
Wind Turbine Generator Systems Failures - Probabilities and Mechanisms

WP 1 : Deliverable 1.1

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The objective of the project Design for Reliable Power Performance (D4REL) is: to improve the reliability and controllability of offshore wind turbines to reduce the operational uncertainty of future offshore wind power plants. Despite research in failures in electrical systems of wind turbines, they remain problematic and fail often.

Work Package 1 of the project, in particular, deals with improving the availability of the electrical generator systems by using modular conversion system concepts that are fault tolerant, re-configurable and self-healing.

To address failures and improve reliability, it is important to develop an understanding of failures and failure mechanisms occurring in the generator system. This report addresses this issue by looking at failures in wind turbine generators and their power electronic converters, their probabilities and their failure mechanisms. It represents the D4REL deliverable 1.1 - 'Report describing the different failures with their probability'.

Section 1 of this document looks at the failures occurring in generator systems and their reported probabilities. Section 2 describes the major failure mechanisms of Power Electronic Converters and Section 3 describes the major failure mechanisms of the Generator. Section 4 looks at the effect of wind speeds and weather on failure rates. Finally, Section 5 draws some conclusions on the study.

1 FAILURES IN GENERATOR SYSTEMS

The reliability of wind turbines has improved over time. However, turbines still see failure rates of more than one failure per turbine per year [1]. The drivetrain of the turbine is a major contributor to failure rates with the power electronic converter, the generator and the gearbox account for about 0.2, 0.1 and 0.1 failures per turbine per year respectively [2].

A number of studies have been carried out on failure rates of wind turbine components, however, there is little data in the public sphere about failures at a sub-component level. *Lyding et al.* [3] have studied failure rates of power electronic converters at a sub-component level with data from the WMEP Database. It is found that about half of all the faults in the power electronic converters are due to faults in semiconductors. Figure 1.1 shows the distribution of failures amongst the sub-components.

An industry based survey by *Yang et al.* [4] gave similar results with maximum respondents selecting semiconductor power devices as the most fragile component in converters.

Alewine et al. have looked at failures occurring in Wind Turbine generators [5]. They studied over 1200 generators from a wide variety of manufacturers, Figure 1.2 gives the distribution of faults over the components of the generator. This distribution is for generators rated above 2MW.

A more recent study on failures in wind turbines looks at the difference in DFIG and PMG drivetrains [6]. It looks at the failures in the generator and power electronic converter of each system type. The DFIG system is studied on the basis of a large population set and therefore, can be considered to be representative of the technology. The study identifies the slip ring and brush system as a major problem point. Figure 1.3a and Figure 1.3b describe the failure rates in the generator and the partially rated converter of the DFIG system.

The study finds that the generator in the PMG drive train is more reliable than its DFIG counterpart. However,

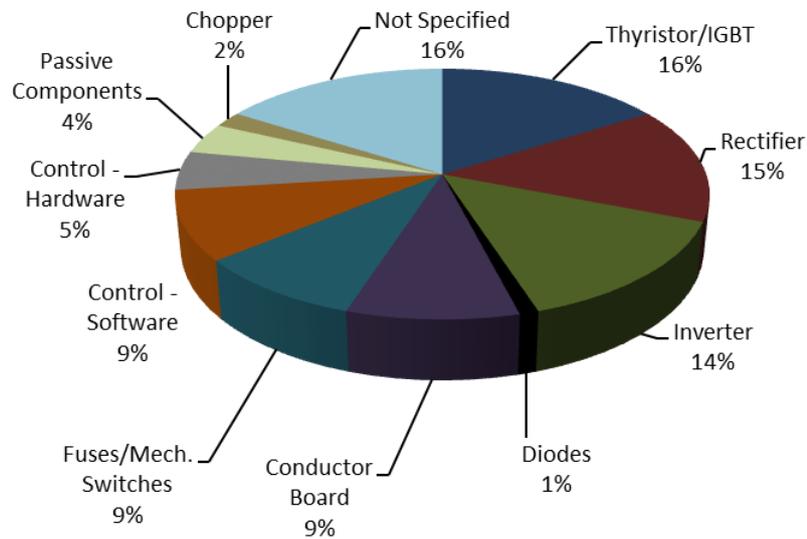


Figure 1.1: Share of Sub-Component Failure Rates in Power Electronic Assemblies [3]

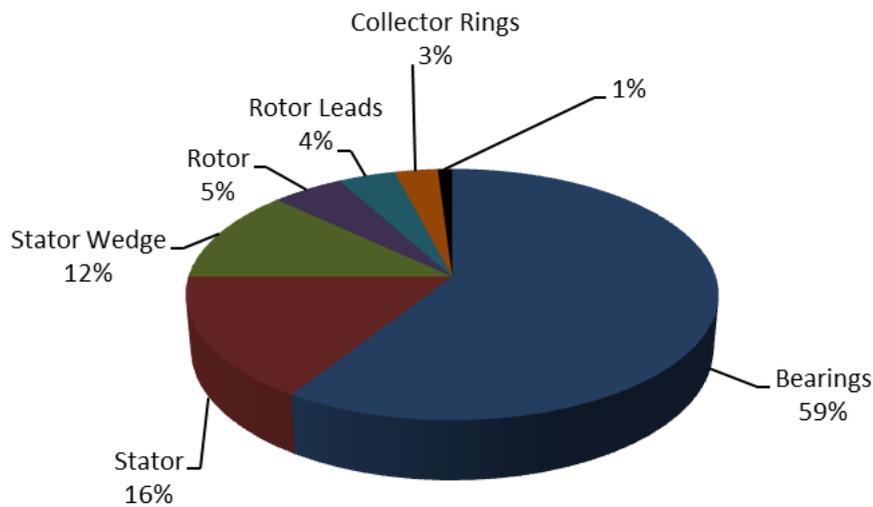


Figure 1.2: Share of Sub-Component Failure Rates in Generator Assemblies [5]

the failure rate of the Fully Rated Converter used in a PMG drivetrain has a failure rate that is almost six times as high as the failure rate of the Partially Rated Converters in DFIG drivetrains. This could be attributed to higher power handling causing greater cooling issues and greater stress on the converter. Figure 1.4 gives the failures in Fully Rated Power Electronic Converters in PMG drivetrains.

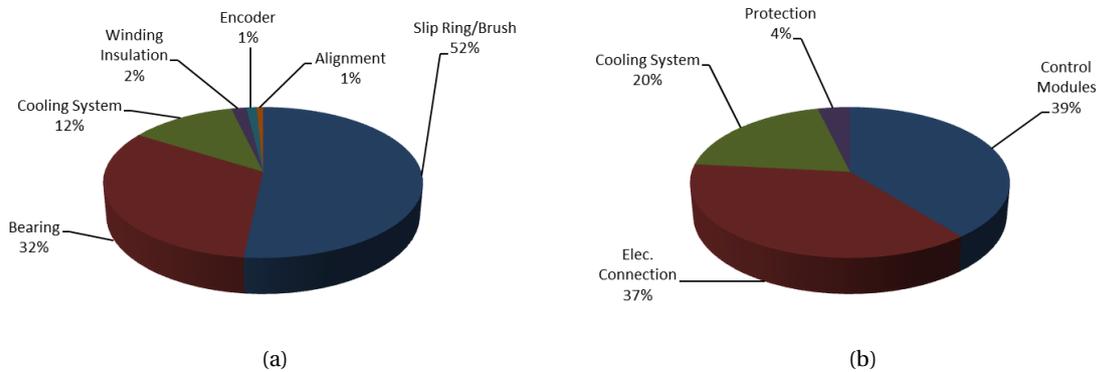


Figure 1.3: Share of Failures in DFIG systems (a) for Generators (b) for Partially Rated Power Electronic Converter [6]

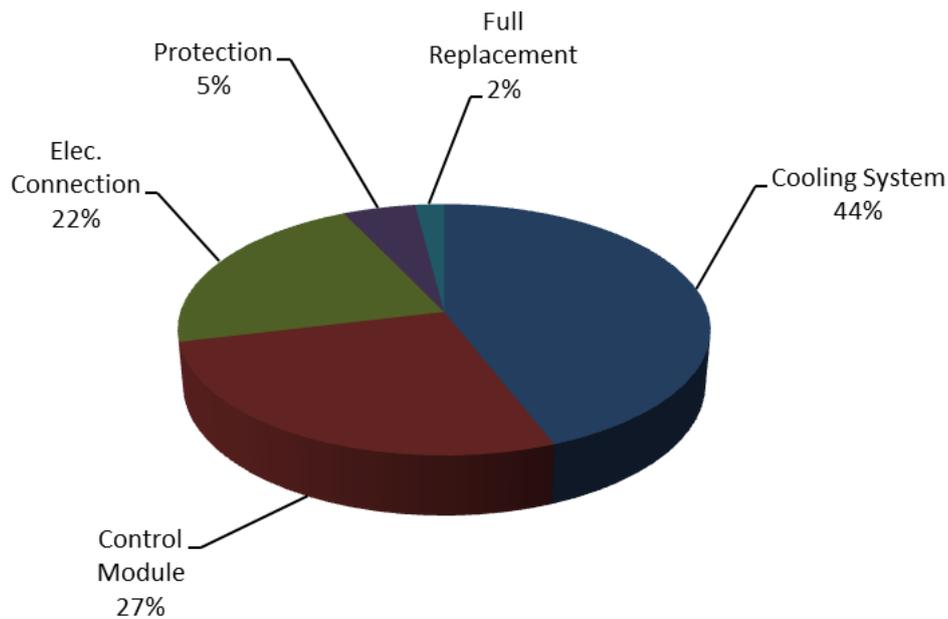


Figure 1.4: Share of Failures in Fully Rated Power Electronic Assemblies in PMG Drivetrains [6]

2 FAILURE MECHANISMS IN POWER ELECTRONIC CONVERTERS

Published work has shown that the semiconductor switches are most likely to fail in a power electronic converter, therefore, this section starts by looking at the failure mechanisms of IGBTs.

Figure 2.4 gives an overview of failure mechanisms in Power Electronic Converters. These aspects are further elaborated in the following sections.

2.1 SEMICONDUCTORS

2.1.1 BOND WIRE LIFT-OFF

Bond wire lift-off has been considered as one of the principal forms of failures in IGBTs and diodes. Failure of wire bonds occur as a result of fatigue caused either by shear stresses generated between the chip and wire, or due to repeated flexure of the wire [7].

Bond wire lift-off in particular occurs due to cracks propagating along the bond wire-chip interface. These cracks develop and propagate due to thermo-mechanical stresses caused by temperature cycling and the fact that aluminium (bond wire material) and silicon (chip material) have very different Coefficient of Thermal Expansion (CTE) [8].

However the use of improved bonding methods, protection layers [9] and molybdenum-aluminium strain buffers [7] have reduced these failures to such an extent that they do not seem to pose any particular threat to IGBT reliability.

2.1.2 BOND WIRE HEEL CRACKING

This failure, also, is due to the thermo-mechanical effect of the wire subjected to temperature cycling. Under such a cycling, the wire undergoes flexure fatigue [7].

However, this failure mechanism is a slow process and rarely occurs in modern IGBTs [7].

2.1.3 SOLDER JOINT FATIGUE

Solder joint fatigue is considered a major failure mechanism in power electronic components [10]. This failure occurs because the solder layer is subjected to mechanical stresses under temperature cycling, because of the difference in the CTEs of the two materials between which the solder is present.

IGBTs have two such joints - silicon chip and ceramic substrate, and ceramic substrate and base plate. Of these, the DCB ceramic-base plate solder joint is especially prone to failure due to a greater mismatch between the CTEs of the two materials resulting in shear stress in the solder layer and eventually cracks and voids [11].

Solder fatigue cracks are generally found close to the DCB ceramic due to higher temperatures. These cracks lead to a reduction in the heat conduction capability of the solder layer causing an increase in the temperature of the junction with further exacerbates the problem [7].

These effects may be a result of external heating (thermal cycling) or by internal heating due to losses in the IGBT (power cycling) [9].

2.1.4 ALUMINIUM RECONSTRUCTION

Thermal cycling in IGBT's and diodes cause tensile and compressive stresses due to different CTE's of aluminium and silicon. This can cause diffusion creep, grain boundary sliding and plastic deformation [7].

This becomes an issue for reliability when there are pre-existing step coverage problems at the emitter contact [7]. In effect, Aluminium reconstruction reduces the cross-section of metallisation resulting in an increase in the resistance of the aluminium contact.

2.1.5 LATCH UP

Latch-up is a failure inherent in the IGBT and occurs when the collector current cannot be controlled by the gate.

The figure shows the lateral component of the current through the p-type body layer. This results in a voltage drop across the the body layer which forward biases the np junction. If this voltage is large enough then the parasitic npn transistor is turned on which in turn turns the main pnp transistor. This structure is shown in Figure 2.1. Once this happens the parasitic thyristor made of these two transistors will latchup. This makes the IGBT lose control through the gate [12].

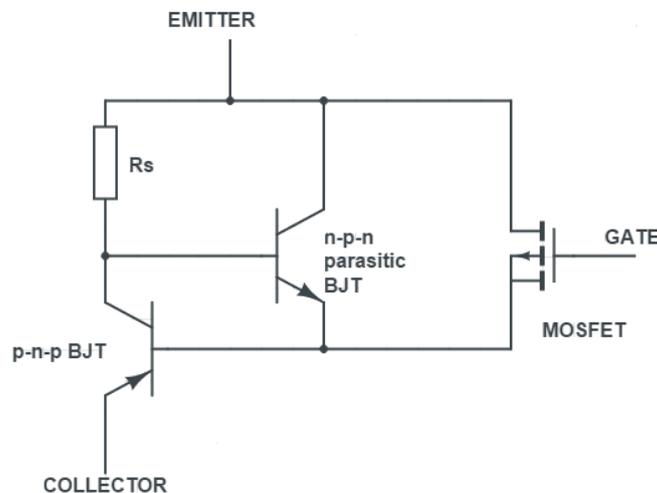


Figure 2.1: IGBT Equivalent Circuit

Latch-up is of two types, static and dynamic. Static latch-up happens at high collector currents which turn on the parasitic transistors. Dynamic latch-up occurs due to switching transients especially during turn off. This is done by the displacement currents of the parasitic capacitance between the p region of the pnp transistor and the n region of the parasitic transistor [13].

2.1.6 COSMIC RAY FAILURE

Burnout in semiconductor devices can be initiated through self-sustaining discharges in the silicon by recoil nuclei [7]. Energetic neutrons create ionizing recoils within the substrate. Originally, this failure mechanism was attributed to high voltage devices only. However, studies show that cosmic radiation-induced breakdown can not be disregarded for power devices of voltage classes as low as 500V [reference paper cosmic]. This makes cosmic ray failure mechanism of interest for wind turbine power electronics as well.

2.1.7 PRESS-PACK TECHNOLOGY

Press-pack semiconductors eliminate the dominant failure mechanisms of standard wire bonded semiconductors like bond wire lift-off and solder joint failure. However, they suffer from other failures such as fretting, spring fatigue and spring relaxation.

When press-pack IGBT's are subjected to temperature cycling and the variation in CTE's of the layers will lead to reciprocating sliding causing fretting damage. This results in a deterioration in thermal and electrical properties [11].

Spring fatigue and spring relaxation occur due to the compression and relaxation cycles caused by power cycling. These failures lead to an increase in contact resistance [11].

Latch-up and Cosmic Ray Failure described in Section 2.1.5 and Section 2.1.6 can occur in press-pack semiconductors as well.

2.2 CONTROL

According to *Birk et al.* the Converter Control Unit (CCU) is one of the components with the lowest reliability. As with the semiconductors, the failures in the CCU is related to thermal cycling [14].

In this document the gate driver is considered to be part of the control hardware. Apart from failures due to thermal cycling issues, failures may also occur due to conditions of the IGBT. Continued narrow overvoltage spikes between collector and emitter may open the gate emitter resistance [13]. This would result in a loss in the driving signal and misfiring of the IGBT and could result in thermal breakdown or steady-state power dissipation [reference MOSFET Gate Open Failure Analysis In Power Electronics]. Also, modern IGBT's can work at much higher temperatures than the gate drive circuit components, in the event that such a scenario is experienced, the driver circuit could suffer from these thermal effects [13].

2.3 PASSIVE COMPONENTS

Industry experience shows that failures in resistors and inductors are rare [4]. Therefore this section deals primarily with the failures in capacitors.

Two types of capacitors are used in wind turbine power electronic converters - aluminium electrolytic capacitors and metallised polypropylene film capacitors. The electrolytic capacitor offers high power density

at a lower cost but suffers from reliability issues while the film capacitor offers higher reliability but a lower power density [15].

2.3.1 ALUMINIUM ELECTROLYTIC CAPACITORS

Failures in electrolytic capacitors include degradation of parameters, short circuits, open circuits and electrolyte leakage.

Short circuit or breakdown failures may be dielectric breakdown or thermal breakdowns. Dielectric breakdowns are primarily due to defects in the device itself while thermal breakdowns occur due to a rise in temperature of the device. This is a common short circuit failure in electrolytic capacitors [16].

Open circuit failures occur either due to electrochemical corrosion leading to lead fractures or the drying of capacitor cores when they are subjected to high working temperatures [16].

Parameter degradation is common among electrolytic capacitors over their lifetime. This includes capacitance decrease, series resistance increase and loss tangent increase [16].

2.3.2 POLYPROPYLENE FILM CAPACITORS

Even though polypropylene film capacitors are self-healing, when the energy passing through the localised discharge path created by local breakdowns is larger than the energy required for self-healing, then the capacitor fails in the short circuit mode [17].

The contact between the ends of electrode edges and the spray ends are irregular. Under the combined effect of mechanical stress, electrodynamic force, thermal stress, as well as the electric spark effect caused by the potential difference between electrode edge and sprayed end, the contact degrades gradually and eventually leads to the detachment of the sprayed ends and an open circuit fault [17].

Another short circuit mechanism is the absorption of moisture by the dielectric film. This is caused by humidity [18].

In both Aluminium Electrolytic Capacitors and Metallised Polypropylene Film Capacitors have wear out or parameter degradation as a dominant failure mode. Capacitor Voltage stress and Temperature stress are two major causes of this failure mode. Humidity also plays a role, especially for polypropylene film capacitors.

Figure 2.2 and Figure 2.3 gives the important failure mechanisms and parameters for semiconductor switches and capacitors respectively.

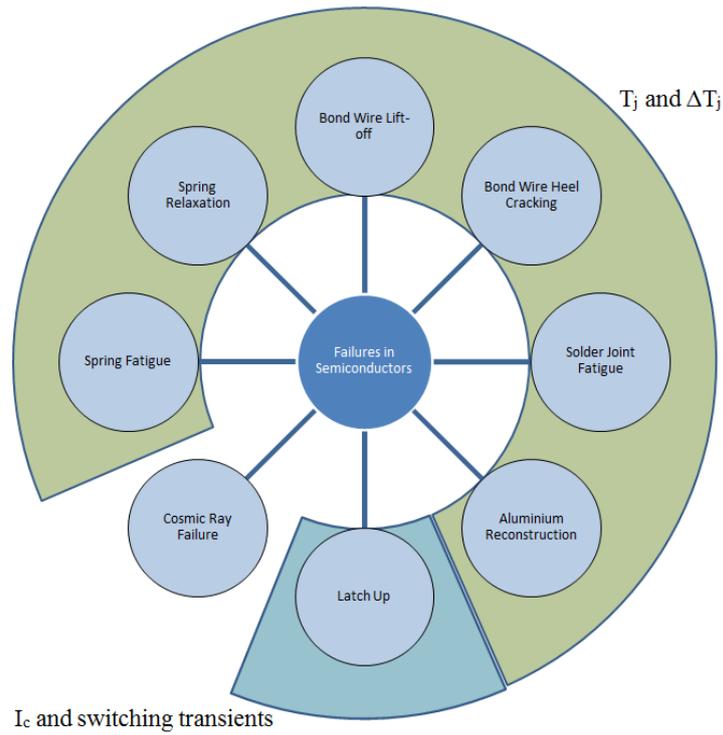


Figure 2.2: Driving Parameters for Failures in Semiconductor Switches

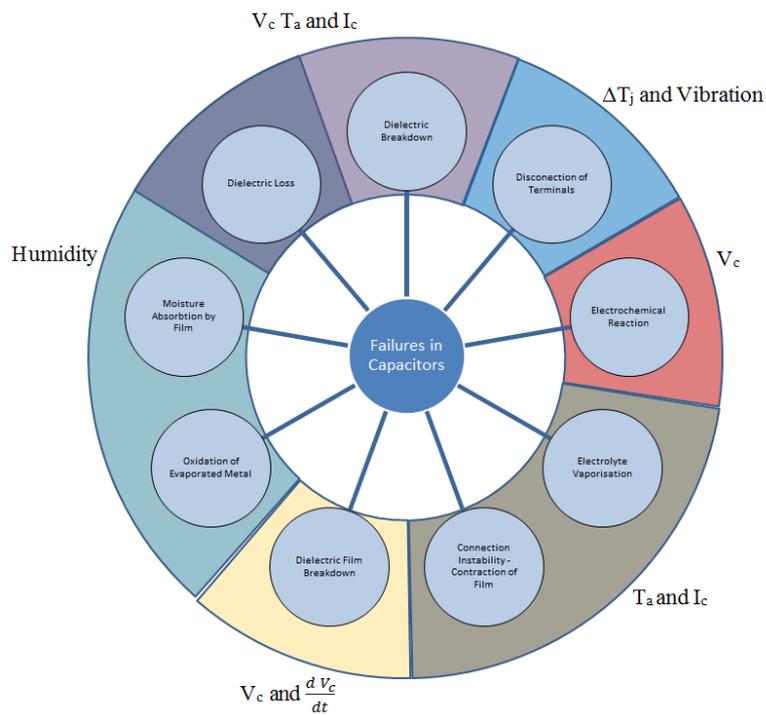


Figure 2.3: Driving Parameters for Failures in Capacitors

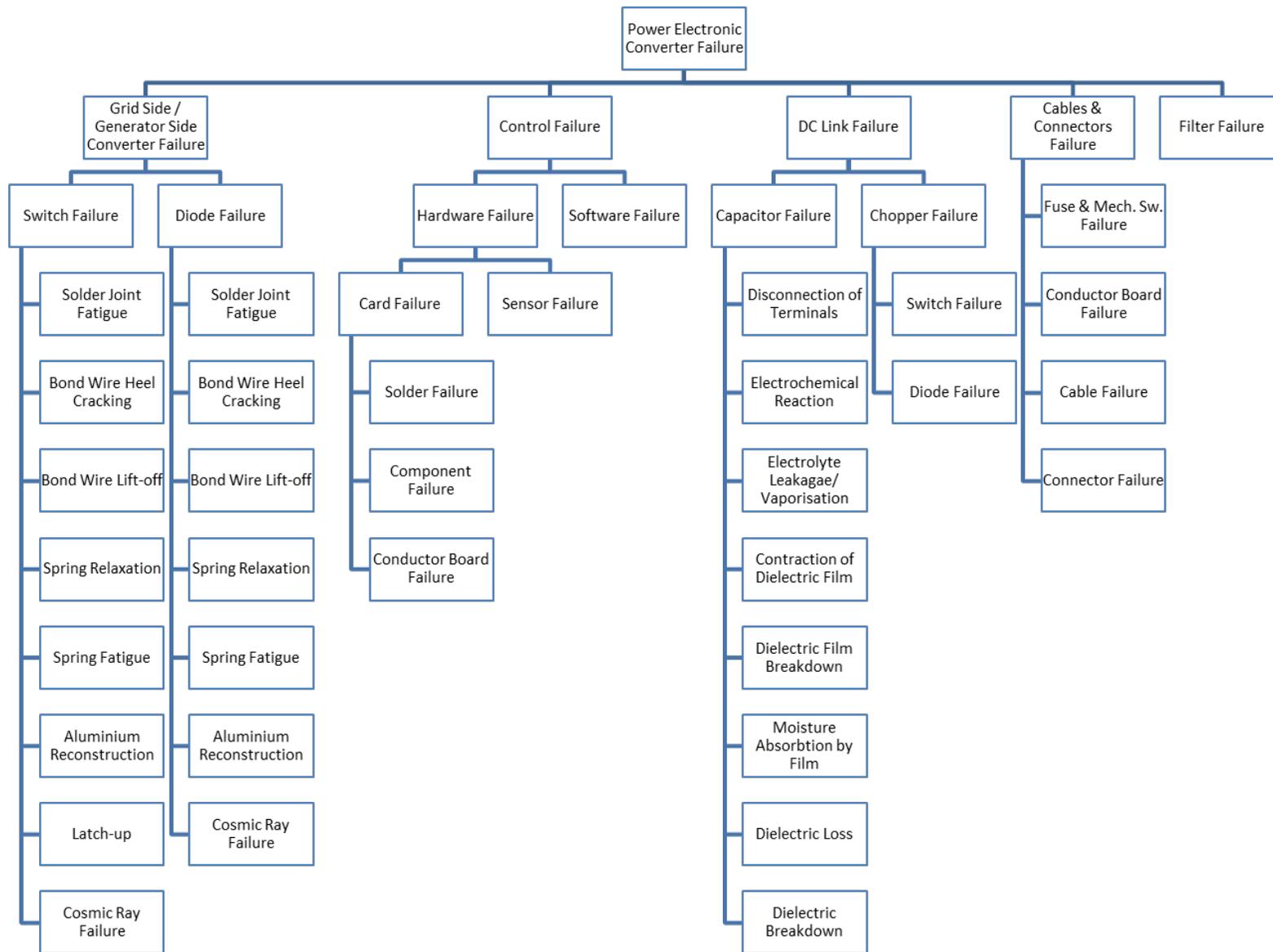


Figure 2.4: Fault Tree of Power Electronic Converters

3 FAILURE MECHANISMS IN GENERATORS

Figure 3.1 gives an overview of failures in generators. These are further elaborated in the following sections.

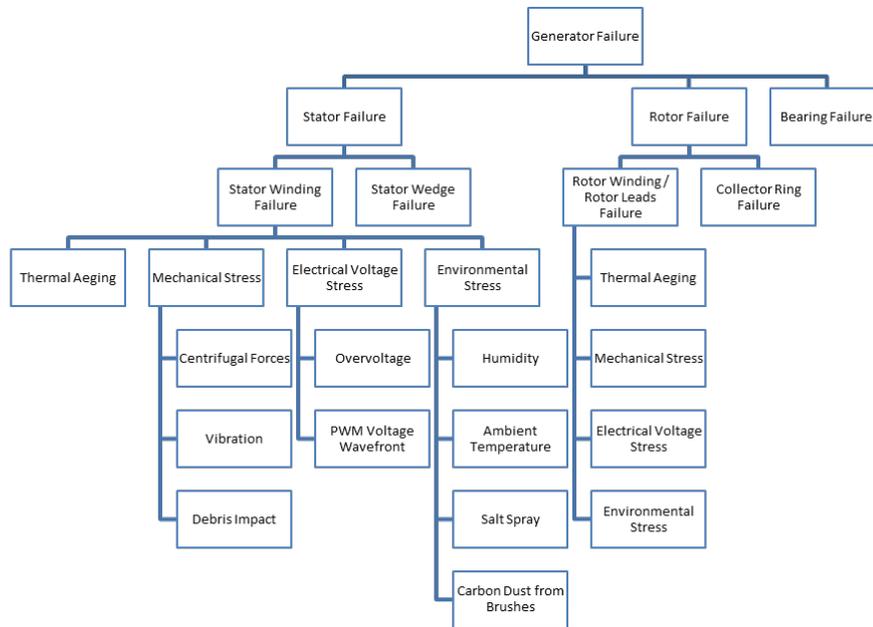


Figure 3.1: Fault Tree of Generators

3.1 STATOR AND ROTOR WINDING

Although electrical breakdown causes the final failure in an insulation system, it is not the dominant ageing factor. It is believed that ageing is dominated by thermal degradation, mechanical stress due to vibration and switching pulses, and stress caused by different thermal expansion coefficient of the materials [19].

The Power Electronic Converter operated using PWM is another reason for the stressing and possible failure of the windings. This is applicable for the rotor winding in the DFIG and the stator winding for the Permanent Magnet Synchronous Machine. The fast travelling voltage wavefront, especially pronounced when PWM is used, generates reflection waves at the cable-generator junction. These reflected waves cause overshoots or spikes at the front of the voltage wave [20]. According to *Gao et al.* these spikes can be in the order of 2.5kV for a system rated at 690V [21].

Another factor that could be an initiator of failures in the windings of wind turbines is the environment. Off-shore wind turbines are especially exposed to moisture and corrosive saline water. Moisture may condense on windings and initiate surface tracking in winding insulation.

3.2 STATOR WEDGE

A major failure that has been identified in Wind Turbine generators is the failure due to the loosening of magnetic stator wedges. This loosening of slot wedges could lead to grounding faults or mechanical damage to the coils. Magnetic stator wedges are used to reduce the effective stator slot opening and offer some benefits such as smoothing of the airgap flux, improving efficiency and reduce temperature rise [22].

With stator wedges being made out of magnetic material they will vibrate under the effect of rotating fields causing the bonding of the stator wedges to weaken. Also the ferrous nature of the wedges speeds up corrosion through oxidation [5].

Magnetic Stator Wedge faults could offer an option for fault avoidance.

3.3 ROTOR LEAD DAMAGE

The Doubly Fed Induction Generator (DFIG) requires power to be fed to the rotor through a Power Electronic Converter. This power is transferred through the Rotor Leads. These leads pass through the hollow shaft of the generator. As a consequence, any thermal issues occurring due to the bearings can cause damage to the leads and failure of the generator [5]. Also, the end bearing of the generator has additional thrust forces due to the mounting angle of the generator causing higher temperatures and greater possibility of causing rotor lead failure.

3.4 COLLECTOR RINGS

The slip rings are also affected by the use of power electronic converters. The voltage spikes generated can cause voltage flashovers between the rings [21].

Another reason for failure in collector rings could be the degradation of insulation between them due to thermal cycling.

4 EFFECT OF WIND SPEED AND WEATHER

The weather can have a major impact on failure rates in wind turbines. Humidity at the location of installation can lead to an increase in failures, especially in the power electronic converters and the generator. Also, in offshore wind turbines the corrosive nature of the salt laden air could also cause problem to sub-assemblies. However, these can be overcome with suitable nacelle or sub-assembly sealing.

Also, a number of failure mechanisms in the power electronic converter are caused due to temperature cycling effects. Therefore, it can be expected that the external temperature at a location could have an effect on failure rates. It has been shown by *Tavner et al.* that electrical sub-assemblies are indeed more prone to the deleterious effect of varying temperatures [23]. Further very low temperatures could have a serious effect on the thermal grease, solder and capacitor electrolytes used in converters. *Tavner et al.* also found a periodicity in failure rate data of 6, 8.4 and 12 months [24]. The 12 and 6 month periodicity is attributed to seasonal

variation of weather while it is hypothesised that the 8.4 month periodicity occurs due to gusting in August. Studies [23] highlighted the annual seasonal periodic nature of the Wind Energy Index (WEI) which may be used as a measure of wind speeds. This periodic nature introduces power cycling leading to increased fatigue by mechanisms described in previous sections. Months with higher WEIs also saw higher failure rates. In fact a report by REISI as quoted in [24] stated that above wind speeds of 12m/s, the frequency of failures is about twice as high as the frequency of wind classes. This could be attributed to high stresses on components that are already fatigued due to long term fluctuating loads.

5 CONCLUSIONS

It is seen that temperature driven failures are a major factor for failure mechanisms for the components in power electronic converters and generators. Therefore, it can be assumed that thermal management is very important from the view of reliability.

A few conclusions are listed below,

- For the semiconductors, junction temperature, T_j and ΔT_j are the major stress factors contributing to failures both in Bond Wire type and Press-Pack type technologies.
- For the capacitors as well, the temperature of the capacitor T_c is a major factor in failure.
- This dependence on ΔT_j of failure mechanisms could be the reason there are a large number of failures in power electronic semiconductors in wind turbines, where there are large variations in output power due to the intermittent nature of the wind resource.
- It can be seen that thermal management in the converter design is an important factor from the view-point of reliability.
- Press-pack semiconductors seem to offer advantages in terms of lifetimes and reliability as they remove some major failure mechanisms of semiconductors. However, there do not seem to be any lifetime models to describe these components. This needs to be investigated further to conclude if there are benefits of using this technology.
- Replacing Magnetic Wedges with Non-Magnetic Wedges could avoid their frequent failure.
- Rotor leads and Collector Rings account for nearly 10% of failures according to [5] and the brush-slip ring system is a major failure prevalent in DFIG drivetrains [6]. Therefore, the Brushless DFIG could be an interesting case study from the aspect of reliability.
- A better brush system could also play a part in reducing this type of failure.
- Rotor leads failure is also affected by the temperatures of the shaft and in particular, the generator bearing. Better thermal management could help alleviate this failure.
- With stator winding faults accounting for about 15% of faults in the generator systems, multi-phase generators or generators with multiple winding sets may be useful in increasing the availability of wind turbines.

REFERENCES

- [1] E. Echavarria, B. Hahn, G. J. W. van Bussel, and T. Tomiyama, "Reliability of Wind Turbine Technology Through Time," *Journal of Solar Energy Engineering*, vol. 130, no. 3, p. 031005, 2008. [Online]. Available: <http://solarenergyengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1474176>
- [2] F. Spinato, P. Tavner, G. van Bussel, and E. Koutoulakos, "Reliability of wind turbine subassemblies," *IET Renewable Power Generation*, vol. 3, no. 4, p. 387, 2009. [Online]. Available: <http://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2008.0060>
- [3] P. Lyding, S. Faulstich, B. Hahn, and P. Tavner, "Reliability of the Electrical Parts of Wind Energy Systems - a Statistical Evaluation of Practical Experiences," in *EPE Wind Energy Chapter Symposium*, 2010.
- [4] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An Industry-Based Survey of Reliability in Power Electronic Converters," *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1441–1451, May 2011. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5729810>
- [5] K. Alewine and W. Chen, "A review of electrical winding failures in wind turbine generators," in *2011 Electrical Insulation Conference (EIC)*. IEEE, Jun. 2011, pp. 392–397. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5996185>
- [6] J. Carroll, A. McDonald, and D. McMillan, "Reliability Comparison of Wind Turbines With DFIG and PMG Drive Trains," *IEEE Transactions on Energy Conversion*, pp. 1–8, 2014. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6967839>
- [7] M. Ciappa, "Selected failure mechanisms of modern power modules," *Microelectronics Reliability*, vol. 42, no. 4-5, pp. 653–667, Apr. 2002. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0026271402000422>
- [8] S. Ramminger, P. Türkes, and G. Wachutka, "Crack mechanism in wire bonding joints," *Microelectronics Reliability*, vol. 38, no. 6-8, pp. 1301–1305, Jun. 1998. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0026271498001413>
- [9] H. Berg and E. Wolfgang, "Advanced IGBT modules for railway traction applications: Reliability testing," *Microelectronics Reliability*, vol. 38, no. 6-8, pp. 1319–1323, Jun. 1998. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0026271498001504>
- [10] K. Fischer, T. Stalin, H. Ramberg, J. Wenske, and R. Karlsson, "Investigation of converter failure in wind turbines," Tech. Rep. November, 2012.
- [11] C. Busca, R. Teodorescu, F. Blaabjerg, S. Munk-Nielsen, L. Helle, T. Abeyasekera, and P. Rodriguez, "An overview of the reliability prediction related aspects of high power IGBTs in wind power applications," *Microelectronics Reliability*, vol. 51, no. 9-11, pp. 1903–1907, Sep. 2011. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0026271411002526>

- [12] N. Mohan, T. Undeland, and W. P. Robbins, *Power Electronics - Converters, Applications and Design*, 3rd ed. John Wiley and Sons, 2002.
- [13] R. Wu, F. Blaabjerg, H. Wang, M. Liserre, and F. Iannuzzo, "Catastrophic failure and fault-tolerant design of IGBT power electronic converters - an overview," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, Nov. 2013, pp. 507–513. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6699187>
- [14] J. Birk and B. Andresen, "Parallel-connected converters for optimizing efficiency, reliability and grid harmonics in a wind turbine," in *2007 European Conference on Power Electronics and Applications*. IEEE, 2007, pp. 1–7. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4417318>
- [15] M. Boettcher, F. W. Fuchs, and D. Kiel, "Power Electronic Converters in Wind Energy Systems - Considerations of Reliability and Strategies for Increasing Availability," in *Proceedings of the 14th European Conference on Power Electronics and Applications*, 2011, pp. 1–10.
- [16] W. Lifeng, Z. Shihong, D. Yinyu, G. Yong, and P. Wei, "Research on failure analysis method of the key components in SMPS," in *2011 Prognostics and System Health Management Conference*. IEEE, May 2011, pp. 1–6. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5939540>
- [17] L. Fuchang, D. Xin, L. Jin, Y. Zonggan, and W. Nanyan, "On the failure mechanism of metallized polypropylene pulse capacitors," in *2000 Annual Report Conference on Electrical Insulation and Dielectric Phenomena (Cat. No.00CH37132)*, vol. 2. IEEE, 2000, pp. 592–595. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=884029>
- [18] H. Wang and F. Blaabjerg, "Reliability of Capacitors for DC-Link Applications in Power Electronic Converters—An Overview," *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3569–3578, Sep. 2014. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6748007>
- [19] R. Brutsch, M. Tari, K. Frohlich, T. Weiers, and R. Vogelsang, "Insulation Failure Mechanisms of Power Generators [Feature Article]," *IEEE Electrical Insulation Magazine*, vol. 24, no. 4, pp. 17–25, Jul. 2008. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4581636>
- [20] W. Yin, "Failure mechanism of winding insulations in inverter-fed motors," *IEEE Electrical Insulation Magazine*, vol. 13, no. 6, pp. 18–23, Nov. 1997. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=637150>
- [21] G. Gao and W. Chen, "Design challenges of wind turbine generators," in *2009 IEEE Electrical Insulation Conference*, no. June. IEEE, May 2009, pp. 146–152. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5166334>
- [22] R. Curiac and H. Li, "Improvements in energy efficiency of induction motors by the use of magnetic wedges," in *2011 Record of Conference Papers Industry Applications Society 58th Annual IEEE Petroleum and Chemical Industry Conference (PCIC)*. IEEE, Sep. 2011, pp. 1–6. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6085890>

- [23] P. Tavner, D. M. Greenwood, M. W. G. Whittle, R. Gindele, S. Faulstich, and B. Hahn, "Study of weather and location effects on wind turbine failure rates," *Wind Energy*, vol. 16, no. 2, pp. 175–187, Mar. 2013. [Online]. Available: <http://doi.wiley.com/10.1002/we.538>
- [24] P. Tavner, C. Edwards, A. Brinkman, and E. Spinato, "Influence of Wind Speed on Wind Turbine Reliability," *Wind Engineering*, vol. 30, no. 1, pp. 55–72, Jan. 2006. [Online]. Available: <http://multi-science.metapress.com/openurl.asp?genre=article&id=doi:10.1260/030952406777641441>