# Influence of the Mission Profile on the lifetime modelling of the Wind Turbine Power Converter – A review

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***Abstract*—Offshore wind energy is currently the leading offshore renewable energy technology and plays an essential role in achieving a low carbon economy in Europe. Offshore wind turbines, as a result of the harsher offshore environment, suffer from high O&M costs, and as such a high overall LCOE. These higher O&M costs can be reduced by focusing on the most critical subassemblies of the OWT, by either improving the reliability of the subassembly or by better understanding the failure mechanism, and thus optimizing the O&M strategy. The power converter is identified as one of the most critical subassemblies as risk of the operation of the OWT in terms of maintainability and availability. The reliability of the power converter is heavily influenced by both its steady-state and its dynamic thermal behavior, and as such great attention will be paid to the literature related to the thermal behaviour of the power converter. This paper seeks to provide a comprehensive overview on how the typical mission profile of an OWT influences the thermal loading. The paper seeks to propose a comprehensive and up-to-date literature review related to the lifetime modelling of the power converter, and to highlight some of the main challenges yet to be tackled in the reliability analysis of the power converter, suggesting future areas of research.**

***Keywords — Levelized Cost of Energy (LCOE), Operation and Maintenance (O&M), Power Converter Reliability, Insulated-gate bipolar transistor (IGBT) component, Floating Offshore Wind Turbine (FOWT), Lifetime Modelling, Thermal Cycling***

## I. INTRODUCTION

As of 2018, the cumulative installed capacity of offshore wind in Europe was 18.5GW, and will continue to grow very rapidly [1][2]. European offshore wind farms are primarily concentrated within the North Sea, Irish Sea, and the Baltic Sea, with an average water depth of 27m. In order to access the richer wind resource located further offshore, at deeper water depths (>50m), and to deal with the decline of available shallow water sites, the use of Floating Offshore Wind Turbines (FOWT) will be required [3]. FOWT, however, due to the harsher environmental conditions, will likely suffer from high O&M cost, which may account for as much as 30% of the LCOE [4] of the offshore wind farm, and must be reduced to make offshore wind energy competitive with other power generation technologies. This large O&M cost can be reduced by optimizing the O&M strategy of the most critical subassemblies of the OWT system, and by improving its reliability. An essential aspect of optimising the O&M strategy involves performing a Failure Mode and Effects Analysis (FMEA) on a generic offshore wind turbine system. An FMEA reviews the different subassemblies of the OWT system and identifies the potential failure modes and their cause and effect on the OWT system. The FMEA analysis in [4] found that the power converter, yaw system, and the gearbox had the most severe impact regarding risk to the operation of the OWT (in terms of maintainability and availability) [5]. This was shown and validated in another paper by Sepulveda et al., who defined the different subassemblies of the OWT in terms of a Risk Priority Number [5]. The power converter was ranked as the subassembly with the highest RPN rating, and as such will play an essential role in reducing the O&M cost of the offshore wind farm. Based on four public domain surveys, focusing on onshore wind turbine systems, it was found that the subassembly characterized as 'Electric System and Electric Control' has the highest failure rate, but a relatively short downtime, in the context of OWT systems. The failure rate of the power converter and control tends to be higher than other subassemblies by a factor of around two to four [6]. This was considered insignificant in the case of onshore wind turbines, as repairs could be done easily and quickly, but this is no longer the case with OWTs. The problem with the offshore environment is that the frequently failing power converter will require longer transit times, and accessibility to the OWT will become more restricted [7]. Another study [8] found that the movement of power converters from Partially Rated Converters to Full Rated Converters caused for an increase in the failure rate by a factor of five.

A reliability analysis carried out on 400 wind turbine systems, using PMSG and FRC, found that the cooling system has the most significant impact on the reliability of the power converter, followed by the converter control module, and then the electrical connections. Issues related to the failure of electrical components such as the Insulated Gate Bipolar Transistor (IGBT) are included in the electrical connection failures. Most electrical connection failures were defined as major repairs, and required between € 1k and 10k to fix, and as such had serious financial implications in terms of the O&M cost associated with the power converter. Majority of cooling system and control module faults were considered as minor repairs, and required less than € 1k to repair [9]. Also, based on an industrial survey which focused on the different components within the power converter, it was found that the DC link capacitor [10] and the semiconductor devices [11] were the most sensitive components within the power converter [12][13]. This information has therefore led to a massive amount of research involved in optimising the DC link design [14], the cooling system[15], and to better understand how the semiconductor device fails under a variety of different conditions (such as changing the power converter topology, mission profile). It is therefore essential for the lifetime modelling of the power converter to be given serious attention to optimise the O&M strategy of the FOWT system, and thus reduce the LCOE of the offshore wind farm. This paper seeks to provide a comprehensive and up-to-date overview on the influence that the mission profile has on the lifetime modelling of the power converter. The paper will then address some of the knowledge gaps which exist in this area, and will end by proposing some potential future research areas.

## II. STATE-OF-THE-ART REVIEW SUMMARY

A typical power electronics module which makes up the structure of a wire bonded IGBT consists of various layers of different materials. The Silicone chip (semiconductor device) is soldered onto the power substrate (Direct Copper bonded ceramic substrate). This substate has two tasks of providing electrical isolation between the baseplate and the semiconductor device whilst also providing a path for the heat dissipated by the device to the cooling system (liquid cooling is much more common within modern power converters). Electrical interconnections within the power converter module are achieved by the means of an aluminium bonding wire. Then finally a thermal interfacing material is applied between the baseplate (typically made of copper) and the heatsink to minimize the thermal resistance. To protect this module both mechanically and from the environment, it will be encapsulated [16][17].

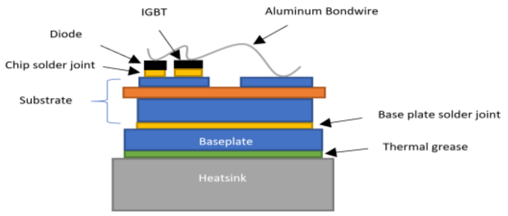

*Figure 1- Structure of an IGBT module*

The reliability issues associated with a module based IGBT are caused by the fact that the IGBT module consists of various materials of different CTE (coefficient of thermal expansion). When the IGBT module experiences thermal cycling, thermal induced stresses will be produced at both the solder joints within the system and at the interconnection between the silicon chip and the aluminium bond wire. These thermal-mechanical stresses experienced within the IGBT will be responsible for solder-joint fatigue [18][19] and bond wire lift-off [20][21], which are the two dominant failure mechanisms experienced within the IGBT module. Information on the number of cycles before either of these failure mechanisms are triggered can be found based on physics of failure model and SCADA data, and as such plays an important role in optimizing the O&M strategy for the power converter of the offshore wind turbine.

Based on acceleration tests of the IGBT it was found that increases in either the junction temperature fluctuation or the mean junction temperature will cause for a reduction in the lifetime of the IGBT device [22]. Bond wire lift-off is caused by the thermo-mechanical stresses caused by the CTE difference between the Al bond wire and the Si chip and the temperature cycling it experiences[23]. This will cause for a crack to initiate and then propagate at the interface of the two materials. The lift-off of the bond wire will occur when the crack size has reached a certain level. The reliability of bond wire lift-off however is of less importance nowadays as the improvements in bonding methods, strain buffers, and protections methods have reduced this type of failure to the extent that it does not pose any significant threat to the reliability of the power converter [24]. Solder joint fatigue is caused by the thermal stresses produced as a result of the thermal cycling and the difference in CTE of the two layers of material sandwiching the soldering joint. Within an IGBT exists two such solder joints, one between the ceramic substrate and the silicon chip & the second between the ceramic substrate and the baseplate. The solder joint under the highest level of stress is situated between the ceramic substrate and the baseplate due to the larger difference in CTE. The shear stresses produced will cause for a crack to be produced and will propagate throughout the solder joint and lead to a reduction in the heat handling ability of the IGBT, which in turn will increase the junction temperature of the device [25]. Both failure modes tend to be triggered by temperature and thermal stresses acting on them [26]. As the most critical stressor to the power electronics is the thermal behaviour, it is often used as an indicator of the remaining life of the power converter

Other failure mechanisms for the power converter includes latch-up, bond wire heel cracking, and the failure of the CCU. Latch up is a failure mechanism of the IGBT caused by the switching off transients or by a high level of collector current and results in a loss of gate control. Bond wire heel cracking is caused by the fatigue created by the repeated flexure of the bond wire but as this is a slow process it rarely will happen within a modern day IGBT. The converter control unit (CCU) is one of the components of the power converter with the lowest level of reliability [27]. The failure of the CCU is caused by either thermal cycling or due to repeated overvoltage spikes between the collector and emitter junction of the IGBT. This will result in the loss of control of the power converter and will result in thermal breakdown [27].

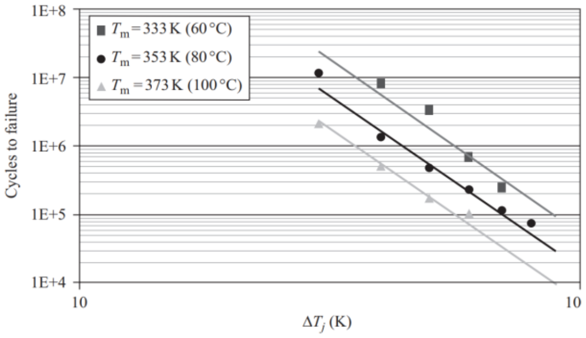

*Figure 2- Influence of the thermal behaviour of the IGBT on its lifetime [6]*

The prediction of the amount of time before the power converter fails is based on the dominant failure mechanisms and the thermal stresses acting on the IGBT module. It is therefore essential to understand how the thermal stresses acting on the IGBT module are generated within an offshore wind turbine system. The input condition to the thermal generation model includes the condition of the grid, the ambient temperature, and the incoming wind field acting on the offshore wind turbine. Further information regarding the influence that grid code compliance has on the thermal performance of the offshore wind turbine can be found in [28]. The offshore wind turbine system will initially convert the kinetic energy of the wind into mechanical energy (based on the torque acting on the rotor and the speed of the rotor). The next stage involves either a gearbox which will step down the torque and increase the rotational speed or in the case of a direct drive system will completely omit the gearbox from the design. This mechanical energy will then be converted into electrical energy using the PMSG (common generator type associated with an offshore wind turbine) and the power flow between the OWT and the grid will be regulated and controlled via the use of the Full Rated Converter [29]. The flow of electrical power within the IGBT will produce power losses in the form of heat. These power losses will be caused anytime the IGBT module conducts current (conduction losses) and anytime the IGBT module is switched on or off (switching losses) [30]. The power losses will act as an input to the thermal model of the IGBT module and will be used to calculate the temperature at the junction and the case of the device. Information regarding the influence of different circuit topology such as the unequal thermal loading experienced within a three-level converter is addressed in [31]. The ability to reduce thermal loading of the semiconductor device by the movement towards press-pack technologies (which eliminate the dominant failure mechanisms experienced in module based IGBTs but introduces new failure mechanisms such as spring fatigue [33]) is discussed in [32]. The ability to modify and improve the thermal performance of the power converter by using modulation techniques such as discontinuous pulse width modulation is discussed in [34][35].

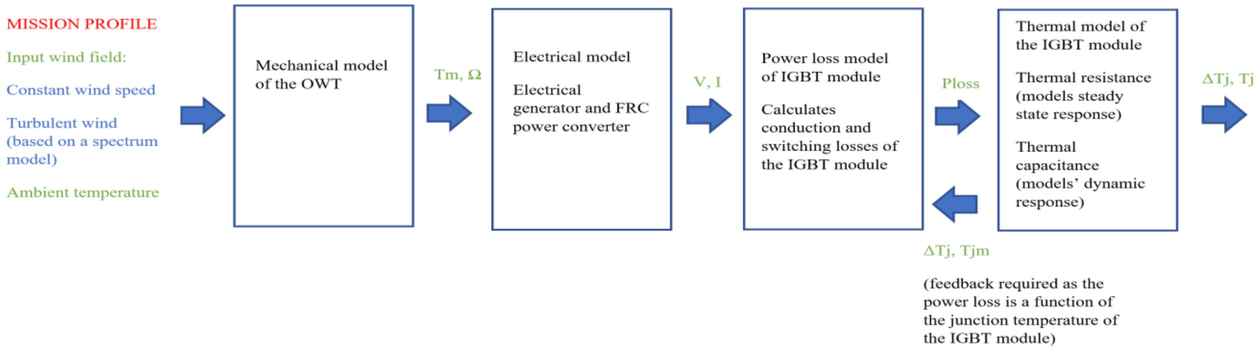

*Figure 3- Thermal stress generation process for an OWT system*

The thermal model used for the IGBT module will convert the power losses of the semiconductor devices into the temperature level at different points of the device. Current literature represents the devices in terms of thermal resistances for the steady state behaviour and thermal capacitances to represent the thermal dynamics of the device [36]. Currently the thermal models are either based on foster network, which will involve parallel connections of the RC elements, or cauer network, which will involve the series connection of the RC elements. The foster model will be provided by the manufacturer of the IGBT module [37], and will be based on the mathematical fitting of the measured thermal behaviour of the devices. The cauer model is based on the physical properties of the device and can readily be converted from the foster model provided by the manufacturer's datasheet. A more advanced thermal model has been proposed and combines the advantages of both the cauer and foster network. This model allows for more accurate predictions of the steady state and dynamic response of the junction and case temperature. Using this improved model, the power loss output of the IGBT module will be filtered through a single layer cauer RC unit. The output of this single layer RC unit will provide the case temperature of the IGBT module and will provides larger fluctuations in the case temperature (compared with the purely foster based thermal module). The output of the Foster's network will provide the function temperature of the IGBT module [38]. The final step of the lifetime modelling of the power converter involves the conversion of the thermal stress profile of the IGBT into its remaining useful life. The random thermal profile of the IGBT can be converted into regulated thermal cycles using the rain flow counting method. The regulated thermal profile can then be used to predict the lifetime based on the lifetime model provided by the manufacturers. The lifetime model will then provide the number of thermal cycles till a particular failure mechanism is triggered and typically will be based on the B10 lifetime (this would be the lifetime required for 10% of the testing population of IGBT modules to fail). The total consumed lifetime can then be found according to miner's rule, which involves finding the summation of the consumed lifetime for each thermal cycle [38]. The mission profile assesses the influence of the wind speed and the ambient temperature on the thermal loading of the power converter. The influence of different disturbances on the thermal behaviour of the power converter is characterized by their dominant time constant. The long-term thermal loading of the power converter takes into consideration the influence of the hourly/daily/yearly variations of the wind speed and ambient temperature on the thermal loading of the power converter. The long-term thermal loading of the power converter will involve intensively large fluctuations in both the case and junction temperature. Under long-term thermal loading the most intensely consumed B10 lifetime is for the chip solder and the baseplate solder [38]. The medium-term thermal loading of the power converter accounts for the turbulent nature of the wind speed, the ambient temperature, and the mechanical behaviour of the OWT. Under medium-term thermal loading, it was found that the junction temperature will be higher than the case temperature. The fluctuation amplitude is much less intense that that experienced with long term thermal loading. At average wind speeds of less than 11m/s, it can be that the fluctuation amplitude of Tj and Tc increases with wind speed. The fluctuation amplitude is much smaller in amplitude for average wind speeds exceeding 11m/s. Significant temperature cycling will occur during the cut-in or cut-out behaviour of the OWT. [38]The most consumed B10 lifetime under medium term loading is the baseplate solder, followed by bond wire lift-off, and then the chip solder. The most consumed B10 lifetime occurs around the rated wind speed due to the activation of the pitch system. Short-term thermal behaviour of the IGBT is mainly dominated by the nature of the periodic AC current flowing through it and grid faults. Short-term thermal loading of the power converter will involve a relatively constant case temperature. The junction temperature will oscillate at a constant swinging amplitude at the fundamental frequency of 50Hz in the UK. Currently the manufacturers cannot provide an accurate lifetime model for the short-term thermal loading, as the minimum cycling time during the test was 2s and the fluctuation amplitudes under test were much larger. Under short-term thermal cycling the lifetime of the power converter is purely based on the junction temperature (mean and fluctuation amplitude). The short-term thermal behaviour of the power converter cannot distinguish between the different failure mechanisms (such as bond wire lift-off and solder joint fatigue). The largest damage to the power converter happens at a wind speed range of around 14m/s to 15m/s which is the point of where the turbine generates the maximum output power [38].

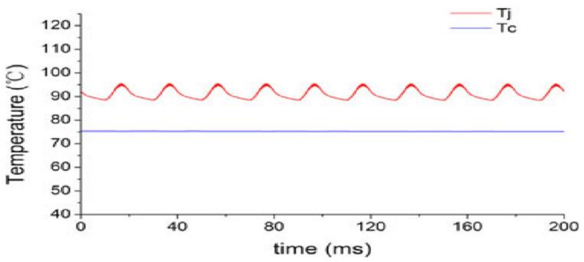

*Figure 4- Short term thermal loading of the power converter[38]*

Another paper proposes an alternative method of estimating the junction temperature of the IGBT/diode at fundamental frequency taking into consideration the mission profile (wind speed and ambient temperature profile). The original method used for simulating the short term thermal behaviour of the device involves converting the average power loss of the IGBT (diode) into 4 discrete pulses (used to represent the half sinewave power loss of the IGBT (diode) experienced every fundamental cycle). Each pulse will last for a duration of 1/8th of the fundamental period and the amplitude of each pulse will be equal to a given factor specified in[39] multiplied by the average power loss. This method however has the shortcoming that it misses out the transient stage of the junction temperature (as it takes a few fundamental cycles before it reaches steady state) [40]. The newly proposed method in [41] for estimating the junction temperature helps combat this problem and allows for the computational time to be reduced. The new proposed method involves estimating the junction temperature (long term) using a derived mathematical expression which only requires the thermal parameters (provided by the IGBT/diode manufacturer datasheet), the average power loss, and the fundamental frequency to estimate the junction temperature fluctuation of the IGBT/diode. This newly proposed method improves the accuracy of estimating the junction temperature fluctuation at a variety of different fundamental frequencies (tested at a minimum fundamental frequency of 1Hz and a maximum of 50Hz).

Recent work has been done in improving the accuracy of the prediction of the lifetime of the IGBT/diode and its thermal circuit. This newly proposed method involves calculating the damage caused by predominant failure mechanisms such as solder joint fatigue and using it as feedback to the thermal model. As the crack propagates through the solder joint of the IGBT/diode, this will result in an increase in the thermal resistance of the IGBT/diode whereas the capacitance is less sensitive to damage and as such is assumed to be constant in the new model [42]. The increase of the thermal loading as more damage in the solder joint is captured in this model and as such will reduce the lifetime expectancy of the IGBT/diode compared with the traditionally used linear model[42].

Another analysis carried out in [43] assessed the influence of the dynamic nature of the wind on the thermal performance of IGBT/diode. The use of Blade Element Momentum theory allowed for the impact of wind shear (how the wind speed increases with elevation above ground) and how the wind field is distributed over the entire wind turbine rotor to be taken into consideration. Unsteady BEMM then allowed for the force acting on each component of the blade to be calculated (allowing for the mechanical torque to be derived). This simulation found that the low frequency turbulent component of the wind (0 – 0.01Hz) had a minor impact on the thermal dynamics of the IGBT/diode as a result of the high inertia associated with the wind turbine rotor and PMSG. Further details of this analysis can be found in [43]

The DC link capacitor is another weak point within the power converter as it suffers from a high failure rate. It is therefore essential for the influence that the mission profile has on the lifetime of the DC link capacitor to be assessed. The most used model to predict the lifetime of the DC link capacitor can be found in [44] and calculates the lifetime of the DC link capacitor using models provided by the manufacturer. This lifetime model then assesses the lifetime of the DC link capacitor using information on the DC link voltage (under test and operational condition), the activation energy, the ambient temperature, and the hot-spot temperature of the DC link capacitor. Within the wind industry the two commonly used type of capacitors used includes the aluminum electrolytic capacitor which provides a high power density and a low cost and the metalized polypropylene (MPF) capacitor which provides a longer lifetime and can handle higher voltage levels [45].

To find the lifetime of the DC link capacitor it is important to predict the temperature of the “hot-spot” of the DC link capacitor. The first step of this process involves finding the power loss of the capacitor and then inputting it and the ambient temperature (part of the mission profile) to the capacitor thermal model to find the hot-spot temperature. The power loss of the capacitor can be found based on the Equivalent Series Resistance (which is a function of the frequency) and the high frequency current ripple of the DC link capacitor. Where the ripple current flowing through the DC capacitor can either be found using two different techniques. One technique involves calculating the power losses by calculating the PWM harmonics associated with the DC link capacitor, this method is however time-consuming and requires a complex double Fourier analysis [46]. A simulation software can also be used to find the harmonics of the DC link without the requirement of calculating the DC capacitor current [47]. The calculated power loss and the ambient temperature profile will be inputted to the thermal model of the capacitor and allow for the hot-spot temperature (Tc) to be calculated.

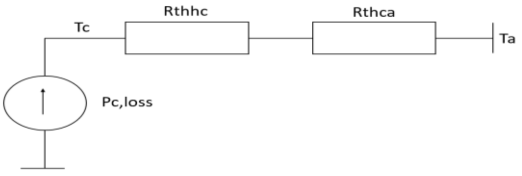

*Figure 5- Thermal circuit of the DC link capacitor*

The lifetime of the capacitor can then be found by inputting the wind speed profile to the electrical model of the drivetrain. This model will provide information on the amount of current ripple and voltage ripple at the DC link of the power converter system. This information from the electrical system coupled with the ambient temperature profile will act as the inputs to the thermal model of the capacitor and will calculate the hot-spot temperature. This information from the thermal model and the electrical model can then be used to predict the lifetime of the DC link capacitor based on the commonly used model provided by the manufacturer [48]. The manufacturers typically provide the B10 lifetime of the capacitor, which is the time taken for 10% of the sample population of the DC link capacitors to fail (it is important to check the test conditions and the type of capacitor when calculating the lifetime of the DC link capacitor). In general it is found that for a higher current ripple, higher ambient temperature, or a higher DC link voltage will all lead to a reduction in the reliability of the DC link capacitor [49].

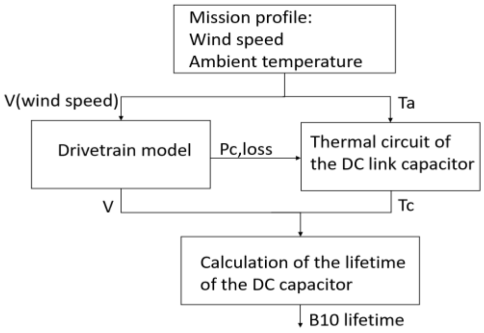

*Figure 6- Flowchart used to find the B10 lifetime of the DC link capacitor*

## III. KNOWLEDGE GAPS AND PROPOSED AREAS OF FUTURE RESEARCH

This section seeks to address some of the knowledge gaps which currently exist in assessing the thermal performance of the power converter. Majority of studies in this area have assessed the influence of the turbulent nature of the wind, the ambient temperature, and tower shadow on the thermal performance of the power converter. This however does not take into consideration the mechanical dynamics (and non-linearities) of the entire OWT system, and as such will not provide an accurate medium/long term thermal loading of the power converter. Furthermore, FOWT systems tends to have larger dynamic responses compared to fixed bottom systems, and as such the current methods may not be sufficient in assessing the influence of the mechanical behaviour on the thermal loading of the power converter. Currently, the important dynamics associated with a FOWT system, such as the hydrodynamics (where the wave could be included as part of future mission profiles when assessing the thermal dynamics of a FOWT system), the motion of the platform (surge, heave, sway, yaw, pitch, roll) and others have been neglected in assessing the medium/long term thermal loading of the power converter. Another important weakness in the current assessment of the medium/long term thermal loading is that the models used for the aero-hydro-servo-elastic dynamics (relative mainly to the rotor, the tower, and the foundation) and the thermo-electro-magnetic dynamics are completely decoupled. In reality, the two systems interact with each other, and as such a fully coupled approach may be required to capture any interaction that could be important in the evaluation of the medium/long term thermal-fatigue caused within the IGBT module. It is also currently unknown how the different topologies of the FOWT systems (semi sub, TLP, spar) [50] will influence the thermal performance of the power converter and as such this should be given serious attention, especially as an increasing number of FOWT farms are now planned.

Based on these current limitations in our knowledge, a list of some proposed areas of future research are listed below:

- To identify which aspects of the FOWT aero-hydro-servo-elastic dynamics may have a substantial impact on the thermal dynamics of the power converter;
- To compare the influence of different FOWT topologies (Spar, TLP, Semisubmersible) on the thermal performance of the power converter;
- To optimize the design of the power converter taking into consideration the FOWT topology

The first research area proposed involves the development of a holistic aero-hydro-servo-elastic model coupled with a thermo-electro-magnetic model (taking into consideration the DC link capacitor also, as it is typically ignored in the analysis but is considered one of the critical drivetrain components) of the drivetrain. The system would be fully coupled, and as such would address the problem of the two systems not interacting with each other. This model would also address the limitations in the mechanical models currently used and would allow for the mechanics of the complete FOWT to be taking into consideration. Performing a spectrum analysis of the thermal performance over an appropriately long simulation run (to capture all the essential mechanical dynamic behaviour) will allow to better understand which are the strongest coupling between the aero-hydro-servo-elastic and the thermo-electro-magnetic dynamics. This knowledge will help guide the design of the FOWT and the power converter system (in terms of cooling system, control system, etc.).

Another proposed area of research will involve comparing the influence of the three different FOWT systems (Spar, Semi sub, TLP) on the thermal performance of the power converter.

For example, FOWT of the semisubmersible type tend to have a larger dynamic response than the TLP and spar type, and as such is predicted to cause more thermal-fatigue damage to the power converter. This as a result means that the design and control of the power converter within a semi-sub system would be very different to that of other FOWT topologies.

Another proposed area of research is a newly designed control system for the power converter based on the dynamics of the FOWT system (for example applying a filter to reduce the impact of dominant frequencies present in the power spectrum of the power converter). This would allow for the thermal stresses acting on the power converter of the specific FOWT to be reduced and as such would allow the reliability to be improved.

Finally, on the longer term, the design and optimization of a completely new FOWT system, taking into account the consideration above, is suggested. This new design would not only take into consideration both the mechanical integrity of the structure but would also take into consideration the thermal fatigue experienced within the power converter. The finalized design would achieve a good level of performance in terms of the mechanical behaviour and the thermal behaviour of the power converter.

## IV. CONCLUSION

A comprehensive and systematic literature review on the influence that the mission profile has on the lifetime of the power converter has been presented in this paper. The paper initially addressed that the weak points within the power converter includes the IGBT module and the DC link capacitor. The dominant stressor influencing the lifetime of the DC link capacitor and the IGBT modules are its thermal behaviour. The hot-spot temperature is used for the capacitor and the steady state and dynamic behaviour of the junction temperature for the IGBT module. The thermal behaviour will trigger the dominant failure mechanisms of these two devices, which is why lots of research in this area involves understanding how different aspects of the design influence the thermal behaviour of the power converter. Many factors influence the thermal behaviour of the power converter, but this paper addressed the influence of the mission profile on the thermal loading and as such the lifetime of the power converter. The DC link capacitor lifetime involved using information from both the electrical system and the thermal circuit of the capacitor to calculate its B10 lifetime (which is a lifetime model provided by the manufacturer of the capacitor). This information alongside information from the electrical model can be used to derive the B10 lifetime of the capacitor. This module IGBT which is sensitive to not only the steady state thermal behaviour but also the dynamic behaviour of the junction temperature. This led to the thermal behaviour of the IGBT being investigated at various different time constants. Short term thermal loading caused for a constant and small fluctuation in the junction temperature and a constant case temperature. Medium term thermal loading which is primarily caused by the turbulent nature of the wind and the behaviour of the mechanical system. The medium-term thermal loading involved larger fluctuations in the junction and case temperature and the largest damage to the device occurs near the rated wind speed due to the activation of the pitch system. The long-term thermal loading takes into consideration the influence of environment conditions (such as the hourly/daily changes in the wind speed and ambient temperature) on the thermal behaviour of the IGBT module. The long-term thermal loading involves the largest fluctuations in the case and junction temperature and as such has the largest impact on the lifetime of the IGBT module. The paper then addresses some of the limitations in the state-of-the-art method used to assess the influence of the mechanical dynamics on the thermal performance of the power converter. For example, the impact that the motion of the FOWT system (such as the pitching of the platform) or the influence of the hydrodynamics on the thermal performance is yet to be addressed. This gap in knowledge needs to be addressed to increase the accuracy of the medium term/long term thermal loading profile of the power converter. The paper then ends by suggesting some future areas of research which will be of benefit to the industry.

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