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Title: Towards reliable power converters for wind turbines: Field-data based identification of weak points and cost drivers

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Introduction

Numerous studies have identified the power converter as a frequent source of failure in variable-speed wind turbines (cf. [1]-[4]). This is in line with the experiences made by wind-turbine operators worldwide, who state the limited converter reliability to be a considerable driver of maintenance cost and downtime. However, the development of remedial measures is hindered by the fact that little is known about the causes and mechanisms underlying the converter failures.

Comprehensive research has been carried out on the thermal- and power-cycling induced failure mechanisms known to be life-limiting in IGBT-based converters in other applications (see e.g. [5]-[12]): the lift-off or fatigue-damage of the bond wires, and the fatigue of die-attach or baseplate solder joints. However, the results of a first study on the root causes of converter failure [13] suggest that those mechanisms play a minor role in wind turbines and emphasise the importance of a field-experience based approach to the problem.

On this background, a research cluster for enhancing power-converter reliability in wind turbines has been started in Germany [14]. In this cluster, numerous companies join forces with Fraunhofer institutes and academia in order to move from suspected failure causes to clear evidence and, in the next step, to effective countermeasures. The project consortium includes wind turbine and converter manufacturers, converter-component suppliers, wind-turbine operators, maintenance service providers, an insurance and companies specialised in measuring and monitoring technology. Besides an extensive root-cause analysis, which is based on comprehensive field-data analysis, directed measurement campaigns and post-mortem analysis of failed converter components, the research subjects of the cluster include the condition monitoring of converters and fault-tolerant generator-converter systems, with the overall objective to enhance the reliability and maximise the availability of power converters in wind turbines.

This presentation / paper presents results of the statistical field-data analysis carried out within the research cluster described above.

Approach

The objective of the following analysis is to identify the predominantly failing components within the power-converter system as well as the main cost drivers, including both the repair cost and the revenue losses resulting from converter unavailability. In this way, the work aims to provide a basis for directing subsequent research to the most critical components of the converter system.

For that purpose, the analysis makes use of a data set of maintenance and operating data that includes repair-cost and downtime information for each failure event. The results presented in the following are based on a fleet of 103 wind turbines located in 11 onshore wind parks in Germany, spanning in total 11141 months of wind-turbine operation during 2003-2014. All turbines are equipped with doubly-fed induction generators (DFIG) and partially-rated IGBT-based low-voltage converters (two-level back-to-back voltage source converters). The fleet consists of turbines of three manufacturers. The commissioning dates of the turbines range from 1999 to 2007, and the turbines have got rated capacities in the range of 1500-2300kW.

In contrast to the preceding study described in [13], the complete converter system is taken into consideration. Based on failure descriptions and information on used spare parts contained in the maintenance records, the failures of the converter are classified according to the following categories:

- phase module (including IGBT modules and corresponding driver boards, DC-link capacitors, busbars)
- converter control board
- crowbar
- cooling system
- semiconductor fuse
- main circuit breaker
- grid-coupling contactor
- other

Note that within the scope of this analysis, only faults requiring on-site repair and the consumption of material / spare parts are considered as failures (i.e. faults remedied e.g. by a remote reset or by cleaning components are not included). Because phase modules are typically replaced as complete units, the data does not allow a further localisation of the defect inside the phase modules.

The average failure rate of each converter-component category is calculated according to

$$f = \frac{\sum_{i=1}^{I} N_i}{\sum_{i=1}^{I} X_i \cdot T_i} \qquad (1)$$

with N_i denoting the number of failures of the component in the time interval i, X_i describing the number of wind turbines reporting to the database in time interval i, and T_i being the duration of the time interval i. All failure rates are given in failures per wind turbine and year. Note that calendar time is used for the calculation, i.e. turbine downtime is not excluded.

Correspondingly, the average repair cost c_{rep} and average downtime t_{down} arising from each component category per turbine and year are calculated using

$$c_{rep} = \frac{\sum_{i=1}^{I} C_{rep,i}}{\sum_{i=1}^{I} X_i \cdot T_i} \qquad (2)$$

and

$$t_{down} = \frac{\sum_{i=1}^{I} t_{down,i}}{\sum_{i=1}^{I} X_i \cdot T_i}. \qquad (3)$$

Results and discussion

Figure 1 shows the average failure rates in the different converter-component categories as well as the overall rate of converter failure events. With a mean number of 0.21 failures per turbine and year, the phase modules have the highest failure rate among the considered component categories. On average, there were 0.51 converter failure events per year on every turbine.

Due to the fact that in case of approx. 1/5 of the failure events, components from several categories were replaced to restore the functionality, the sum of the component failure rates is higher than the overall converter failure rate.

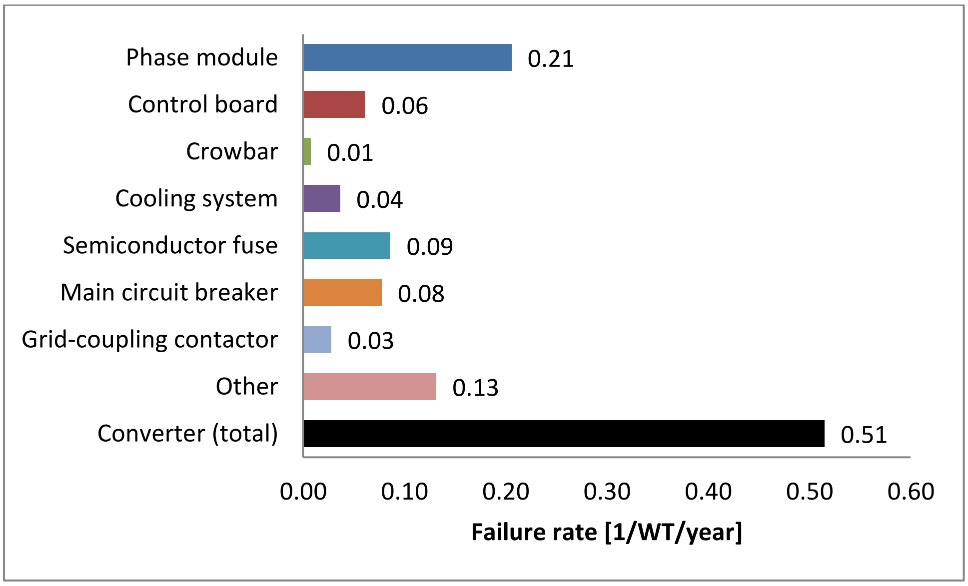

Fig. 1: Average failure rates of the converter components

Figure 2 illustrates the percentage distribution of failed components over the different categories. Besides the phase modules, the semiconductor fuses connected to these, the main circuit breaker and the converter control board constitute the largest portions.

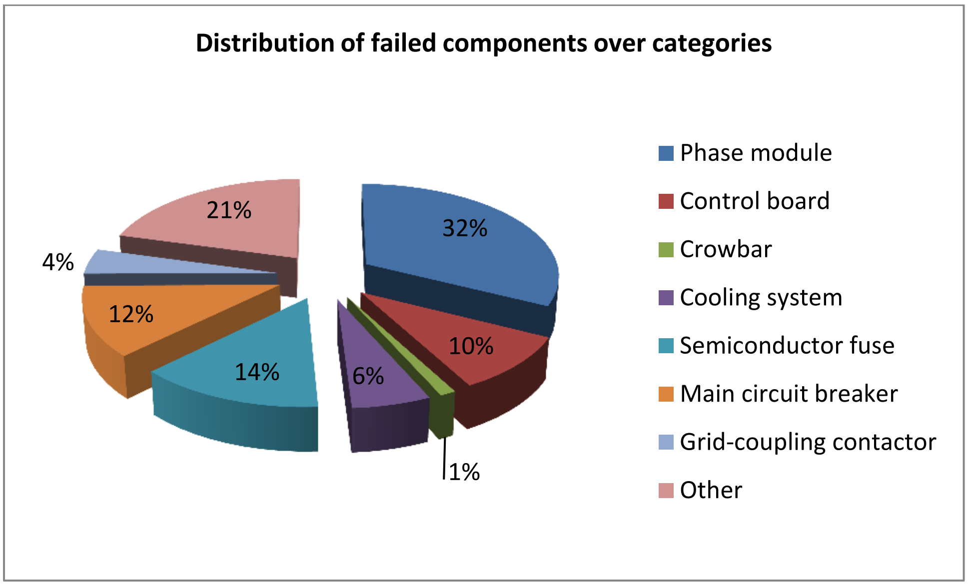

Fig. 2: Distribution of converter failures over component categories

Figure 3 shows the distribution of repair cost over the component categories. Note that some uncertainty arises from the abovementioned failure of several components in one incident, as in those cases the repair cost is a bulk sum and the exact shares for repair of the different defect components are unknown. In these cases, the repair cost corresponding to the respective failure events is estimated based on the following assumptions:

If multiple component categories are affected in the failure event, but the phase module remained intact, the repair cost is equally distributed over the concerned categories. In case there are multiple affected categories and these include a phase module, the cost is divided at the ratio of 90:10 (or 80:10:10 in case of three affected categories), as the cost for replacing a phase module by far exceeds the cost of replacing other components.

A similar procedure is used to estimate the downtime caused by failures in each category (see the downtime distribution in Figure 4). However, due to the fact that no systematic difference in the downtimes related to phase-module and other converter failures could be observed in the data, the downtime is assigned to the affected component categories in equal portions for all multiple-category failures.

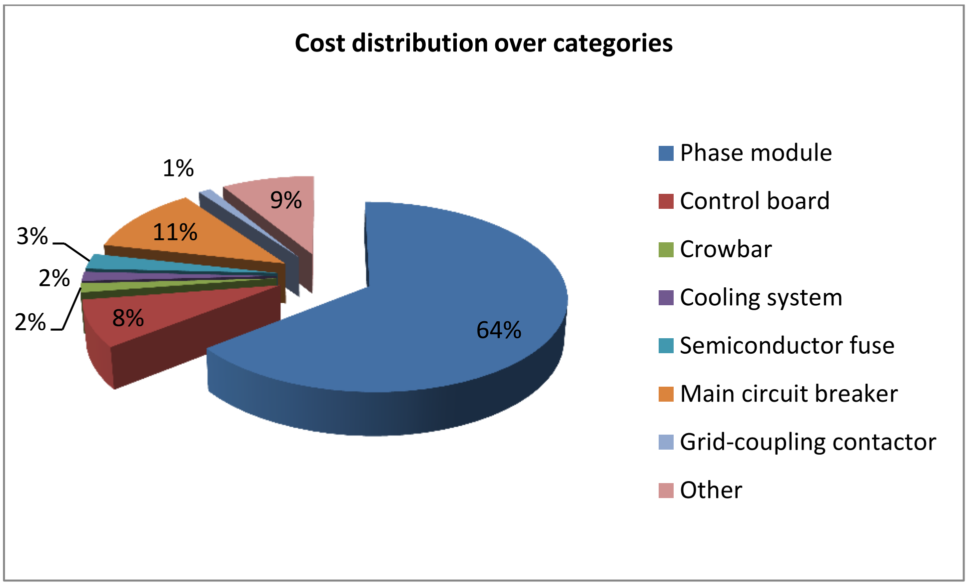

Fig. 3: Distribution of converter repair cost over component categories

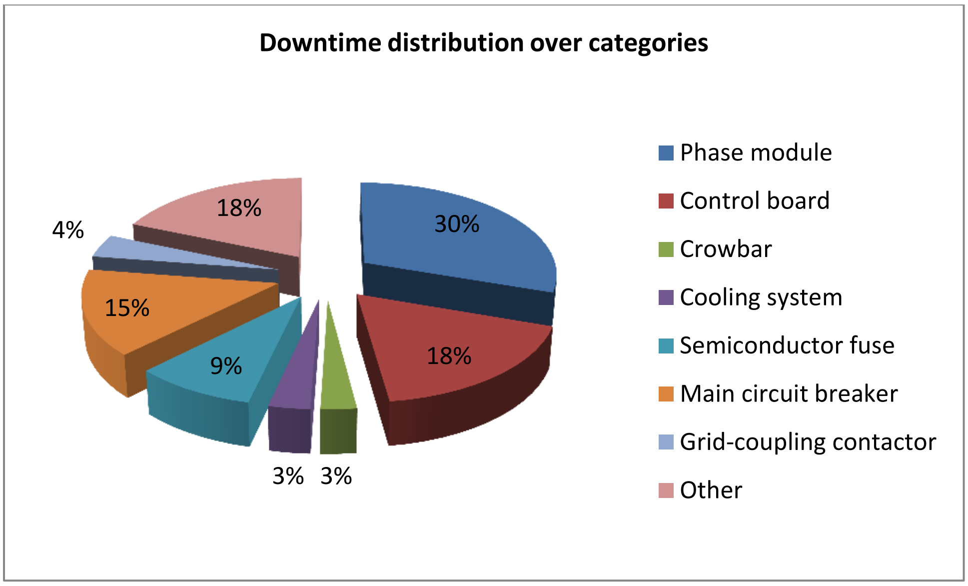

Fig. 4: Distribution of converter-related downtime over component categories

In order to assess the economic impact of the downtime, the average revenue loss resulting from converter unavailability is estimated. With an average rated capacity of P_r = 1.66 MW per turbine and assuming a sales price of electricity of C_{el} = 85 €/MWh as well as a capacity factor of cf = 0.18, the mean converter-related downtime of 23.1h translates into an annual revenue loss of approx. 600€ per wind turbine and year according to

$$c_{rev.loss} = P_r \cdot cf \cdot t_{down} \cdot C_{el} \,. \tag{4}$$

This can be compared with the average repair cost due to converter failure per turbine and year of approx. 3600€ calculated using Eq.(2) , see Table 1.

Table 1: Economic impact of converter failure through downtime and repair cost

Average downtime (t_{down})	23.1 h/turb./a
Associated revenue loss ($c_{rev.loss}$)	588 €/turb./a
Repair cost (c_{rep})	3596 €/turb./a

Conclusions

Within the main converter systems of the analysed fleet of wind turbines with DFIG and partially-rated converter, the phase modules stand out with a high failure rate. With 0.21 failures per turbine and year, this is in a similar order of magnitude as the value of 0.12-0.15 failures/WT/a obtained for IGBT-module failures in the converters of DFIG turbines in [13].

Particularly outstanding, however, is the economic impact of phase-module failures due to their high repair cost: Approx. 64% of the annual cost for converter repair is caused by failures of the phase modules. The economic impact of the repair cost is found to be considerably higher than that resulting from the turbine downtime.

In summary, the phase modules can be concluded to be both the weak point in terms of reliability and the main cost driver in the considered converter systems. This suggests that future research should focus particularly on clarifying the root causes and developing reliability-enhancing solutions for this component.

Learning objectives

The main objectives of this talk / paper are:

- stressing the importance of an field-experience based approach for enhancing the reliability of power converters in wind turbines
- stepping from subsystem-level reliability analysis to component-level analysis
- identifying the weak point and main cost drivers within the converter system, in order to focus subsequent research accordingly

Abbreviations

DFIG Doubly-fed induction generator

IGBT Insulated gate bipolar transistor

WT Wind turbine

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