufacturers and often can only be identified with considerable time delay, play an important role here. Also the transformer failures on the driver board of a certain type of module, which have been found during the analyses in the Innovation Cluster (see Section 3.2.1) and confirmed by the companies' post-mortem analysis results, fall into this category. Although this weak point was eliminated in the next version of the power-module type, it still leads to failures of wind-turbine converters due to its widespread use in the field.

In addition to the failures that can be attributed to driver board defects, there are also those with a cause related to the driver board, but with the destruction of power semiconductors as a consequence. This includes the coupling of radiated or conducted interference into the driver board, which have their origin e.g., in brush arcing on damaged slip rings of DFIGs, in flashovers on degraded contacts in snubber capacitors, or sometimes even in the sole proximity to the switching power semiconductors. The exposure to high interference levels, which can even exceed the maximum level applied during EMC tests, can lead to the generation of additional switching events or increased switching frequencies via the gate signal. In the less critical case, these cause increased switching losses and thus a higher temperature of the IGBTs; in the more critical case, a short circuit can be the result of simultaneous switching of top and bottom IGBTs. A comparable effect is attributed to the occurrence of reflection effects in optical interfaces.

Another case in which a faulty driver can cause IGBT failure is that the gate voltage provided by the driver board is too low to switch the IGBTs to the fully conductive state. This was stated to be observable especially under the influence of moisture. From the loss-minimal switching operation, the power semiconductor device in this way gets in a quasi-linear operation, in which it is conducting but afflicted with an increased (gate-voltage dependent) resistance. The high power loss created in this state leads to the thermal destruction of the IGBT within a very short time.

Also in numerous other cases, the cause of power-semiconductor failures lies outside the chip or packaging level. In particular, DC-side short circuits are to be mentioned in this context. These occur e.g., due to insulation degradation (of the insulation foils between the current terminals of the power modules as well as in the area of DC busbars or laminates) under the influence of moisture or condensation or due to a failure of snubber or DC-link capacitors. The frequency of DC-link capacitor failures, which were only rarely found in the Innovation Cluster dataset, is apparently very different depending on the manufacturer. In the case of a DC-side short circuit and the associated voltage drop in the DC link, the freewheeling diodes in the connected IGBT modules form a bridge rectifier, through which high currents flow into the short circuit. These lead either to a complete destruction of the diodes or to an initial damage resulting in reduced strength. The same effect can be caused by short-circuit failures of adjacent power modules connected to the same DC link as they cause a break-down of the DC-side voltage. This often leads to "partner failures" or consequential damage in neighboring IGBT modules.

Snubber capacitors can also be the cause of over-voltage failures of power semiconductors. A significantly more common failure mode than short-circuit failure is the detachment of the film-roll contact inside the film capacitors, which are typically used as snubber capacitors. Consequently, the capacitor is no longer low-inductance and with that loses its capability of limiting high-frequency over-voltages, which may cause over-voltage failures of the semiconductor devices.

In addition to the failure causes described above, water damage (for example due to coolant leakage) and mechanical damage (e.g., due to incorrect mounting of modules) were detected. However, their portion has been stated to be not higher than approx. 10%.

Finally, the statement of a power-module manufacturer is remarkable according to which about one-fifth of the returned modules carry insects or heavy pollution. This confirms observations made in the pre-project CONFAIL [27,28] and the need for improved protection of the converters from dust and the intrusion of insects. The involved manufacturers agreed on the statement that moisture is a factor with a massive impact on the reliability of power converters in wind turbines.

4. Discussion

In the following, we summarize and discuss the findings in light of the guiding overall question, which are the main causes of converter failures or failure-relevant influencing factors in the wind application. For this purpose, we take into account the following:

- the research carried out within the Innovation Cluster,
- input from and discussion with various companies, including power-module and converter manufacturers, wind-turbine operators and maintenance service providers, as well as
- information from conferences and literature.

Overall, it can be stated that the failure causes and mechanisms leading to the frequent failure of wind-turbine converters and, in particular, their core components (phase-module category) are complex and very diverse. There is no single main cause underlying the high failure rates observed across turbine fleets of different manufacturers and types. However, a number of relevant influencing factors have been identified, which are presented below.

4.1. Factors with a Relevant Influence on Converter Failure

4.1.1. Humidity and Condensation

There are numerous indications that the presence of high humidity and the occurrence of condensation in converters have a considerable influence on the incidence of failures. The occurrence of condensation in wind-turbine converters is clearly proven by reports and pictures of entirely "wet" converters in the field. Furthermore, it is not uncommon that returned components bear traces of contact with condensed water. In addition, the humidity and temperature field-measurements carried out in various wind-turbine converter cabinets in Germany and Scandinavia as part of the Innovation Cluster have confirmed the occurrence of dew-point temperatures larger than 20 °C. In combination with the fact that, according to the manufacturer, an increased risk of local condensation is to be expected already several Kelvin above the dew point, also these measurements confirm that converters in a wide variety of wind-turbine types and at different sites repeatedly experience high humidity levels and most likely also condensation.

Nevertheless, it is common practice in the wind application to use converter components that are not specified for environments with condensation. In view of this, the strong indications for moisture or condensation-induced failures identified in the Innovation Cluster are not surprising: These include the accumulation of phase-module failures in liquid-cooled converters during and shortly after seasons with high absolute humidity and dew-point temperature, respectively, which has been observed in WT fleets India, Scandinavia and Germany, cf. Section 3.1.2. Also the occurrence of converter failures in zero-load situations (see Section 3.1.2 and [35]), i.e., during periods in which no active power is fed to the grid, is likely to be attributable to moisture or condensation. The observation of such zero-load failures is in line with numerous reports from the field of converter failures that occurred when turbines were restarted after longer periods of downtime, especially in Germany. Such failures during turbine restart are known to have occurred repeatedly even in WTs with existing converter-preheating routines. This could be partly attributed to unrecognized defects in the heating system, but has likely been related to an insufficient effectiveness of the preheating devices or routines otherwise.

Among the already known mechanisms of moisture-induced failures is the obvious short-circuit risk resulting from contact with condensed water (becoming conductive due to dissolved ions). In addition, the effects of moisture and condensed water include:

- insulation degradation in the DC-link busbars/laminates, but above all of the DC terminals and busbars of power modules, which leads to short-circuit failure and with that often to a damage of modules connected to the same DC link
- a reduction of the blocking capability of the power semiconductors due to electrochemical migration and aluminum corrosion, which was demonstrated by [43] under the combined influence of 85% relative humidity, a temperature of 85 °C and voltages above 65% of the nominal blocking voltage, and for which the occurrence even at lower humidity, temperature and voltage-stress levels is subject of further investigations

- the impairment of moisture-susceptible driver components by corrosion or electrochemical migration, which can, besides a full loss of function of the driver board, through an insufficient gate voltage lead to thermal damage of IGBTs (see Section 3.3).

The fact that moisture can cause the impairment of insulation materials and insulation distances matches well with the beneficial effect of lower DC-link voltage levels revealed in [36]. Also this supports the hypothesis that moisture and condensation play a central role for the occurrence of converter failures.

4.1.2. Overheating

Another important factor in the context of converter failure is a lack of cooling and the resulting overheating of converter components. In air-cooled converters, this is caused by defective or ineffective fans. In the case of liquid-cooled converters, the causes often lie in clogged coolant pipes or air bubbles in the cooling system (e.g., confirmed by [44]). In addition to effects on the power electronics, specifically the overheating of the converter's control electronics (cf., for example, [45]) and the destruction of the DC-busbar insulation by high temperatures in the converter cabinet are known issues.

A factor with direct influence on the temperature of IGBTs and diodes is the effectiveness of the thermal paste between the DCB substrate, a possible baseplate and the heat sink. At the current state of knowledge, it cannot be stated clearly whether converter failures in contemporary turbines to a relevant extent have their cause in the thermal paste. While in a wind farm installed in 1997 with a very old turbine generation, the outpouring of thermal paste accompanied by the ingress of air was identified to have caused an overheating of the power electronics, this is not known with certainty from any other turbine type. The impression of an aged thermal paste given in [27,28] is contrasted by measurements of the power-module manufacturer, which instead of degradation showed an improvement in the thermal conduction properties over time. There is no doubt, however, that a homogeneous application of the thermal paste in the assembly of power modules is crucial to ensure an effective dissipation of heat from the semiconductors.

4.1.3. Weak Components

It is to be regarded as certain that components with insufficient strength, e.g., due to manufacturing defects, are among the main causes of the frequent driver-board failures. This is supported by the post-mortem analysis results presented in Sections 3.2.1 and 3.3 of this paper, but also e.g., by the damage analysis of more than 100 failed stacks from wind-turbine converters presented in [23].

In the field of power semiconductors, the analysis of a module manufacturer identified "weak chips" to be the cause of only a small portion of the investigated failures. However, it should be kept in mind that there is a considerable amount of unexplained IGBT-module failures, which could also be related to weak single components.

Tests during the manufacturing process and the partially applied burn-in testing of power modules serve to recognize and reject chips or modules without a sufficient strength, so that their installation in the field can be avoided. Nevertheless, numerous zero-time failures (i.e., failures during commissioning of the wind turbine) and a clear infant-mortality behavior of phase modules have been revealed in the field-data analysis carried out within the Innovation Cluster [33,36]. This suggests that in addition to problems related to transportation or installation that might explain an instantaneous failure, there is also an insufficient strength of individual components, e.g., due to variations in the production process. Such insufficient strength can also exist in the form of lacking robustness against environmental influences such as moisture. If the components used are not specified for the real conditions experienced in the field (such as the occurrence of condensation), there is de facto an "improper use", which is among the typical causes of infant-mortality failures named in [46].

4.1.4. Asymmetric Current Sharing and Uncontrolled Switching of IGBTs

The parallel connection of power semiconductors is generally afflicted with the risk of an uneven distribution of the current and thus of an overload or an accelerated lifetime consumption of the most heavily loaded devices. Asymmetries can occur on the one hand between power modules, in particular when modules of different forward-voltage (VF) classes are combined. Although this is in contrast to the usage instructions, this case has repeatedly been encountered in the field. In addition, contact resistances play an important role in the development of current asymmetries. These are particularly influenced by the screw connections (i.e., their tightening torque) in the power path.

However, current asymmetries can also occur within power modules between parallel-connected power semiconductors. As explained, for example in [47], even a small parasitic inductance in the emitter or source line that is different in the parallel current paths causes a current asymmetry in parallel voltage-controlled power semiconductors. Likewise, a parasitic inductance in the gate-driver circuit is problematic, resulting in a lack of control over the gate voltage [48]. This can result in differences in the current load of parallel-connected IGBTs of up to a factor of two to three [49]. According to the experience of a converter manufacturer, there are also in the wind application significant (design-dependent) differences in the failure rates of IGBT modules with very symmetrical or asymmetrical internal current sharing.

Finally, electromagnetic interference coupling into the driver circuit of IGBTs, but also reflections in optical interfaces, as explained in Section 3.3, can cause uncontrolled additional switching of the power semiconductors, with undesirable effects on the converter reliability.

4.1.5. Contamination

Another factor that is most likely having a relevant negative effect on converter reliability is contamination. In the wind application, contamination of the following types is known to occur in power converters:

- with coal dust (from generator brushes, especially in the absence of an extraction system),
- with dust from the environment (e.g., from agriculture, ore dust from mining),
- with salt (at offshore and nearshore locations),
- with and through insects.

The observation that the heavy contamination of converters in wind turbines is a widespread problem is not only visible in the maintenance reports evaluated in the Innovation Cluster. It is also particularly evident in the information provided by a module manufacturer based on the comprehensive analysis of returned components (see Section 3.3). From this it can be concluded that the converter cabinets often do not sufficiently protect the converter components against contamination. Despite formal compliance with protection classes (typically IP54), the protective function of the cabinets is often not given in practice, e.g., if there are large openings in cable feedthroughs, if filter pads are missing or cabinet doors are not completely closed. Particularly in combination with moisture, contamination has the effect to bridge or reduce clearances and creepage distances and can in this way cause malfunction or flash-over/short circuit failure.

4.1.6. Human Error and Maintenance Practice

A relevant cause for the occurrence of converter failures in wind turbines are human errors during installation, commissioning or maintenance work. Known typical cases from the wind application, in which human error led to converter failure are, e.g.,:

- the leakage of coolant onto converter components leading to immediate short-circuit failure or time-delayed corrosion of the tracks and components of circuit boards in the converter [50],
- incorrectly wired converter heaters in systems without temperature feedback, which prevented converter preheating and in this way led to condensation failure during cold start-up,

- wrong valve positions in the converter cooling circuit, resulting in a permanent "overcooling" with subsequent failure due to condensation [44],
- short-circuit failure due to tools or screws remained in the converter after maintenance as well as due to insufficiently fastened cables, that subsequently loosened owing to vibration,
- too high or too low tightening torque for screw connections, e.g., at the power terminals of IGBT modules; the former case is a afflicted with enhanced mechanical stress inside the module, the latter case with the risk of hot spots and asymmetric load distribution due to the resulting high contact resistance.

Likewise, the maintenance practice has a significant influence on converter reliability. If only defective converter modules are replaced after a failure, adjacent modules with an existing but not obvious or measurable damage remain in the field. The same problem arises when used modules with a hidden pre-damage are re-used as spare parts. In both cases, there is a risk of an early secondary failure.

4.2. Unlikely Causes of Converter Failure

The results of the Innovation Cluster work have not only provided indications what factors do influence or very likely affect the incidence of converter failures in wind turbines. They have also revealed factors and mechanisms that, at least in an overall view, do not play a relevant role in the converter failures observed during the past years. These are discussed in the following subsections.

4.2.1. Thermocycling-Induced Fatigue at Chip/Packaging Level

The first and foremost mechanism to name in this context is the thermocycling-induced fatigue of bond wires, bond-wire contacts and solder layers in power modules observed in other power-electronics applications. In the scientific literature, this failure mechanism is widely postulated to be also the prevailing mechanism leading to failure of WT converters.

However, the results of the Innovation Cluster clearly refute that this failure mechanism plays any significant role in the field failures of wind turbine converters today. For example, converters in DFIG systems that are exposed to particularly severe thermal cycles on the generator side do not generally show a lower converter reliability than WTs with other generator-converter concepts; rather, their phase-module failure rates determined in the Innovation Cluster are significantly lower than those of WTs with asynchronous generators and full power converters [35]. Nor is there a general predominance of failures of the generator-side converter part in DFIG systems, which would be expected in the case of fatigue-dominated failure behavior [35]. While these findings might still be explained with a particularly strong design (with respect to power-cycling life) of the generator-side converter in DFIGs, further evidence results from the failure behavior of the phase-module components determined in the Weibull analysis presented in [33,36]. Instead of a wear-out failure behavior with an increasing failure rate, which would be expected in case of degradation or fatigue-related failures, the converters of all investigated WT types showed a clear infant-mortality behavior. Particularly important in this context is also the finding, that IGBT modules returned from the wind application showed no signs of bond-wire detachment from chips or of chip delamination (see Section 3.2.1, Section 3.3 and previous damage analyses described in [28]).

Thus, as a central result of the failure-cause analysis in the Innovation Cluster, it can be stated that the fatigue caused by thermal cycles is not among the relevant life-limiting mechanisms in wind-turbine converters today. Rather, the IGBT modules fail due to other factors before fatigue effects lead to any relevant damage.

4.2.2. Transients during Connection to the Grid

Another potentially critical factor investigated within the Innovation Cluster are electrical transients occurring during turbine start-up in the moment of grid connection, e.g., resulting from imperfect synchronization with the grid. If these transients had a major effect on the incidence of failure, phase-module failures would have to be observed especially on WTs with frequent start-stop cycles. This was investigated for WT fleets of five different manufacturers, as presented in [34]. In all cases, turbines with higher numbers of start-stop cycles per year did not experience phase-module failures more frequently than WTs with less start-stop cycles. In view of this result, it is unlikely that electrical transients occurring during the grid connection of wind turbines play an important role in the context of converter failure.

4.2.3. Vibration

Vibrations can lead to loosening of plug and screw connections, to fretting corrosion and to fatigue effects due to cyclic mechanical load and are thus as well among the potential failure causes of WT converters. In the case of a single WT type with the converter located in the nacelle, vibration was in fact reported as the most likely cause of converter failures. However, taking into account the entire diverse fleet analyzed in the Innovation Cluster, the picture is different. According to the results presented in [36], there are no indications that a converter position inside the nacelle is disadvantageous compared with a position in the tower base. It is therefore most unlikely that vibration is among the main causes of converter failure in wind turbines.

4.2.4. Cosmic Radiation

Power-semiconductor components can basically be destroyed by cosmic rays (i.e., the neutron radiation these cause on the surface of the earth). The radiation intensity depends on solar activity and varies cyclically with cycle times of approximately 11 years [51]. Cosmic radiation is strongest in the area of the magnetic poles of the earth and weakest at the equator. In addition, its intensity increases with the altitude above sea level.

On the basis of the field data evaluated in the Innovation Cluster, it was investigated whether a temporal correlation between the fluctuation of the neutron radiation flux and the failure rates of the WT converters or phase modules could be found [34]. Owing to their greatest proximity to the magnetic north pole and their therefore comparatively strong exposure to cosmic radiation, the analysis was focused on wind farms in Scandinavia.

The results provide no indication that cosmic radiation is a significant cause of the evaluated converter failures. Rather, a temporal variation of the phase-module failure rate is observed, especially in Scandinavian wind farms, which speaks against this hypothesis. In addition, theoretical failure-rate estimations for three types of wind turbines have confirmed that cosmic radiation could explain only a negligible fraction of the converter failures in the Innovation Cluster dataset. However, in view of the significant difference in cosmic-radiation sensitivity of IGBTs and diodes of different manufacturers and types, a general conclusion cannot be made. Despite the results obtained from the field data evaluated in the present work, it cannot be ruled out that in certain WTs (in particular at high altitudes, in multi-MW systems with full converters and thus overall large chip area or in converters with high voltage stress on the semiconductor switches), cosmic radiation is or could become a relevant cause of converter failure.

5. Conclusions

5.1. Summary and Main Conclusions of the Present Work

The present paper summarizes and concludes several years of research carried out in a consortium of three research institutes and 16 companies. With the objective to shed light on the previously largely unknown causes and mechanisms of the frequent power-converter failures in wind turbines, field data from a large and diverse worldwide WT fleet covering almost 7400 years of WT operation has been compiled and analyzed. For the same purpose, field-measurement campaigns have been carried out on selected turbines and damage-analysis results from a large amount of returned power-converter components have been evaluated.

In the investigated fleet of more than 2700 onshore and offshore turbines distributed over four different continents, converter-system failures occurred on average at a rate of 0.48 a^{-1} per turbine. With a mean failure rate of 0.16 a^{-1} failures per WT, the largest contributor to this are the core components of the power converters denoted phase-module components: the power-semiconductor modules with their gate-driver boards, the DC-link capacitors and busbars. In view of the fact that this component category forms also the main repair-cost driver, a particular focus has been set on the investigation of phase-module failures.

With regard to the causes and mechanisms leading to the frequent failure of power converters in wind turbines, the described research has shown that these are complex and very diverse. A single main cause of failure that would be valid across the WTs of different types and manufacturers cannot be recognized. However, the insights gained in the Innovation Cluster have made it possible to identify a number of relevant influencing factors and gain important hints towards the failure causes and mechanisms. Likewise, several hypotheses concerning formerly suspected failure causes could— at least for the investigated, mostly widely applied WT types—be refuted based on the results. Table 2 classifies the considered potential influencing factors with respect to their identified relevance for converter failures in wind turbines.

Table 2. Relevance of the investigated potential influencing factors for power-converter failures in wind turbines according to results of the Innovation Cluster.

Investigated Factor	**Converter Component**	**Relevance**	
		High	**Low**
Contamination	All	X	
Cosmic radiation	Power modules		X
Current asymmetries, uncontrolled IGBT switching	Power modules	X	
Human errors	All	X	
Moisture and condensation	All	X	
Overheating	All	X	
Thermal-cycling induced fatigue on chip/packaging level	Power modules		X
Transients during grid coupling	Power modules		X
Vibration	All		X
Weak single components	Driver boards, power modules	X	

A particularly important result is that the thermal-cycling induced fatigue of bond-wire contacts and chip solder, which has been widely postulated as main failure cause of power-converter unreliability in wind turbines in the scientific literature, do not play any significant role in the frequent converter failures in this application. After the relevance of these extensively researched mechanisms had been questioned in [27,28] for the first time on the basis of a study limited to only two WT types, the results of the comprehensive field data analysis within the Innovation Cluster as well as the damage analyses of returned components have clearly confirmed that these "classical" failure mechanisms are not limiting the converter life in today's turbines. On the contrary, failure occurs due to other factors and mechanisms long before a fatigue-related end of life of the power-converter is reached. This shows that today's converter design, which is in the first place focused on power-cycling capability, is effective and successful with respect to fatigue effects but lacking strength against other stressors occurring in the wind application.

According to the results of the Innovation Cluster, the factors moisture and condensation have a particularly pronounced effect on converter reliability. Their relevance is not limited to individual turbine types or sites, but has been observed for a variety of WTs with liquid-cooled converter and different climate zones.

An influencing factor requiring further investigation is the electrical loading of the turbines. Previous analyses of the authors [35] indicated that operation at high electrical loads (i.e., with an active power close to, at or above the rated power of the WT) are a trigger for converter failure. The present paper has investigated the relationship between the capacity factor, which characterizes the average electrical load of a turbine, and the power-converter failure rate in turbines of different generator-converter concepts and manufacturers. While the observed failure rates differ largely among the WT groups, no relevant correlation with the capacity factor has been found, indicating that in the majority of considered WT types, turbines operating at higher average loads are not generally affected by converter failures more often than WTs with lower utilized capacity. To better understand the role of the electrical loading in the context of converter failure, the investigation of strong wind gusts and short exceedances of the WT rated power is of particular interest.

5.2. Future Work—Recommendations and Outlook

In view of the still high power-converter failure rates in wind turbines and the massive economic impact these have particularly in offshore wind parks, where the limited accessibility for repairs and the involved logistics drive up the direct and indirect costs of failures, the full clarification of the factors and mechanisms leading to these failures and the development of effective remedial measures should be given top priority in future research. In order to direct the research to the practically relevant questions, an application-specific and field-experience based approach is deemed to be vital. New designs or packaging technologies aiming at a further increased power-cycling capability are not expected to effectively improve the situation in the wind application as long as the failures occurring there are not caused by fatigue effects. The same applies for advanced control techniques intended to reduce the thermal cycling. However, once the issues causing today's early failures of converters in wind turbines are fully understood and remedied, it is expected that thermal-cycling induced fatigue will become the life-limiting factor also in practice so that converters in wind turbines will in fact reach their design life. This makes clear that cutting down power-cycling strength in the design for the sake of cost reduction would be a short-sighted measure that cannot be recommended.

The comprehensive evaluation of field data and converter-failure related experience within the Innovation Cluster has provided important indications about practically relevant failure causes and influencing factors in the field. In spite of the large amount of data compiled and evaluated in this project, however, certain technologies (such as PMSG-based turbines with fully rated power converter, IGBT- or IGCT-based medium-voltage converters, large turbines with rated capacities above 3.6 MW) have not at all or not in a sufficient amount been covered by the database to allow their analysis. Another limitation is that a verification of the derived hypotheses and an in-depth understanding of certain failure mechanisms cannot be achieved on the basis of field data alone. Therefore, the subsequent work initiated at Fraunhofer IWES in collaboration with several project partners follows a complementary bottom-up/top-down approach: On the one hand, it seeks to extend the field-data analysis to the above-named technologies and additional offshore fleets and includes comprehensive measurement campaigns on the spectrum of real loads and environmental stressors occurring in the wind application. On the other hand, it covers laboratory investigations with a particular focus on moisture- and condensation-induced effects and accelerated testing on both converter-system and component level under combined electrical and environmental loads.

5.3. Recommendations for Documentation of Failure Events

The field data collected and evaluated in the Innovation Cluster is very diverse in format, structure, level of detail and nomenclature. Despite the availability of standardized designation systems such as the Reference Designation System for Power Plants (RDS-PP) [52], this diversity is still characteristic for field data from the wind application. The consequence is a high effort required for data processing (import, conversion into a suitable uniform file format, differentiation between failure events and other entries, failure categorization, etc.) before an evaluation by means of mathematical methods is possible. Advancing to a standardized, automated recording of failure and operating data is therefore considered an important step to be able to utilize field data more efficiently in the future, in particular also for root-cause analysis.

In addition, there is great potential for improvement in the documentation about failure events and the damaged components. The post-mortem analysis of returned components is particularly valuable if the following information is available for every damaged component under investigation:

- wind-turbine ID, type and location
- component position within the converter (e.g., grid side or generator side, phase)
- timestamp of the failure event
- wind speed and turbine power fed to the grid at the time of failure, possibly related conditions such as grid faults or thunderstorms preceding the failure event
- operating time until failure (for re-used components: including previous operating times in other turbines)
- further components damaged during the same failure event

By consequently documenting such "component-tracking" information and providing it for analysis together with the damaged components, wind-turbine operators and maintenance-service providers can make an important contribution to the improvement of converter reliability in wind turbines in the future.

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