Development of a Vulnerability Map of Wind Turbine Power Converters

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Abstract. With the amount of turbines that are already installed and that are planned to be installed in order to meet all the carbon emission objectives set by Governments worldwide, a means of producing a way to determine and highlight weak links or components that are more likely to fail would be extremely beneficial. One way to do this is via vulnerability maps. This paper looks at producing a vulnerability map for the power converter of a wind turbine using maintenance reports. The vulnerability map is a useful means to identify which sub-systems/components to consider when determining lifetime extension of wind turbine drivetrains. All the components that were either replaced or repaired are grouped together to determine their failure rates. Their rates are then ranked from highest to lowest and each component that makes up a typical power converter diagram coloured according to its failure rate, from red for the highest, through to orange, yellow and green for the lowest. The results show that there are three clear components that failed more often than the rest. An additional analysis looks at whether the location of the turbines alter the vulnerability map and this is confirmed. Although the same three components have the highest failure rates, their values change according to which country they are installed.

1. Introduction

The global wind energy capacity currently stands at 743 GW, with 2020 being declared a record year for the wind industry due to 93 GW being installed in 2020, which is a 53% increase on 2019 [6]. In order to meet the world's target of net zero by 2050, this value needs to increase drastically. The Global Wind Energy Council [6] states that they need to be installing wind power three times faster in order to reach this target. Therefore, a large number of wind turbines have been installed, with a much larger amount due to be installed, which all need to operate efficiently and effectively throughout their designed service life, with minimum downtime.

A wind turbine is made up of a number of sub-systems [16] including: (i) a support structure such as a tower, (ii) a rotor module in which the blades are attached and (iii) a nacelle which houses the drivetrain module. The drivetrain is classed as the heart of the wind turbine because it is where the wind that is turning the rotor blades is converted into electrical power, which is supplied to the grid. It is also one of the main sub-systems of the wind turbine that causes the most downtime, mainly due to the fact that it contains a number of mechanical and electrical assemblies.

Drivetrains often include a torque and speed conversion process (such as a gearbox), always use an electrical machine to convert mechanical power to electrical power and nowadays use a power converter to decouple the variable voltage and frequency of the generator and the fixed voltage and frequency of the grid [11]. Each of these pieces of equipment are made up of a number of sub-assemblies and in turn a number of components. Therefore, if any sub-assembly or component in any piece of equipment within the drivetrain fails, then there could be serious consequences for the supply of power, which in turn will incur large costs for the owner/operator. With this in mind, it would be extremely beneficial to develop a method of determining and highlighting the weak links and conditions of the components within the drivetrain equipment, so that the owner/operators know which components to prioritise, with regards to maintenance and spare parts, for example.

One method is by constructing a vulnerability map. A vulnerability map identifies the layout of all the sub-assemblies and/or components present either within a piece of equipment or assembly and indicates the various levels of damage per sub-assembly/component [12], from low to high. Such a vulnerability map can then be used during inspection processes to identify which parts are vulnerable to failure, for example during a lifetime extension evaluation procedure.

One of the main advantages of a vulnerability map, is that it is an easy to read document which clearly identifies each component's failure vulnerability.

Other benefits of establishing a vulnerability map, include:

(i) Establishing an efficient and useful inspection/maintenance model/plan.
(ii) Establishing the remaining useful life of the components, which assists with the lifetime extension evaluation procedure.
(iii) Reduction in risks and mitigation planning when used within the design process.
(iv) Assisting with purchasing spare parts just in time for replacement, to ensure minimum or zero downtime.

A number of sources have identified the power converter as the assembly with the highest failure rate, therefore this paper will specifically look at vulnerability mapping for wind turbine power converters. A data-driven approach to vulnerability is used in this paper; this is in contrast to the model-based vulnerability mapping for the gearbox (Figure 1) based on ranking the fatigue damage of the components at rated wind speed [12].

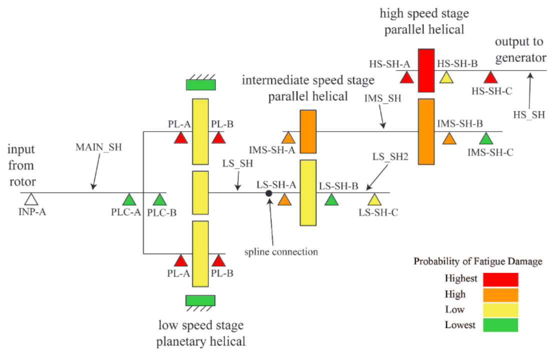

Figure 1. Vulnerability Map of 750 kW Gearbox [12]

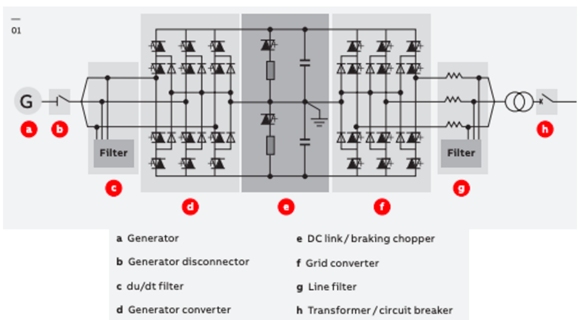

Figure 2. ABB's PCS6000 Power Converter Layout [1]

Developing such a vulnerability map for a power converter system, depicted as an example in Figure 2, which highlights the most vulnerable sub-assemblies and/or components will be extremely useful when investigating the lifetime extension of wind turbine drivetrains. It is particularly relevant to Stage 4 in the flowchart of proposed methodology for lifetime extension of Wind Turbine Drivetrains described in [15].

Therefore the main objectives of this piece of work are to:

(i) Establish suitable topologies of a power converter, both by higher-level sub-assemblies and by lower level components.
(ii) Identify the failure rates of the sub-assemblies and components within the power converters.
(iii) Develop a vulnerability map using both the topologies and the determined failure rates.
(iv) Determine if the vulnerability map varies for different wind turbine locations.

The rest of this paper is structured as follows: Section 2 will detail the literature review conducted, Section 3 will describe the methodology. The results will be explained in Section 4, followed by the Conclusion and Further Discussions in Section 5.

2. Literature Review

A vulnerability map for the components within a 750 kW wind turbine gearbox was established by Nejad et al. [12]. This vulnerabilty map was used to determine a suitable inspection and maintenance plan. It used fatigue damage of the components, i.e. bearings and gears, to establish the map, ranking the components between the lowest and highest.

Wang et al. [17] also developed a vulnerability map for the components of a wind turbine gearbox, as well as for the main bearings all within the same map, but the size of this turbine was a 10 MW medium speed offshore turbine. Again the fatigue damage was calculated using four methods, which were the "stress or equivalent load duration distribution, the Palmgren-Miner linear accumulative damage hypothesis, and long-term environmental condition distributions". The components were ranked from lowest to highest with regards to fatigue damage.

Where research has been done on vulnerability maps for wind turbine gearboxes and main bearings, not as much has been done on the other components situated within the drivetrain, such as the generator and power converter.

According to Zhu et al. [18] the gearbox, generator and blades have the highest failure rates. They mention how the main root causes of failure include design and operational issues, environmental conditions and maintenance practices. They list the typical failure modes as: faults, overheating, overspeed, seizure of the bearings and jammed bearings. The associated causes include: environmental conditions, fatigue, mechanical failure, misalignment, overload, loss of control and zero excitation.

Applying the failure, modes, effects and criticality analysis (FMECA) to a number of wind turbines in different climates and identifying any gaps, was a method used by Ozturk et al. [13]. They found that the typical generator failures were wear on the bearings and miscellaneous items. Typical electric system failures were wear on the switches, miscellaneous items, cables/connections, fuses and converter. There were higher failure rates and downtime per failure for direct-drive turbines as opposed to geared-drive. In both turbine types, the generators showed the highest downtime criticality.

The faults of a number of components within the drivetrain were highlighted by Qiao et al. [14]. Faults in the hydraulic system can include oil leakage and sliding valve blockage. The mechanical brake is made up of a disc, calipers and hydraulic mechanism. Failures can include cracking in the disc and over-wearing of both the disc and calipers, which are typically caused by overheating. Faults in the generator can be split into either electrical or mechanical faults. Where electrical faults can include "stator or rotor insulation damage or open circuit and electrical imbalance" and the mechanical faults can include "broken rotor bar, bearing failure, bent shaft, air gap eccentricity, and rotor mass imbalance". They also state that the most common faults occur with the electronic subsystem and that power converters have a high failure rate.

A comparison was carried out by Carroll et al. [4], between the reliability of doubly fed induction generator (DFIG) and permananet magnet generator (PMG) drivetrains within wind turbines, with regards to generators and converters. Their results show that DFIG drivetrains have more generator failures but PMG drivetrains have more converter failures. The largest contributor to generator failure in DFIG drivetrains is with the slip ring/brush, followed by the bearing, cooling system, insulation, encoder and alignment. Whereas the largest contributor to generator failure in PMG drivetrains is with the lubrication system, followed by the cooling system and alignment. The largest contributor to partial rated converter failure which is located in the DFIG drivetrains is the control modules, followed by connection issues, cooling system and protection. The largest contributor to fully rated converter failure is the cooling system, then the control module, connection issues, protection issues and converter replacement.

In a separate paper, Carroll et al. [5] investigated the failure rates of offshore wind turbines. With regards to generator failure modes, the highest number of failures were with the slip ring, followed by the generator bearing, grease pipes, rotor issues and fan. They also mention that the generator has a higher failure rate onshore.

Electrical winding failures within generators in wind turbines was discussed by Alewine et al. [2]. They determined that out of all the 1200 turbines reviewed, "fewer than half of the failures were electrical in nature and most of those were due to mechanical failures of the insulation support structure". They discussed typical electrical failures including rotor banding, conductive wedges, cooling system failures, rotor lead failures, under-designed materials and systems, surges, contamination issues and lubrication.

Due to their frequent failures, the investigation of power converter failures within the wind turbine are an important area to research. Along with their high frequency of failure, they are also one of the main causes of fire. Fischer et al. [9] explain that failures can include electrical overstress. Some of the causes of failures include, lightning strikes, thermal cycling, condensation build up after standstill and salt ingress.

Another paper written by Fischer et al. [10] looked at the root cause of power converters using a field experience based analysis. They mention some common causes of failure which may include: temperature, humidity, vibration, cleanliness, electrical, components and test and qualification. The analysis method they used to identify the failure modes and causes were the failure-data analysis, the operating conditions of the field and "postoperational analysis of converter hardware/modules". They concluded that the thermal cycling which occurs in the generator-side converter was not a predominant factor in causing failure because failures occurred in both the grid-side and generator-side converters. In addition, bond-wire damage and solder cracking, which are both classed as fatigue-related effects were also not a predominant cause of failure. Whereas inadequate protection of the converter's components from the environment were present within the converters. Corrosion and salt traces may have caused conductive paths which were unwanted. Insects were also found within the device which may have reduced the insulation-relevant air gaps thus causing flashover. After standing still for long periods of time the condensation build up could cause overheating, due to inadequate heat dissipation. Finally electrical overstress caused by lightning strikes was found in the samples, supporting what was discussed in [9].

Analysing worldwide operating field data provided by project partners, was another method used by Fischer et al. [7] to look at power converter failures. They reviewed the differences between different generator-converter combinations, different manufacturers and turbine generations. Their conclusions were similar to the conclusions of their other papers, with regards to thermal cycling not inducing fatigue and that environmental factors played a part in the failures. They reviewed all the components within the power converter system and concluded that the "phase-module" components had the highest number of failures. Induction generators with full scale converters had the lowest phase-module reliability. Reliability of the phase-modules were pretty consistent across all ages of fleets, young and old. Results also suggest that humidity and/or condensation play a part in the high failure rate of phase-modules. Failure is also highest when the turbine was operating very close and above rated power.

A large consortium, consisting of research organisations and companies has been established, to determine the main causes of power converter failures in wind turbines. This confirms how important it is to identify these causes of failure to try and reduce the amount of failures that occur, as these failures can have huge economic impacts on the wind turbine industry. Their results from Fischer et al. [8] confirmed the results and conclusions described in [9] and [10] where one of the major causes of failure appear to be related to the environmental conditions, as opposed to fatigue caused by thermal cycling. Other factors contributing to failure were contamination, overheating, design issues, quality issues and human error. The method of analysis they used included field measurements, evaluation of both failure and operating data, specifically for power converters and "post-mortem investigation".

An alternative method to determine the remaining useful life of converters was used by Alsaadi et al. [3] when conducting a comparison between a three level neutral point clamped (3L-NPC) converter and two level voltage source converter (2L-VSC). They used wind speed samples, SIMULINK models, thermal cycles and Weibull distribution in order to determine the expected remaining useful life. This research by Alsaadi et al. which was presented at the Wind Energy Science Conference (WESC) 2021, concluded that the 3L-NPC has the higher reliability.

3. Methodology

Establishing the topology of the power converter is the first step. The Reliawind taxonomy standardisation structure [16] is used as the basis, along with manufacturer diagrams (Figure 2).

Table 1 shows the relevant components extracted from the "Detailed wind turbine taxonomy".

Once the layout is established, the next step is to analyse a dataset. The dataset consists of failure reports/maintenance logs for around 700 primarily onshore wind turbines, located in around 15 different countries.

The data is initially filtered to only include events that occurred due to unexpected failures of power converter components. This reduces the list by 47%. From this reduced list, the components that either failed or malfunctioned are sorted and grouped. Items such as oil, cooling liquid and other consumables are excluded from the total list of failed components. These constitute to 14% of the total. The number of failures per component are then calculated and listed from the highest to lowest failure rate. The flowchart in Figure 3 highlights the key steps.

The vulnerability map is then established by colouring the relevant components in, on the map established previously, using the failure rates calculated from the dataset. Due to the descriptions within the dataset analysed being very component specific (e.g. model, part no. etc), assumptions are made with regards to the locations of certain components. Further work will look at identifying each component and discussing with power converter manufacturers as to where exactly these components reside. The components with the highest failure rate (over 25%) are coloured in red with the medium/high failure rate (between 15% and 25%) in orange, low/medium (between 5% and 15%) in yellow and the lowest in green (between 0% and 5%). The map can be seen in the next section.

The next analysis looks at whether the vulnerability map changes depending upon wind turbine location.

In order to do this the original list of unexpected failures is sorted and grouped per

Table 1. Power Converter Components Selected from "Detailed Wind Turbine Taxonomy" corresponding to Electrical Module a Sub-System of Wind Turbine System [16]

Assembly	**Sub-Assembly**	**Component**
Frequency Converter	Converter Auxiliaries	1 Control Board
Frequency Converter	Converter Power Bus	2 Branching Unit
		3 Capacitor
		4 Contactor
		5 Generator Side Converter
		6 Generator Side Power Module
		7 Grid Side Converter
		8 Grid Side Power Module
		9 Inductor
		10 Load Switch
		11 Pre-Charge Unit
Frequency Converter	Power Conditioning	12 Common Mode Filter
		13 Crowbar
		14 DC Chopper
		15 Generator Side Filter
		16 Line Filter Assembly
		17 Voltage Limiter Unit
Power Electrical System	Power Circuit	18 Cables
		19 Machine Contactor
		20 Machine Transformer
		21 MV Busbar/Isolator
		22 MV Switchgear
		23 Soft Start Electronics

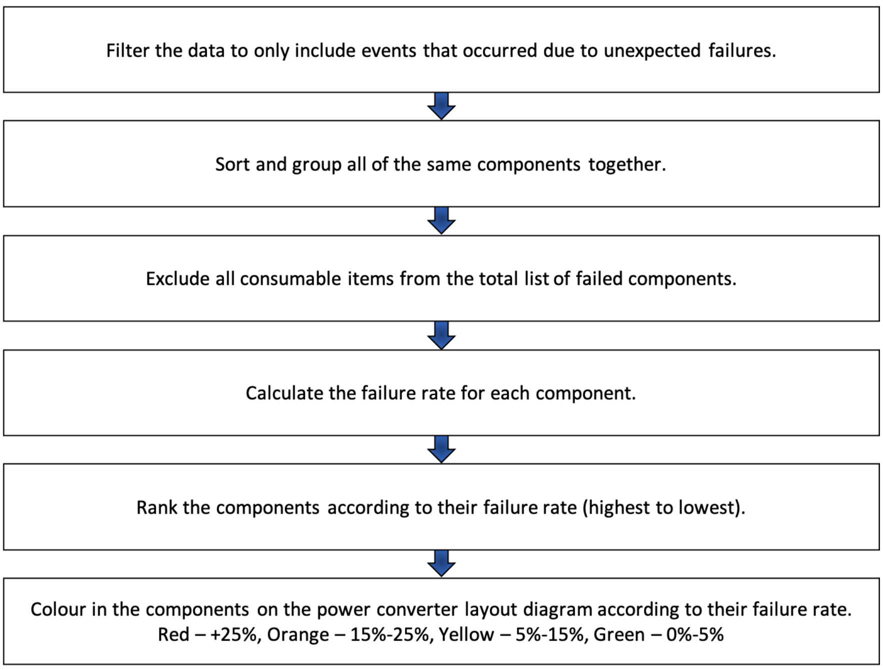

Figure 3. Flowchart Showing Proposed Method to Derive Power Converter Vulnerability Map

location, prior to grouping the failed/malfunctioned components. Six out of the 15 countries are investigated. These six countries are selected as they have failures in multiple turbines spread over more than 10 different wind farms.

Afterwards, the number of failures per component are calculated and listed from highest to lowest failure rate. The results per location are then compared and discussed.

4. Results and Discussion

The components associated with the power converter that failed or malfunctioned are show in the bar chart in Figure 4.

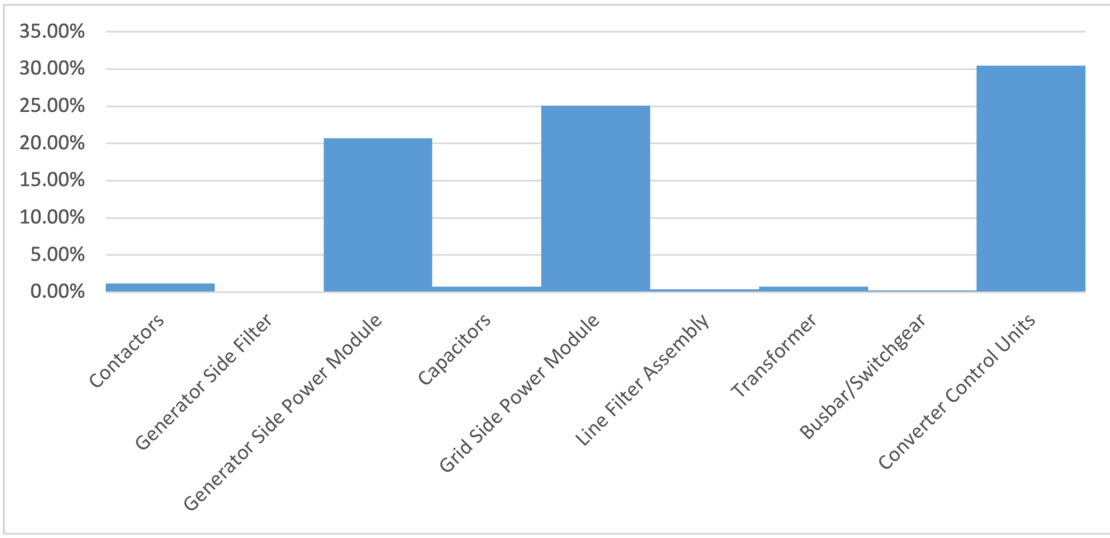

Figure 4. Chart Showing Power Converter Failure Rates For All The Data From All Locations

The chart shows very clearly that there are three components that have failed more than the others. They are:

(i) Converter Control Units (30%).
(ii) Grid Side Power Module (25%).
(iii) Generator Side Power Module (21%).

In their early design life, out of almost 400 turbines, 185 turbines required converter control units replacements. 96 turbines had failed grid side power modules and 83 turbines had failed generator side power modules, with 45% and 43% respectively requiring 2 or more replacements per turbine, plus 48 turbines having both grid and generator side power modules replaced.

Information from Figure 4 is then used to colour in the components according to their failure rate and Figure 5 shows the vulnerability map built based on all the data from all the locations.

Regarding the question as to whether the location of the turbines changes the vulnerability map, Table 2 lists the 6 out of the 15 countries alphabetically and shows which components failed the most per location.

For all locations, the top three components that failed the most are the same, which are the converter control units, generator side power module and grid side power module but they just appear in different positions due to different failure rates. The grid side power modules failed most in three locations (France, Italy and Poland), with the converter control units failing most in the other three (China, Germany and Sweden).

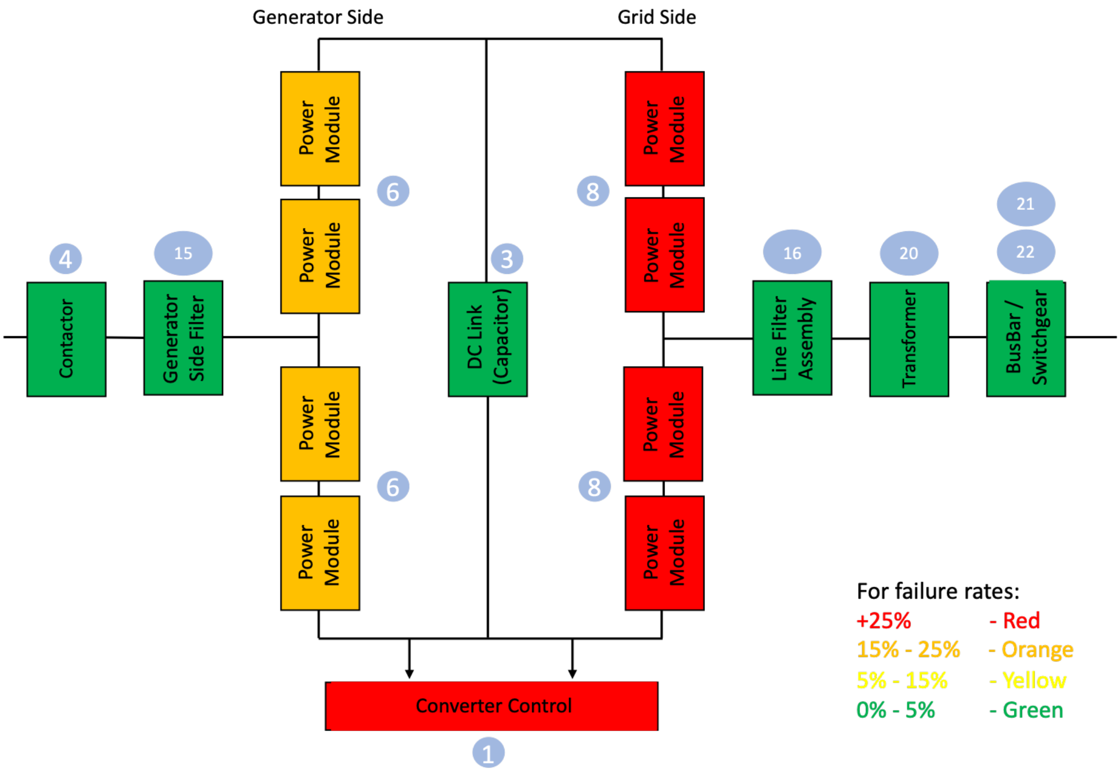

Figure 5. Vulnerability Map Built Based On All The Data From All The Locations (NOTE: Numbering refers to components listed in Table 1)

Table 2. Highest Power Converter Component Failures per Location

Location	1st Highest Component Failure	2nd Highest Component Failure	3rd Highest Component Failure
China	Converter Control Units (33.79%)	Generator Side Power Module (29.66%)	Grid Side Power Module (28.97%)
France	Grid Side Power Module (28.00%)	Generator Side Power Module (24.00%)	Converter Control Units (21.71%)
Germany	Converter Control Units (38.46%)	Grid Side Power Module (23.08%)	Generator Side Power Module (15.38%)
Italy	Grid Side Power Module (31.43%)	Generator Side Power Module (22.86%)	Converter Control Units (17.14%)
Poland	Grid Side Power Module (27.91%)	Converter Control Units (27.91%)	Generator Side Power Module (25.58%)
Sweden	Converter Control Units (41.57%)	Grid Side Power Module (18.67%)	Generator Side Power Module (6.63%)

In China and Poland the failures rates of the top three components (Converter Control Units, Generator Side Power Module and Grid Side Power Module) are all very similar, whereas in Germany and Sweden the failure rate of the converter control units is much higher than the grid side power converter, which is in second place. Also in Sweden there is a big difference between the grid side power module and generator side power module, which are in second and third place respectively.

The results from Italy and Sweden are selected and Figure 6 highlights how the vulnerability maps change according to different locations.

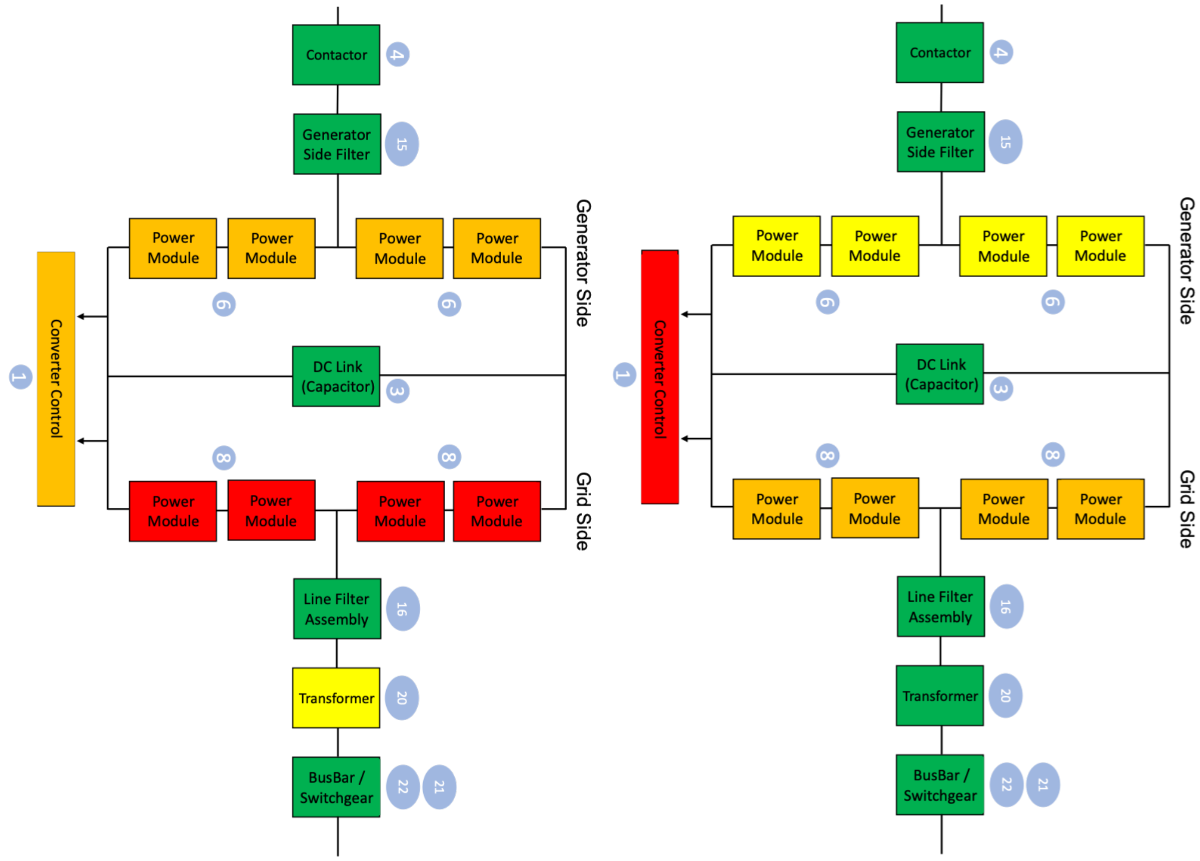

Figure 6. Power Converter Vulnerability Map for Italy (LEFT) and Sweden (RIGHT)

5. Conclusions and Further Work

The analysis carried out has been done for one type of turbine, so the vulnerability map produced cannot be generalised for all turbine types but these results do confirm the results and conclusions determined in multiple papers written by Fischer et al., that the power module is one of the components most likely to fail. In this analysis there were three clear components that failed more then the others and they were the converter control units, grid side power modules and generator side power modules. These three components were the top three no matter where the wind farms were located. The only differences were their position in the top three based upon their failure rates.

By developing a topology of the power converter and calculating the failure rates of each sub-system/component housed within the power converter, the failure rate values can be used to rank each sub-system/component from high to low. Each sub-system/component is assigned a colour, either red, yellow or green, depending on the calculated failure rate value, high, medium or low, respectively.

The vulnerability map is easy to read and provides sufficient information to clearly identify which sub-systems/components to consider when determining lifetime extension, to enable an efficient inspection and maintenance plan for this purpose to be established.

Future work will look at further breaking the power converter topology down and identifying the exact location of each component within the power converter, as this will help provide a more accurate vulnerability map. This will require further information from the internal structure of the power converter units, which can be achieved e.g., through elicitation and corresponding with power converter manufacturers. Investigating why failure rates changed for certain components within turbines in different locations (countries) plus looking for correlation between external drivers such as wind speed, temperature, humidity etc. and component failures is also planned for future work.

6. Acknowledgement
Thanks go to the EPSRC for supporting this work through the EPSRC Centre for Doctoral Training in Wind and Marine Energy Systems and Structures (Grant Number EP/S023801/1).

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