The hidden challenge of wind energy: ensuring reliable power converters

Words: Dr Fraser Anderson, Dr Katharina Fischer and Professor Andreas Reuter of Fraunhofer Institute for Wind Energy Systems IWES

Wind energy has become a cornerstone of the global renewables transition. However, a persistent issue threatens efficiency and cost-effectiveness: the reliability of power converters. These crucial components, responsible for transforming the variable electrical output of wind turbines into grid-compatible electricity, are among the most failure-prone parts of modern turbines, resulting in considerable repair costs and revenue losses.

A comprehensive study[1] analyzing over 22,000 operational years of wind turbines worldwide has revealed significant insights into failure trends, influencing factors, and potential solutions to enhance the longevity of power converters.

Understanding failures

Power converters in wind turbines ensure that the electricity generated matches the grid's requirements. They adjust voltage and frequency, enabling smooth integration into power grids. However, frequent failures of these components lead to costly downtime, maintenance challenges, and reduced energy output.

In collaboration with partners covering the entire wind energy value chain, Fraunhofer IWES has therefore built up an extensive wind turbine power converter failure database, including information about the corresponding environmental conditions.

Our study analyzed field data from over 10,000 wind turbines of different converter designs across diverse geographical locations, both onshore and offshore. Postmortem analyses of field-returned components complement the analysis[2].

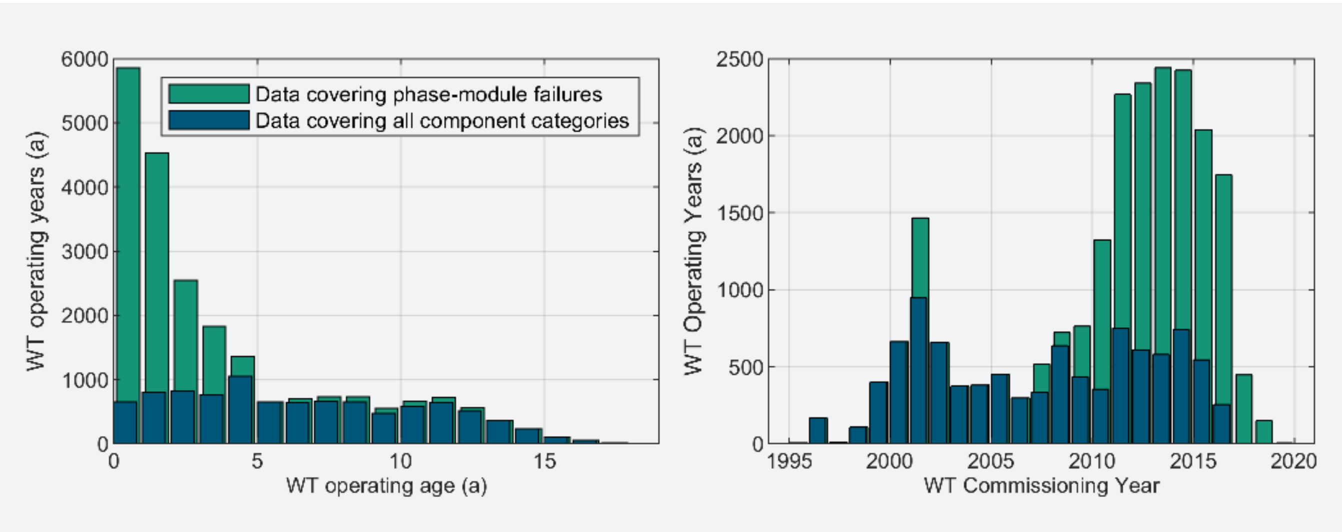

Figure 1: Field data underlying the converter reliability study; (a) amount of data from wind turbines of different operating age and (b) from turbines with different commissioning years. Green bars show data covering failures of phase-module components (IGBT modules and corresponding driver boards, DC-link capacitors and busbars), blue bars indicate data covering failures of all converter component categories[1]

The findings highlight design related and environmental factors that impact the reliability of power converter components.

Key findings on failure trends

One of the most striking revelations is the failure pattern of power converters through time. Unlike many industrial components that follow a classic 'bathtub curve', with high initial failure rates, a long period of stability, and then increasing failure rates due to aging, and unlike mature electronics with a mostly constant and finally increasing failure rate, wind turbine power converters transition directly from early failure behavior to degradation failures.

This means that turbines often experience converter failures early in their lifecycle, followed by a continuous decline in reliability rather than a period of stability.

Another key finding is the difference between air-cooled and liquid-cooled converters. Liquid-cooled systems, which are now standard in modern turbines, exhibit a lower overall failure rate than older air-cooled systems. However, their cooling systems themselves are more prone to failure, highlighting a trade-off in reliability.

The role of environmental and design factors

The study identified several environmental and design factors as key drivers of power converter failure. Humidity and temperature were found to be significant contributors. Higher absolute humidity significantly raises failure rates. A doubling of the average humidity level resulted in an 80% increase in failure intensity of the phase module components, and a 120% increase in failure rates for converter control hardware.

High ambient temperatures also reduce reliability, particularly affecting the phase module components and the converters' cooling system.

Altitude also plays a role, with wind turbines installed at higher altitudes experiencing more frequent cooling system failures. This is likely due to the lower air densities at higher elevations, which affect cooling efficiency. Grid frequency was another factor, with turbines operating in 60 Hz grids tending to experience higher converter failure rates compared to those in 50 Hz grids. This may be due to design optimizations that are more suitable for 50 Hz systems.

The location of the converter in the turbine itself is another key factor. Systems with converters installed in the nacelle tend to experience more failures of main circuit breakers and contactors than those with converters positioned at the tower base. Additionally, the rated power of the converter affects failure rates.

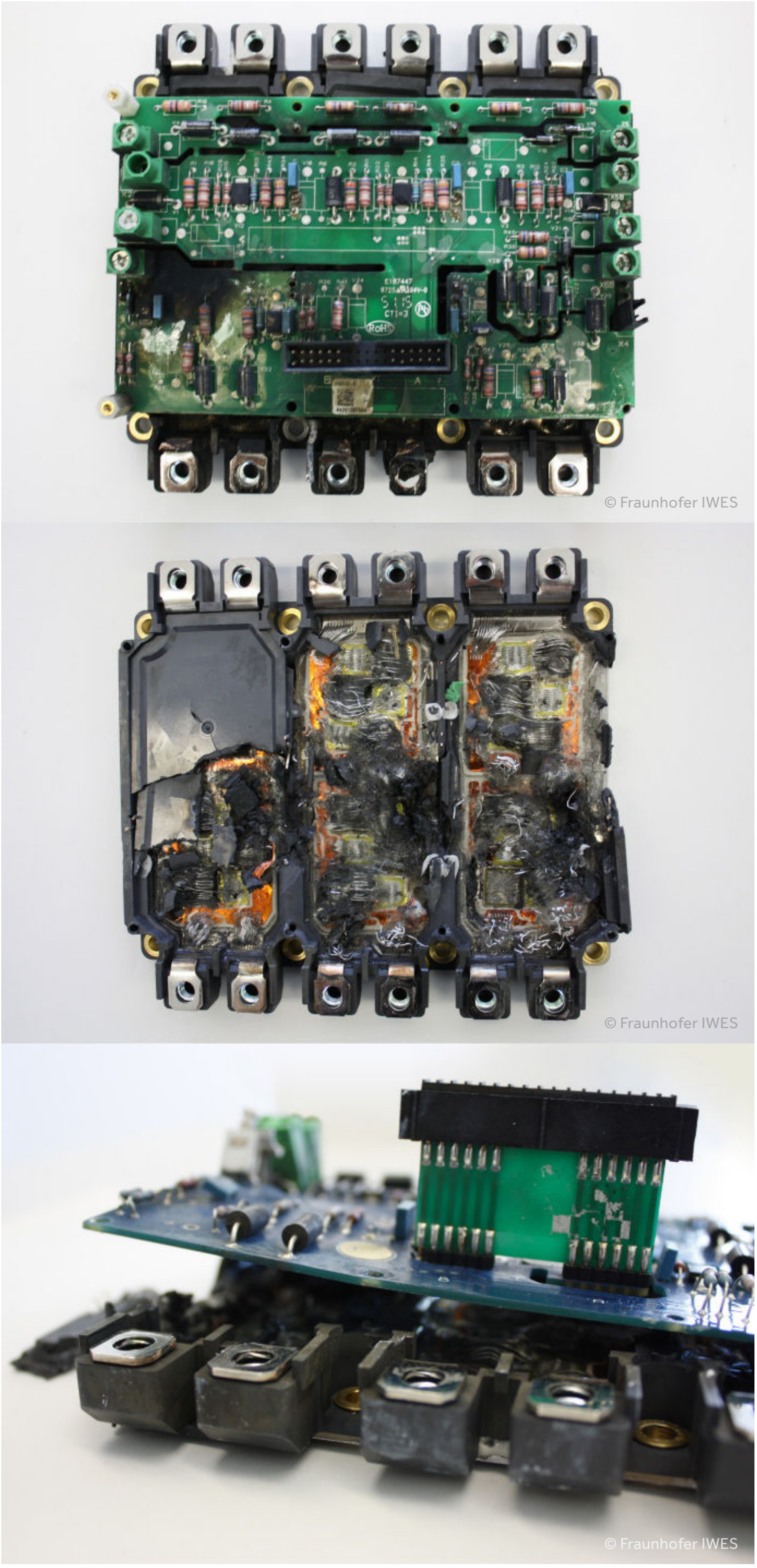

Figure 2: Field-returned IGBT modules from wind turbine converters with typical damages

Wind energy remains one of the most promising solutions for a sustainable future.

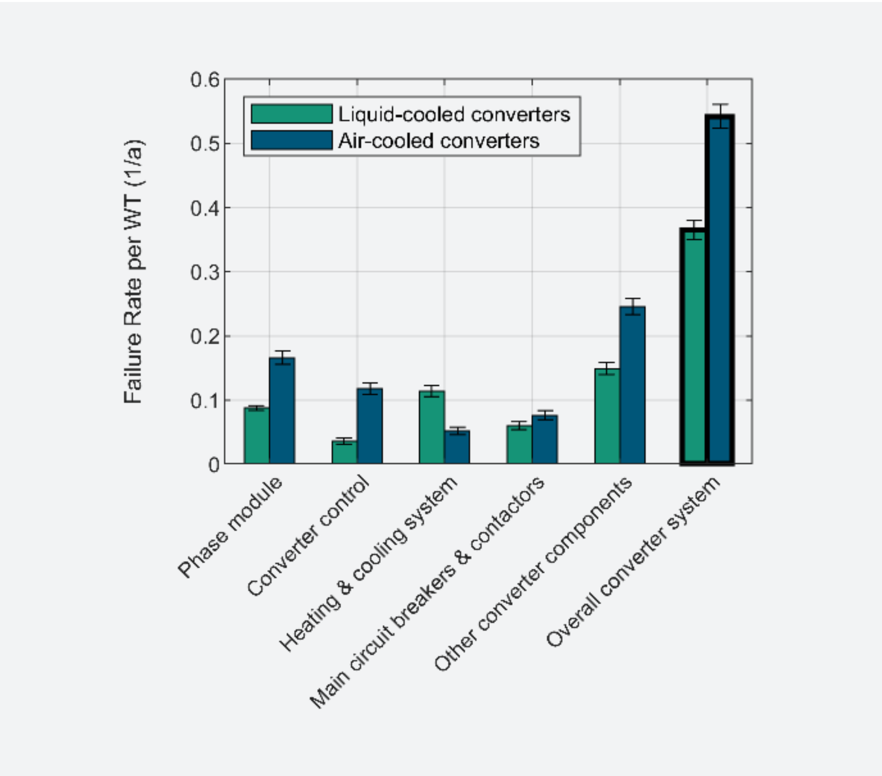

Figure 3: Average failure rates for the overall converter system and its components, comparing liquid-cooled and air-cooled converters[1]

Larger power converters typically show higher failure rates for their core components, likely due to the higher number of paralleled components and larger semiconductor areas. This poses particular challenges for offshore turbines, which generally have higher power ratings and are usually equipped with fully rated converters.

Furthermore, the study emphasized the importance of design and manufacturing quality. Different manufacturers produce IGBT modules with varying levels of reliability. Manufacturer choice can significantly influence failure rates, making component selection a critical aspect of turbine design.

Technological trends and future improvements

The study indicates that power converter reliability has improved over the years, with newer turbine generations showing better performance. However, the persistent challenges of frequent early failures and climate related damages call for further innovation in robust design, manufacturing processes, testing and maintenance strategies.

Key areas for improvement include the development of enhanced cooling systems: while liquid cooling has been shown to improve overall reliability, better system designs and maintenance strategies are necessary to reduce the failure rates of the cooling systems themselves. Converters also require more robust and climate resistant designs to withstand high humidity and temperature conditions, ensuring their longevity and performance.

Application specific testing is another critical factor. Current test procedures need to be extended from component level to converter system level. These tests should incorporate field-typical combined electrical and climatic loads to better simulate real-world conditions.

Advanced condition monitoring systems also hold significant potential for improvement, as they can help detect early signs of failure, enabling condition based maintenance and minimizing unexpected downtime.

Lastly, adopting modular designs for easier replacement of components would streamline repairs, reduce downtime, and lower maintenance costs, contributing to more efficient and cost-effective turbine operation.

Conclusion: the path to improved reliability

Wind energy remains one of the most promising solutions for a sustainable future. However, improving the reliability of power converters is essential for maximizing energy yield and reducing maintenance costs. By addressing converters' design flaws and susceptibility to environmental conditions, the wind industry can enhance performance, ensuring a more stable and cost-effective renewable energy source for years to come.

As turbine sizes continue to grow and installations expand into harsher climates, continued research and innovation in power converter technology and its reliability qualification will play a crucial role in the future of wind energy.

A close collaboration between wind farm operators, turbine manufacturers, component suppliers and researchers, as in the ongoing ReCoWind2 project[3] led by Fraunhofer IWES, remains essential to overcoming the present challenges of power converter reliability.

www.iwes.fraunhofer.de/en.html

References

[1] F. Anderson, K. Pelka, J. Walgern, T. Lichtenstein and K. Fischer, 'Trends and Influencing Factors in Power-Converter Reliability of Wind Turbines: A Deepened Analysis,' in IEEE Transactions on Power Electronics 2025, https://doi.org/10.1109/TPEL.2025.3530163

[2] K. Fischer, K. Pelka, S. Puls, M.-H. Poech, A. Mertens, A. Bartschat, B. Tegtmeier, C. Broer, J. Wenske, 'Exploring the Causes of Power-Converter Failure in Wind Turbines based on Comprehensive Field-Data and Damage Analysis', Energies 2019, 12, 593, https://doi.org/10.3390/en12040593

[3] ReCoWind2: Reliability and Monitoring of Power Converters in Wind Turbines, https://www.iwes.fraunhofer.de/en/research-projects/current-projects/recowind2.html