Characterisation of Electrical Loading Experienced by a Wind Turbine Power Converter

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I. Introduction

To meet EU renewable energy targets for 2020 and beyond, the Levelised Cost of Energy (LCoE) of offshore wind needs to be reduced from £140/MWh to below £100/MWh [1]. Operation and maintenance (O&M) accounts for around 30% of this LCoE [2] and therefore research has focussed on understanding the reliability of components and their impact on the LCoE.

A number of turbine failure datasets have been examined [3] to find the components causing wind turbine failure. It is broadly accepted that generator and mechanical subsystem failures have led to the longest downtimes. In response turbine manufacturers have introduced direct-drive topologies or simplified the gearbox to improve reliability.

Wind turbine drive trains have also introduced more power electronic devices to allow for variable speed operation for improved energy capture. However, past datasets have revealed that control and electrical subsystems, such as the converter, have been the source of highest failure frequency [3].

Furthermore, the datasets are based on mature onshore wind turbines where the number of power electronic devices is much lower than modern wind turbines. These onshore turbines are also relatively accessible for repairs, leading to low downtimes from electrical subsystem failures [4]. In comparison offshore wind farms have greatly reduced accessibility [5]. Therefore high lead times for maintenance crew transport could dominate turbine downtime, increasing the relevance of failure rate over component repair rate.

The number of failures due to power converters is set to increase, with their respective downtime per failure also due to increase, greatly impacting turbine reliability. As such, this paper presents research carried out in power converter reliability analysis.

II. Approach

With power converters becoming increasingly important for turbine reliability, researchers have attempted to predict converter lifetime. Typically this has been carried out using cycles-to-failure against insulated gate bipolar transistor (IGBT) junction temperature swing (ΔT_j) manufacturing data [6]. ΔT_j is calculated by converting power throughput of converters into T_j of IGBT chips using thermal impedance networks. With this T_j data, cycles-to-failure data is used to compute end-of-life.

However, whilst power module failure modes are well understood, manufacturing cycle data is often produced at fixed frequency and magnitude ΔT_j [7]. This is not representative of how a converter is operated in the turbine [6]. Therefore harmful operating conditions may have their impact on reliability omitted.

To address this, an experimental rig is being designed which will apply the power converter under turbine operating conditions using a signal generator, rather than a real generator, to improve flexibility of the rig. The experiments will focus on extreme operating conditions and will also provide opportunities for condition monitoring research.

Prior to this experimental work the potentially harmful operating conditions need to be characterised. This paper outlines a computer simulation of a turbine drive train that is used to determine the most extreme operating conditions to be replicated by the rig.

III. Drive Train Modelling

This section outlines the key aspects of the drive train model and simulation results of a gust under steady and turbulent wind conditions. The model was constructed in MATLAB/Simulink.

The drive train model needs to be relevant to the modern wind turbine industry. Therefore a fully rated speed, direct-drive, permanent magnet synchronous generator (PMSG) was chosen. The state-of-the-art offshore wind turbines being constructed are now reaching 5-6 MW. However, there is not enough data freely available to be able to simulate this size in appropriate detail. Therefore a 2 MW turbine was modelled.

The drive train model can be split into 5 sub-systems; rotor power extraction, generator, machine-side converter (MSC), DC link and turbine control. This section details the key features of the model.

a. Rotor Power Extraction

The mechanical power (P_m) extracted by the turbine rotor is expressed in (1).

$$P_m = 0.5 C_p \rho \pi r^2 u^3 \quad (1)$$

Where C_p is the coefficient of performance, ρ is air density (kg/m^3), r is the rotor radius (m), and u is the wind speed (m/s).

C_p depends on the tip-speed ratio (λ) of the turbine and the blade pitch angle (β). The C_p, λ and β relationship is turbine specific but it is typical to use a numerical approximation (2, 3).

$$C_p = a(b\lambda_i - c\beta - X)e^{\frac{-d}{\lambda_i}} \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + \mathrm{e}\beta} - \frac{f}{\beta^3 + 1} \quad (3)$$

Where a-f are turbine specific constants.

b. Generator

The generator used was a PMSG and was modelled as a 2nd order generator in the *dq0* reference frame [8]. The mechanical component was modelled with the torque swing equation to simulate the acceleration due to difference between mechanical and electrical torque.

c. Machine-Side Converter

The MSC was modelled as a 2-level IGBT-diode pair active rectifier. The output of the MSC was simulated as controllable voltage sources with harmonic injection.

d. DC Link

The DC link voltage is normally maintained by a converter, typically the grid-side converter (GSC). However, as the signals for the MSC are of interest, the DC link has been modelled as an ideal DC voltage source and the GSC omitted.

e. Turbine Control

Power extraction is controlled in 2 ways; maximum power point tracking (MPPT) for below rated speed, and active pitch control for above rated speed.

MPPT is achieved using torque control. Torque control is undertaken by controlling the voltage applied by the MSC on the terminals of the PMSG, which itself is determined by pulse width modulation (PWM) calculated by a control algorithm. Figure 1 details the *dq0*-control of the MSC.

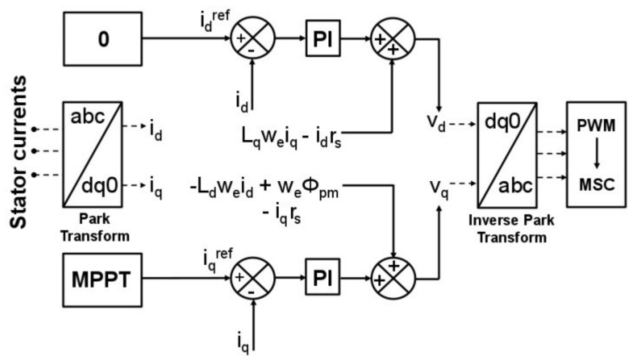

Figure 1: Schematic of machine-side controller.

i_d and i_q are the d and q-axis currents (A), i_d^{ref} and i_q^{ref} are the d and q reference currents (A), L_d and L_q are the PMSG d and q armature inductances (H), ω_e is the magnetic field rotational speed (rad/s), r_s is the PMSG stator phase resistance (Ω), ϕ_{pm} is the permanent magnets' flux linkage (Vs), and v_d and v_q are the required d and q-axis voltages.

Pitch control limits power extraction by pitching the blades away from the optimum angle, reducing the turbine's C_p. The pitch angle is controlled using a proportional-integral controller.

The turbine control is summarised in Figure 2.

In summary a 2 MW, fully rated, direct-drive, PMSG wind turbine with torque and active pitch control and a 2-level power converter has been modelled in Simulink.

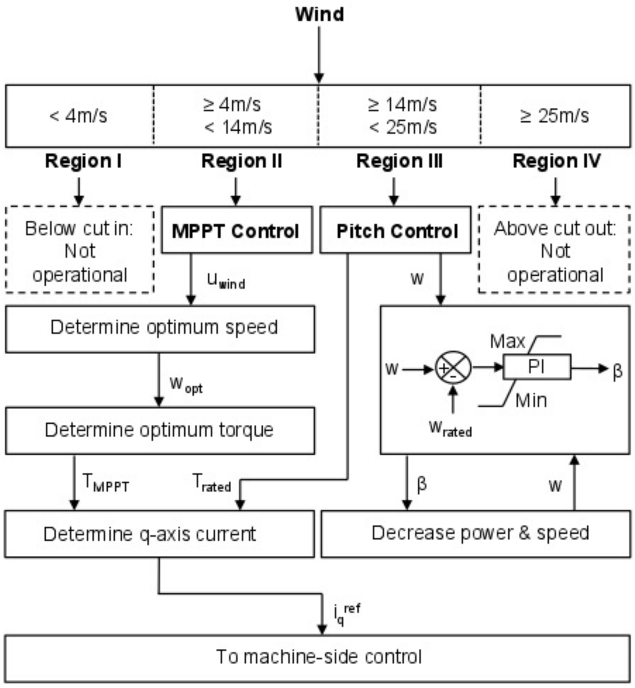

Figure 2: Turbine control algorithm.

ω_{opt} is the optimum rotational speed (rad/s), ω_{rated} is the rated rotational speed (rad/s), T_{MPPT} is the torque required to maximise power extraction (Nm), and T_{rated} is the rated torque (Nm).

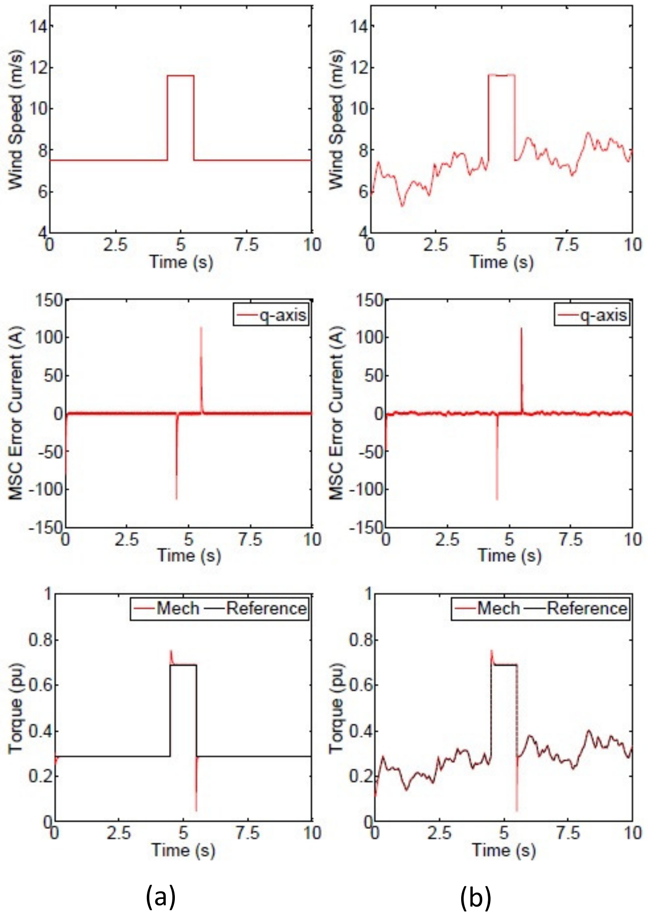

Figure 3: Machine-side converter control response and torque for (a) steady profile (b) turbulent profile.

IV. Results

One potentially harmful turbine operation is the torque fluctuations due to wind speed gusts. Figure 3 details the response of the drive train model to a gust during calm and turbulent wind conditions.

A spike in mechanical torque can be seen as a result of the loading caused by the gust (Figure 3a). The q-axis controller shows an initial drop and subsequent spike in the error current over the length of the transient event. Interestingly the MSC error current magnitude does is not directly proportional to the change in mechanical torque. Therefore it is clear that these gusts may provide undesirable operating conditions.

The turbulence was not visible in the controller response and did not cause large torque spikes, while the gust causes a spike of the same magnitude as the steady profile (Figure 3b). Therefore turbulence will likely have little impact on turbine reliability.

In the final paper a larger range of results, including the impact of active pitch control and switching between turbine operating regions on converter loading, will be presented.

V. Conclusion

The number of failures in wind turbines due to power converters is set to increase due to their increased uptake in modern drive trains. Low accessibility of offshore wind farms means that power converter downtime per failure is due to increase, greatly impacting wind turbine reliability. Therefore there is a need to predict converter lifetime. To address this, an experimental rig is being designed which will subject the converter to real turbine operating conditions and record their impact on converter failure time.

Prior to experimental work the harmful operating conditions need to be understood. Furthermore, the rig will use a signal generator, rather than a real generator, to improve the rig's flexibility. Therefore a 2 MW, fully rated, direct-drive, PMSG wind turbine has been modelled in Simulink. The response of the wind turbine following a gust under ideal and turbulent conditions has been documented.

VI. Learning objectives

The learning objectives are as follows:

- To provide a wind turbine drive train model for characterisation of electrical signals that are experienced by the MSC at different operating points on the power curve.

- To provide data for parameterisation of an experimental rig to test the reliability of MSC under various operating regimes.
- To simulate the electrical signals produced by the generator so a signal generator can be used in the experimental rig.

VII. References

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