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Condition Monitoring of Power Electronics for Offshore Wind

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Abstract
Reliability is vital for the success of offshore wind, which is a significant part of the future energy landscape. Power-electronic converters are used in all existing offshore turbines and will be present in most future designs. The relatively high failure rate of the current generation of power-electronic converters has become an issue, as more and more turbines are deployed offshore. This article presents a review of the ageing-to-failure mechanisms of converters in the context of wind turbine application, stressing the impacts of incessant thermal cycling associated with the reduced frequency operation on the generator side. Possible ways of condition monitoring are discussed for improving reliability and availability. A cost–benefit analysis of condition monitoring is carried out for justification.

Introduction
Offshore wind is increasing at an annual rate of 20–40%, doubling the total capacity every 2–4 years. By the end of 2012, 5 GW had been installed, and this is expected to increase to 40 GW by 2020 when 4% of EU electricity supply is expected to be from offshore wind [1]. The growth is partially attributed to the improved wind resources and reduced planning restrictions, as compared to onshore where exploitation in many places has reached saturation. In some countries, such as Germany and Denmark, there are proposals to refurbish old wind farms with larger turbines if the transmission network can be upgraded accordingly [2].

Overall, offshore wind still faces the challenge of becoming economically competitive with other low-carbon technologies, such as nuclear power and combined cycle gas turbine. For example, with regards to offshore wind, the UK target for 2020 is to bring down its present-time levellised cost of energy by about 30% [3]. To achieve that, the major issues currently addressed are foundations, substations and subsea cables – all major parts of the capital expenditure. But operation and maintenance (O&M) is also a large cost contributor throughout the whole lifetime of any offshore wind project and as such it has the potential to make it or break it.

It was recently estimated by GL Garrad Hassan that by 2025, the O&M market for offshore wind in the UK alone would be over £2bn per annum [4]. Currently, O&M counts for 18–23% of the total cost of energy from offshore wind farms [5]. The earlier offshore wind farms are typically within 10 km from shore with a water depth of less than 20 m. But as the availability of such sites is being exhausted, new offshore wind farms will be moving to further and deeper locations. This means that access will be more difficult and the O&M cost therefore is expected to escalate. To reduce the main components of O&M cost: insurance, downtime, transport, repair and spare parts, design reliability must be improved. Unfortunately, no design is 100% fault-proof as confirmed by bitter experience with offshore wind turbine gearbox and generator failures, so there is also a need for improved visibility over the plant's operation. Condition monitoring can provide this visibility and is the only means of detecting the precursors and preventing catastrophic failures.

Offshore wind turbines were initially rated at 2–3 MW; currently this has gone up to 5–8 MW and is expected to reach 15–20 MW in the future. They are of variable speed drive trains to manage the stresses on the mechanical components. Except for the concept of using a variable ratio hydraulic gearbox and synchronous generator directly connected to the AC grid, all wind turbines include a power-electronic stage to control the power flow and manipulate the rotor speed [6]. From an electrical system point of view, there are two main configurations as shown in Fig. 1:

- the doubly-fed induction generator (DFIG) with a partially rated converter between the machine rotor and grid;
- the arrangement with a fully rated converter connected direct-in-line (DIL) with the stator windings of an induction or permanent magnet generator and the grid (this latter type comprises several modular designs [7]).

Onshore statistics indicate that, on average, the power-electronic converters contribute to about 13% of the wind turbine failure rate and about 18% of the downtime [8–11], which makes them the second most susceptible subassembly after the blade pitch mechanism. At the same time, the average availability of onshore turbines is typically above 95%. For an offshore deployment, however, the same failure rate (even if the failures are trivial) can amplify the downtime impact because of the difficulty of access. This impact will be even more pronounced during windier spells which can otherwise be prime time for generation.

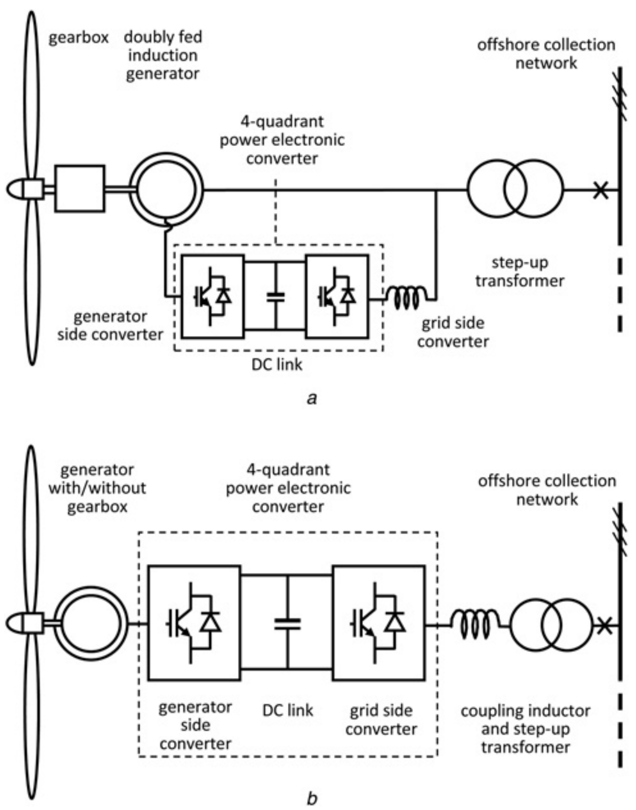

Fig. 1 *Two converter arrangements for wind turbine*
a DFIG
b Generator with DIL converter

Offshore wind turbine manufacturers and operators are unwilling to share the real-life data about failure type, frequency and downtime duration – unsurprisingly – but some publications mention availability recorded in near shore farms, which is significantly lower than the typical onshore figure [10, 11]. Based on the onshore failure rate records, it can be reasonably assumed that a significant portion of the offshore downtime will be the result of power-electronic converter failures.

Regardless of the turbine type, the basic circuit configuration of the converter is similar. Two voltage-source converters (VSCs) share a DC-link, allowing four-quadrant real and reactive power flow viewed from the AC sides of the generator and the grid. Fig. 2*a* shows a VSC diagram, which is typically of three-phase and consists of six insulated gate bipolar transistor (IGBT) arms, each with a diode in antiparallel. They are packaged in the form of a power semiconductor device module which can be rated up to hundreds of kilowatts. Fig. 2*b* is the image of such a power module complete with its packaging. To form a four-quadrant commercial converter module, two of these are used in a back-to-back (BTB) topology with added DC-link capacitors, instrumentation circuitry, control/protection schemes and forced air/water cooling arrangements. The fully rated converter in a wind turbine (in the multi-MW range) can be constructed by paralleling several converter modules [12].

In the BTB topology, although the grid-side VSC operates at the grid frequency, the frequency of the machine-side converter depends on the generator design and the speed. For reasons to be explained later, the frequency will affect the device module thermal cycling, a dominant root cause of failure. Previously, the converters were often based on drive designs, but nowadays the special requirements of wind turbine operation are increasingly recognised.

In connection with the above information, this paper discusses the possibility, cost and potential benefit of applying the concept of condition monitoring to power-electronic converter modules in offshore wind turbines. This will allow visibility over the development of the degradation, so that appropriate control or maintenance actions can be applied.

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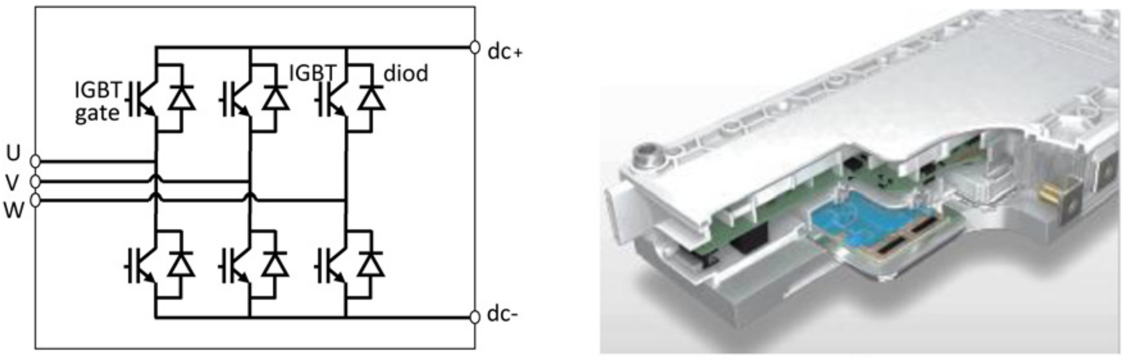

a *b*

Fig. 2 *VSC circuit configuration and a power device module (Source: Semikron)*
a Circuit diagram of a VSC module
b Picture of a power module for VSC

Ageing to Failure Mechanisms in Power Electronics

Recent studies have investigated the reliability, performance and failure mechanisms in power-electronic converters for a fleet of wind turbines [13], targeting the early stage failures (i.e. the infant mortality along the bath-tub curve). As the fleet ages, damages of a wear-out nature will be progressively observable. Industry-based study has already identified that the most fragile converter components are the power semiconductor devices and electrolytic capacitors [14], so their performance in offshore wind context will be of special interest.

Fig. 3 shows a cross-sectional view of the power device module similar to what is widely used in the current generation of power-electronic converters for wind turbines. The structure is made of materials with different coefficients of thermal expansion (CTE). The mismatch between CTEs gives rise to the fatigue stresses during thermal cycling. In this process, cracks and voids can develop across the interfaces between layers of the vertical structure, increasing the thermal resistance along the path of heat dissipation. As a result, the semiconductor junctions will operate at increasingly higher temperatures leading to destruction.

This mechanism is considered [14] a root cause of both bond wire lift-off, which reduces the electrical conductivity, and solder pad degradation, which reduces the thermal conductivity. To avoid/reduce the use of bond wires and solder, press-pack architecture has been developed for the semiconductor devices. It is believed that the press-pack structure could slow down the degradation process by at least an order of magnitude. Fault tolerance through on-line redundancy can also be easily achieved using press-packs since they fail short circuited. This has been suggested as the best way currently available for dramatically improving offshore wind converter reliability [15] and is now being introduced to wind turbines in spite of the higher cost.

It must be pointed out, however, that although more reliable, the press-pack devices can still degrade: during the formation of their conducting alloy and at later operation stages, molten aluminium attacking molybdenum (Mo) can form cracks in the base plate, reducing its thermal conductivity; given time, the electrical conductivity can also deteriorate owing to the generation of intermetallics.

Another peculiarity of press-pack devices is that the metal plates compressing the semiconductor chips

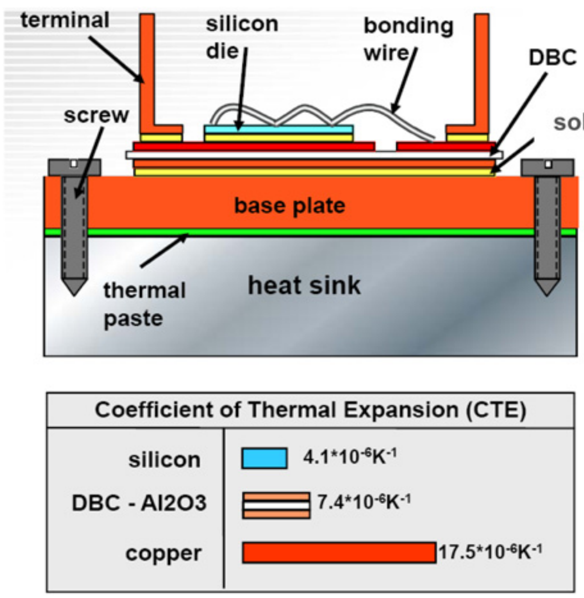

Fig. 3 *Power device module structure (Source: Semikron)*

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conduct both electricity and heat out of the device. They are a live component that cannot be connected to traditional heat sinks. Press-pack systems are therefore cooled by direct flow of non-conductive liquid, such as de-ionised water. Such converters have a monitoring unit that samples the cooling water flow and shuts down if the water dissolved particulates or the ion content reaches certain level when the water can potentially become conductive. Although this is not a failure as such, it necessitates human involvement to change the liquid, and in offshore environments this may be an extra source of downtime (depending on how often it happens).

The above problems can be addressed with condition monitoring, which is the only way to achieve visibility over the system's operation and potentially prevent catastrophic failures.

In the context of existing wind turbine technology, it was mentioned that there is evidence of the machine rotor-side VSC failing more quickly than the grid-side VSC in DFIG systems, although the two converters process roughly with the same real power. This is because, close to the synchronous speed, the machine-side converter operates at very low frequency. However, the rotor current will not be zero because it is necessary to maintain magnetomotive force balance with the stator current, even though the real power processed by the converters is about zero. As a consequence, the thermal capacitance of the power module will have little attenuation effect on the slow variation of the junction temperatures which will then cause deep thermal cycling. Fig. 4 shows the simulated junction temperature curves for

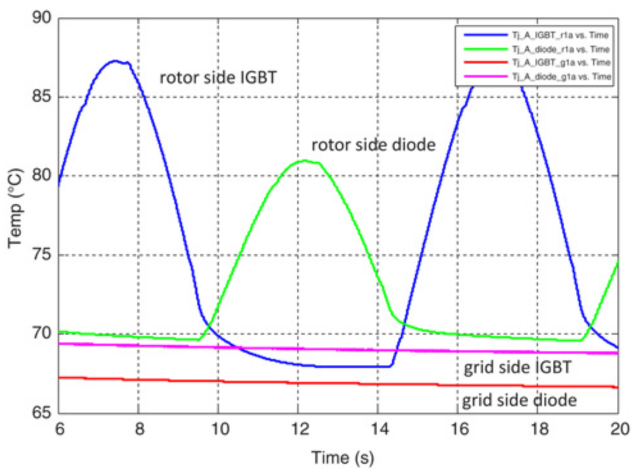

Fig. 4 *Simulated temperature variations in VSCs in a DFIG system*

the machine and grid-side converters near synchronous speed. The junction temperatures of the machine-side IGBT and diode excurse by 10–20°C, whereas those on the grid side the changes are hardly visible. A solution recently proposed is to de-rate the whole turbine system near the synchronous speed, with a reduction of generation efficiency [16].

The speed of a DFIG machine typically varies ±30% around the synchronous speed. At the maximum speed, the stator real power is P_{sn}, and the rotor real power is $P_{rn} = 0.3P_{sn}$. The total real power is $P_{\mathrm{DFIG}} = 1.3P_{sn}$. As the speed reduces, the turbine power would reduce in a cubic relationship. At the synchronous speed, the total real power is then

$$P'_{\mathrm{DFIG}} = (1/1.3)^3 1.3P_{sn} \simeq 0.6P_{sn}$$

This will be purely from the stator side as the rotor power at zero slip is about zero. Therefore, the stator real power and hence stator current will still be as high as 60% of the maximum value assuming a unity power factor. The rotor current will remain correspondingly high. The fact that the rotor real power is zero is due to the rotor voltage (fundamental component) being zero. If the reactive power is to be increased because the wind turbine is not fully loaded, the rotor current provided from the machine-side converter will also increase, thereby increasing losses and the junction temperature variation – a parameter directly related to the power device degradation.

Several lifetime models have been proposed to characterise the ageing process. To account for the effect of thermal cycling, the Coffin–Manson law [17] states that the number of cycles to failure, N_{f}, reduces as the range of junction temperature variation, ΔT_{j}, increases

$$N_{\mathrm{f}} \propto \Delta T_{\mathrm{j}}^{-n}$$

where n is a model parameter. N_{f} also depends on the mean temperature in a complex way. Some self-healing effect may be observed at high temperatures.

For a given mean temperature, a simplified lifetime model of a power device module may be similar to Fig. 5, assuming uniform cycling. For a complicated profile of thermal cycling in practice, the total relative damage is usually calculated in a manner of linear

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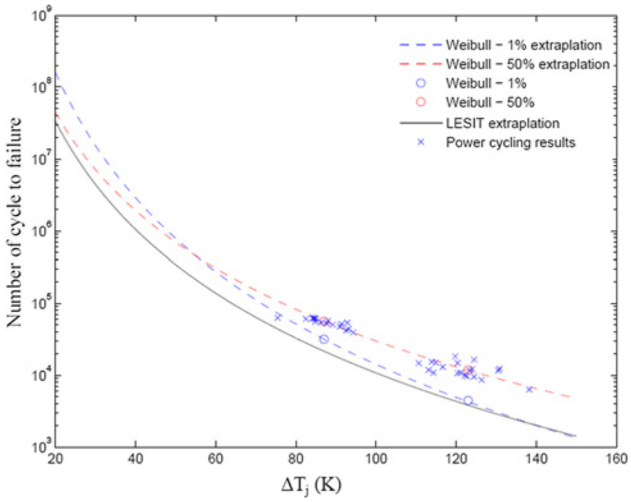

Fig. 5 *Lifetime model [17]*

accumulation

$$D = \sum_{i-1}^{m} R_i = \sum_{i=1}^{m} \frac{N_i}{N_{fi}}$$

where R_i is the fractional damage produced in N_i cycles at stress level i, and N_{fi} represents the number of cycles to failure at that stress level that is, as shown in Fig. 5. Full damage is reached when $D = 1$. It has been pointed out, however, that purely linear methods may not be able to represent the complicated damage accumulation process in the solder pads [18].

For a wind turbine with fully rated DIL converter, thermal cycling can also pose a problem. As offshore turbines become larger, the constraint on tip velocity would require the angular speed to be reduced although the acoustic limit may be somewhat relaxed in the offshore environment [6]. The generator-side converter might then be required to operate at rather low frequency, say maximum 15 Hz. The converter may need to survive 5×10^9 junction temperature cycles with ΔT_j up to 20°C [12], the ageing effect could prove significant.

In addition to power semiconductor devices, other converter components have also caused concern. Capacitors, for example, have been reported as the cause of more than 20% of converter failures [19, 20]. Thin film capacitors with much higher ripple current capability are quickly replacing the older electrolytic technology. Condition monitoring techniques for capacitors have been developed in the past based on on-line measurement of capacitance and equivalent series resistance (ESR) [21]. This article will therefore focus only on monitoring the ageing and fault development of power semiconductor devices.

Condition Monitoring for Power Electronics

The concept of condition monitoring is to extract information about the health condition of a system without disrupting its normal operation. The concept has been applied to motor drives, generator units and transformers whose health conditions may gradually deteriorate over time. For power electronics, particularly power semiconductor devices, condition monitoring is yet to be fully developed because it was traditionally misbelieved that a device either fails or works. This Boolean view adopted by many power electronic systems engineers has prevented a deeper understanding of the ageing mechanisms before complete failure. The pursuit of condition monitoring for power electronics was therefore deterred.

A successful condition monitoring technique depends on two aspects, both of which present certain challenges:

- Capturing of condition signatures that indicate the current health condition;
- Estimation of the remaining lifetime to inform decision on operational management or preventive maintenance.

As discussed above, degradation will usually be accompanied by increased power losses in the module and decreased removal of heat away from it. For this reason, the fatigue stresses will progressively increase, if the degradation goes unchecked and the operating conditions (e.g. the probabilistic distribution of the load level) remain the same. It is therefore important to achieve early detection and precise prognosis of remaining lifetime. For instance, experimental results suggested that a 20% increase of internal thermal resistance of the module would be appropriate to signify the presence of solder fatigue [14].

Changes in the electrical characteristics, for example, switching edges and on-state voltage, are also noticeable with the increase of degradation. Some of these changes, such as on-state voltage, are related to the physical properties of the materials and the interfaces between them. Other signatures, such as the prolonged switching-off edges and increased power losses, are the consequence of elevated junction temperature after the internal thermal resistance has increased owing to ageing. These signatures are generally very sensitive to the operating point of the converter.

To detect the relatively weak signatures, techniques at the device level have been proposed [22–25], but it is still difficult to integrate sensors within the power devices which operate at fast switching frequencies and in a very noisy environment. Converter-level techniques are also being pursued with the incentive of cost saving through the use of the same sensors as for protection, control and normal metering [26–28]. Fig. 6 shows the switching-off transient of an IGBT at different case temperatures; the junction temperature is differentiated by a similar amount as between the different case temperatures. In practice, degradation of the heat conduction property in the module can easily cause the junction temperature to change to such an extent. From Fig. 6, a difference of 15°C causes the switching edge to slow down by about 50 ns for recombination. This is short compared to the total turn off time, about 1 μs. But depending on the switching frequency and DC-link voltage, this can cause a detectable discrepancy in the AC output voltage of the converter whose effect can be captured in the controller signals [28]. The effects of degradation in other drive train components of the wind turbine, such as generator or gearbox, may also propagate into the control system. This is subject to further investigation.

In addition to electrical signals, temperature measurements can also be used to extract important indications of the device condition during operation. Internal temperature is sensed in modern power device modules but direct measurement of the junction temperature is still impossible. The junction temperature affects the power losses inside the module. As a result, condition-dependent temperature signatures can be captured from the outside [26]. The complexity here is that temperature also changes with the operating point which for a wind turbine inherently varies, masking the signatures associated with degradation. Also, temperature measurements can sometimes be deceptive because they depend not only on the electrical operating point at the given moment but also on the history of operation (up to 10–15 min back from the given moment in time). For this reason, electro-thermal modelling is necessary to unmask the effect of the variable operating point. Fig. 7 outlines an algorithm to extract the change in the thermal resistance inside the power device module as an indication of its degree of degradation. With such a temperature-based method, as long as the electrical operating point is closely tracked, it is believed that the degradation in other components of the drive train will not have significant effect on the condition monitoring results.

The algorithm shown in Fig. 7 works as follows: The temperature measurement external to the module, case temperature T_c and ambient temperature T_a, are applied to the heatsink thermal model to calculate the variation in power losses P_{tot} over time. After the dynamic calculations have converged, P_{tot} is used to determine the junction temperature T_j that will cause this power loss (switching and conduction losses) at the given electrical operating point expressed in current, voltage, power factor and so on. The dependence of electrical characteristics of the devices on the temperature has to be known. The increment of the internal thermal resistance, ΔR_{th} with respect to the nominal value R_{th0}, is then calculated as a condition

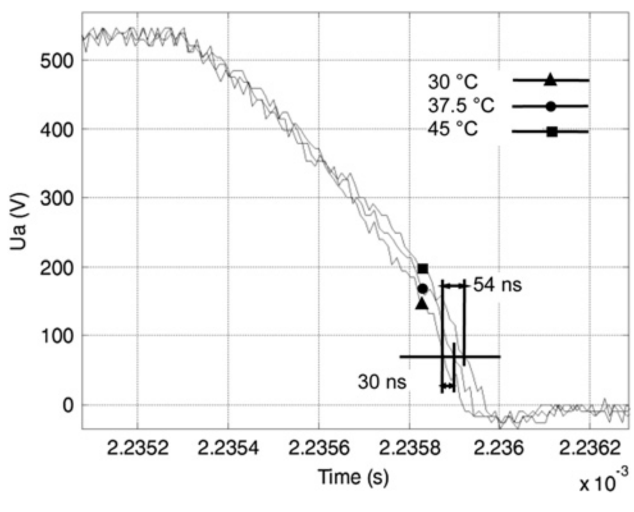

Fig. 6 *Dependence of switching edge on temperature [28]*

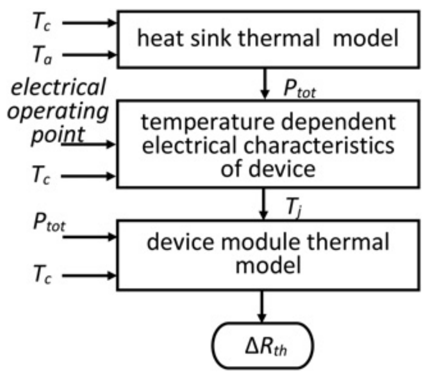

Fig. 7 *A model-based condition monitoring algorithm*

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monitoring signature. Fig. 8 illustrates graphically the calculation result of ΔR_{th} for a small module over a range of converter operating points (with different output current and case temperature), showing that it is indeed possible to extract the change of the internal thermal resistance.

$$\Delta R_{\text{th}} = \frac{T_{\text{j}} - T_{\text{c}}}{P_{\text{tot}}} - R_{\text{th0}}$$

The above description is perhaps simplified to the extreme in some aspects. For example, the thermal capacitance of the device module is ignored, and so is the geometric distribution of multiple power loss sources in the dimensionally larger power module in practice. But it is expected that combined electrical and thermal modelling can provide a platform for condition monitoring power-electronic converters.

Traditionally, condition monitoring takes one of two different approaches: data driven and model based. Because of the variable operating point and the delayed response of temperature, a model-based approach is more likely to be successful, although increasing direct sensing inside the power device module could provide opportunities for a more easily implemented data-driven approach in the future.

In terms of the application of condition monitoring in practice, it is fundamentally important to establish the relationship between the strength of the signatures captured and the level of degradation in the component. In other words, a prognostic approach will be extremely valuable. It will work like a calibration process

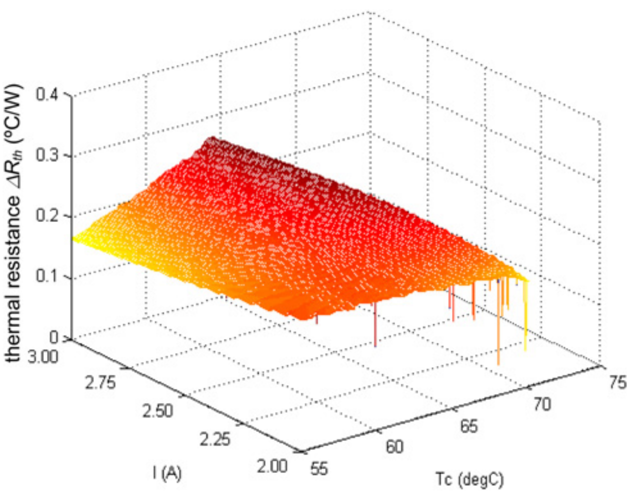

Fig. 8 *On-line detection of increase in internal thermal resistance [27]*

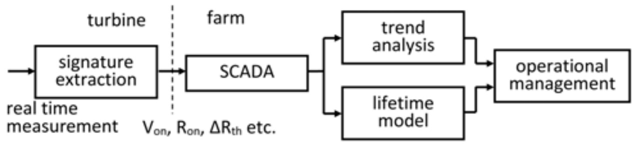

Fig. 9 *Configuration of condition monitoring system*

that is used to predict the remaining time to failure, so that preventive maintenance can be scheduled.

Integration of the condition monitoring functionality into the SCADA system at the turbine or wind farm levels needs to be considered. Local information regarding individual turbine components will be valuable from a maintenance point of view. But such information may become overwhelming when all are collected at a wind farm or higher level. Therefore some local diagnosis and prognosis functionalities should be developed for individual turbines. On the other hand, given that it may be attractive to manage maintenance at the farm level, information about individual turbines could be centrally collected for analysis. For this reason, it is desirable to define some simple indices that measure the condition of the components. For power device modules, percent increase of the internal thermal resistance because of solder fatigue and increase of on-state voltage because of resistance can often be used for this purpose. One complexity here is that the future development of the degradation depends on the current condition of the component [29]. A model-based approach that derives the condition signatures and data-based approach that analyses the trend of change of such signatures could be combined to give an effective solution, as shown in Fig. 9.

Value of Condition Monitoring

Manufacturers and operators are naturally interested in understanding the potential value of condition monitoring as well as the cost and limitations of the current technologies. Condition monitoring is usually applied to systems that are safety critical or have a high financial penalty if the continuous operation is forced to a halt. Examples of such electrical components are found in aerospace systems, nuclear power plants, offshore oil platforms and process industries, just to name a few.

As argued above, the justification for condition monitoring power electronics and other components in offshore wind turbines is based on the fact that access is restricted, meaning that faults cannot be promptly

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rectified and the resulting forced downtimes are significantly prolonged. The value of condition monitoring lies in its capability to keep track of system's condition and issue alarms prior to the failure causing a shutdown, thus it can prevent prolonged forced downtime. Analysis should take into account the probability of the occurrence of converter failures and statistic wind distribution in the year. Reference [30] presents an evaluation for a 2 MW offshore wind turbine unit, and it was concluded that condition monitoring for a full turbine would result in an annual saving over £70 K.

A straightforward example calculation looking at the downtime costs for an average 5 MW offshore turbine can be used to illustrate the point that the value of condition monitoring system applied to its power electronic devices can greatly outweigh the cost of such a system.

But first to reiterate – the problem with converter failures is that even if trivial they cause full turbine shutdown as export of electricity to the grid is rendered impossible. This is why a human operator is required to go on site, correct the fault and restart the system – as has been the practice so far onshore. But what about offshore?

UK offshore wind farms have reported capacity factors as high as 50% for the new higher rating offshore wind turbines – this is mostly due to the fact that the offshore locations have much better wind resource than onshore. We shall use this ballpark figure to calculate the indicative amount of energy the turbine is expected to generate per day

$$5\,\text{MW} \times 24\,\text{h} \times 0.5 = 60\,\text{MWh}$$

The average base level price for energy from offshore is about £30 per MWh, but including the double ROCs (2 × around £60) [31] it becomes around £150 per MWh in total. We shall use the more conservative figure of £140 (including ROCs) as the current buying price per MWh from offshore wind, as suggested by a private offshore wind development consultant

$$£140/\text{MWh} \times 60\,\text{MWh} = £8400$$

This can represent the average loss of revenue per day that could have potentially been delivered by the 5 MW turbine, if it was operating.

O&M companies (e.g. SeaRoc) typically charge £5 k–£6 k for a vessel with 2–3 people crew to be sent out on a maintenance trip. This is expensive in comparison with onshore maintenance, but nevertheless it can be seen that even a single day of unscheduled downtime costs more, so it will be in the operator's interest to restart generation as soon as possible.

The reported average downtime associated with power-electronic failures onshore is fairly short – about 1 day per fault. Offshore, however, access to site highly depends on the weather condition. O&M work is allowed to take place only at wind speed of less than 10 m/s and wave height of less than 2 m. Meteorological data for the North Sea near shore suggests that there could be prolonged periods of time (several weeks during the winter months) without a suitable window for maintenance to take place.

For the sake of our calculation, we shall use a conservative figure of 5 days between the time of the fault causing turbine shutdown and the time when the turbine goes live again. That this is a reasonable and even optimistic assumption for an average offshore servicing time delay as it has to include: (i) the remote diagnostics associated with the fault, (ii) securing the spare parts and the qualified staff to fix them and (iii) organising the logistics of the servicing trip.

$$5\text{ days} \times £8400\text{ downtime losses per day} = £42\,000$$

The longer the forced downtime, the higher the revenue loss will be.

$$£42\,000 + £5000(\text{servicing}) = £47\,000$$

Just for comparison, the average total cost of a wind turbine controller including certain condition monitoring capabilities as offered by companies such as Bachmann and Mita Teknik costs about £70 000, as indicated by Crown Estate offshore wind turbine guides; the cost of the whole converter is similar to that. If over its lifetime of 25 years the turbine experiences only two such failures, they will cost in downtime more than the capital cost of the electronic equipment.

The WMEP data suggests that for the examined range of onshore wind turbines, converter faults occur at a rate of 1.5 per turbine per year [32]. This figure is very high and can have significant cost impact on offshore wind. Consider the scenario where every wind turbine in a farm of 100 MW wind farm (20 × 5 MW turbines)

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experiences at least 5 days of forced downtime every year because of electronics failure. The resultant financial loss is close to a million per year

$$20 \times £47\,000 = £940\,000$$

And even, if this failure rate is reduced in the modern offshore wind turbines to one-third of the quoted-above figure, it can still mean great financial loss over the lifetime of the wind farm and very high associated risk factor for potential investors.

Now, let us consider the cost of a possible condition monitoring system for power-electronic devices. The proposed converter-level model-based approach will need the sensing of different temperatures as well as current and voltage measurements which are already being used in the controller. Some of the power modules come with incorporated temperature sensors and it is possible that their signatures are already being data-logged and used by the controller or the SCADA system. Existing capabilities need to be thoroughly examined, but on average for hardware the additional costs of the condition monitoring system will only be associated with perhaps 6–12 new temperature sensors, expected to cost less than £1000 per turbine including retrofitting and calibration. The signal processing, data management and communication and system licencing costs are expected to be a bit higher than that, but probably within the range of £3 k–£4 k per turbine.

It is true that there are risks associated with condition monitoring related to how accurately it works and the fact that it adds cost and complexity to the wind turbine system (i.e. another bit that could go wrong). But looking at the above average downtime cost and the relatively low cost of such a potential condition monitoring system, it is clear that even if it manages to prevent a single relatively short forced shutdown for the offshore turbine, it would have paid back for its cost. And as the unit capacity of the wind turbine increases, the relative cost of power electronic condition monitoring will become even lower.

Conclusions

Condition monitoring has proved its value with other wind turbine subassemblies (such as gearbox and generator) to such an extent that it is now a regular element of the wind turbine control and SCADA systems. Recent research gives evidence that it can also be applied to power electronics. The fact that offshore wind is in the process of moving into further and deeper territories provides a serious reason to improve the existing technology reliability and operation strategies. In this context there has also been a renewed interest in minimising converter failure rate which causes forced shutdown.

Since the condition monitoring for power electronics is still in its embryonic stage, a lot of engineers and designers disregard it as an option, in preference to the more evolved reliability boost route of fault tolerance with in-built redundancy and use of the novel press-pack technology. This route, however, does not provide visibility over the system's operation and the capability of early detection and prevention of failure. One may argue that there is no point of condition monitoring in a highly reliable system that is maintenance-free. However, the truth is that no technology is fault proof and the improved novel designs may bring about different mechanisms of failure. The argument *for* in-built redundancy is not necessarily an argument *against* condition monitoring. Since its expected cost is relatively low and it provides the badly needed remote visibility, the only possible argument against condition monitoring for power electronics is the actual difficulty of developing and implementing a reliable real-time system for industrial application in operating offshore wind farms. Also, this difficulty should not be the reason to abandon such a potentially beneficial goal, it should only be the reason for finding a better way to achieve it.

Last but not least, at present the benefits for offshore wind alone are deemed enough to justify the scientific and industrial endeavours to achieve power-electronic condition monitoring, but such condition monitoring is also expected to be a welcome feature in a range of other industrial applications.

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