WIND TURBINE NON-INTRUSIVE TORQUE MONITORING

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1. Introduction

Wind energy is seeing huge increases in production with the Global Wind Energy Council reporting that global installed wind capacity has increased from 6.1 GW in 1996 to 318 GW in 2013, and is predicted to rise to 596 GW by the end of 2018 [1]. Offshore wind is expected to play a significant role in meeting this target, with projections of an increase in the proportion of offshore turbines from 2% to 10% of global wind capacity between 2015 and 2020 [2]. As large-scale wind farms (WF) move further offshore, achieving a high availability and capacity factor and ensuring that loss of energy and turbine downtime is minimised, are essential for a competitive cost of energy. The costs of offshore operations and maintenance (O&M) have been quantified as three to five times higher than those onshore [3], with a considerable part, typically up to 70%, associated with unscheduled maintenance [4]. These issues highlight the importance of O&M strategy within economic viability evaluation of large offshore WFs. The adoption of cost effective condition monitoring (CM) techniques is crucial in reducing O&M costs, avoiding catastrophic failures and minimizing costly corrective maintenance. The loading on the WT drive train components is highly variable and the study of transient conditions is fundamental to the development of reliable CM techniques.

Recent studies have shown the potential benefits of adopting CM systems (CMSs) based on the measurement of WT drive train shaft torque for the detection of rotor electrical asymmetry and stator winding faults [5][6], mass imbalance [7], gearbox failures [8], blade mass imbalance and aerodynamic asymmetry [9]. However, the measurement of shaft torque is largely limited to the laboratory environment. The major obstacle to industrial application is the costly and intrusive nature of the required measurement equipment, which is impractical for long-term use on operating WTs.

This paper details research conducted on a low-cost, non-intrusive WT torque measurement method based on timing differences between optical probes along the shaft with a focus on tracking transient conditions for use in a CMS.

2. Theoretical Background

The torque applied to a rotating shaft is proportional to the twist angle between two points on the shaft [10]:

$$T = I\ddot{\theta} + K\theta \quad (1)$$

where T is the applied torque, I is the shaft moment of inertia, K is the shaft torsional stiffness and θ is the relative twist angle given by:

$$\theta = \theta_a - \theta_0 \quad (2)$$

where θ_a is the absolute twist angle and θ_0 is the no-load twist. θ_a can be calculated by measuring the timing difference and rotational speed between two points on the shaft [11]:

$$\theta_a = 120\pi\omega\Delta t \quad (3)$$

where ω is the shaft rotational speed and Δt is the timing difference or phase shift. The no-load twist θ_0 is the absolute twist angle before torque has been applied to the system.

3. Non-Intrusive Torque Measurement Algorithm

The proposed non-intrusive torque measurement approach employs equation (1) to calculate the torque from the phase shift between the pulses generated by two bar codes and optical probes, one at each end of the shaft. The optical probes identify a black or white segment and produce a fixed voltage when reading white and zero volts when reading black, resulting in two pulse trains as the shaft rotates (Figure 1).

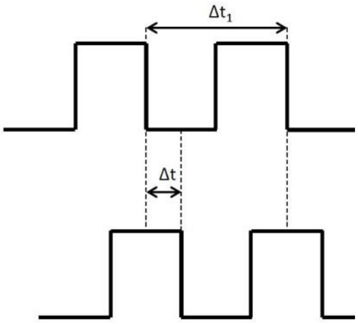


Figure 1: Typical pulse train, where Δt_1 is the period and Δt is the phase shift.

The shaft rotational speed is calculated as:

$$\omega = \frac{60}{\Delta t_1 p} \qquad (4)$$

where p is the number of pulses per shaft revolution and Δt_1 is the pulse period.

For a given shaft stiffness and moment of inertia, the measurement of the phase shift between two pulse trains Δt and the calculation of ω, allow the calculation of shaft torque from equations (1)-(3).

4. Simulation Results

To validate the proposed approach, simulated WT drive train data was created using DNV GL's Bladed software. High speed shaft speed and torque data was collected at 20 Hz under a mean wind speed of 12m/s with 16% longitudinal turbulence intensity. The data was resampled to 50 kHz and interpolated to create pulse trains for the calculation of shaft speed and torque. The resulting algorithm response compared to input data is shown in Figure 2.

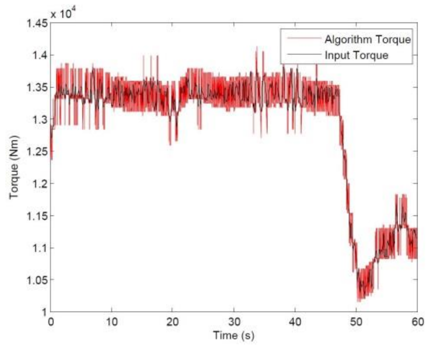


Figure 2: Algorithm response to WT simulation.

The trend of the input simulated data is followed well by the algorithm with a maximum percentage error noise associated of ±3%. An increase in the re-sampling frequency of the input data up to 100 kHz has shown a reduction of the noise levels to ± 1.5%, suggesting that the sampling frequency and subsequent noise were issue requiring further investigation.

5. Test Rig

Physical testing was performed to verify the proposed algorithm. The test rig, illustrated in Figure 3, features a 4-pole 5 kW grid-connected induction generator driven by a 5 kW 4-pole induction motor.

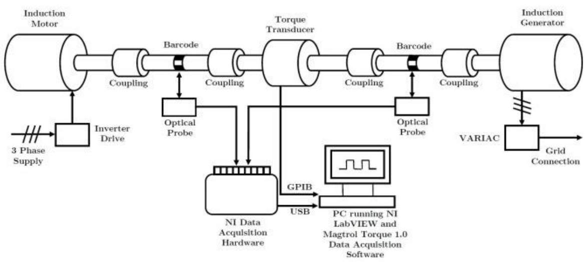
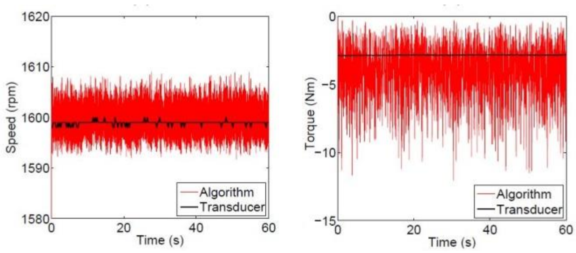


Figure 3: Test rig schematic diagram.

The motor shaft speed was varied via an inverter drive. The generator was connected to a VARIAC in order to vary the stator voltage and hence the shaft torque. An in-line torque transducer, measuring the shaft torque and speed, acted as a reference for comparison with the algorithm output. On either side of the transducer are the bar codes and optical probes used to generate input data.

6. Experimental Results

Tests were performed under steady state and transient conditions. The shaft speed and torque responses were calculated by implementing the proposed algorithm in MATLAB and compared with the transducer measurements. Figure 4 shows results for a steady state test at 1600 rpm and -3 Nm torque. The algorithm mean speed predictions show good agreement with transducer measurements with a percentage error of 0.06% and noise of ±0.3%. The algorithm mean torque predictions overestimate the transducer measurements by 44% with 200% noise. It is believed that the reason for the overestimation is due to the large amount of noise which occurred when calculating the twist, linked to the sampling frequency.

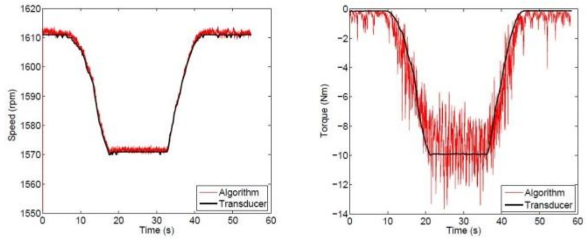


(a) (b)

Figure 4: Algorithm speed (a) and torque (b) response to steady state conditions of 1600 rpm and -3 Nm.

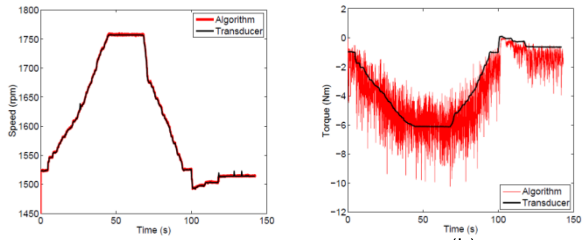
Figure 5 shows results for transient conditions obtained by running the shaft up to 1600 rpm and smoothly varying the torque from 0 Nm to -10 Nm and back to 0 Nm. Both algorithm speed and torque track the transducer measurements well, particularly speed showing a percentage error of below 0.1%.

Figure 6 shows results for transient conditions obtained by keeping the generator stator voltage constant at 50% of the maximum whilst ramping the motor speed from 1525 rpm to 1750 rpm, holding for 30 s and then ramping back to 1500 rpm. The algorithm speed shows again good agreement with measurements with percentage errors less than 0.1%. For torque above 2 Nm, the average error was consistently around 25%, suggesting a systematic error was present.



(a) (b)

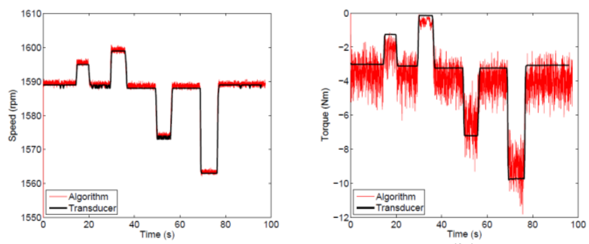
Figure 5: Algorithm speed (a) and torque (b) response to shaft torque variations.



(a) (b)

Figure 6: Algorithm speed (a) and torque (b) response to motor speed variation at fixed generator voltage.

Figure 7 shows the effects of a step change in torque. The shaft speed was initially set at 1590 rpm and, starting from an initial torque of -3 Nm, four torque step changes were applied. The algorithm speed and torque follow the step changes well and without any timing delay. The algorithm predictions show good agreement with the measurements, with errors lower than 0.1% for the speed and a torque mean percentage error of 16-25%. It is believed that the torque error is due to limitations in the sampling frequency.



(a) (b)

Figure 7: Algorithm speed (a) and torque (b) response to step torque inputs.

Although further investigation is required to reduce noise and tune the algorithm, these preliminary results show that the proposed technique is successful in predicting changes in shaft speed and torque and could be a viable method for non-intrusive WT CM.

7. Conclusions

This paper presents a non-intrusive technique for torque measurement on a WT drive train. It can be concluded that:

- Torque measurement is achieved by measuring the angle of twist from the timing between pulse trains produced by two sets of bar codes and optical probes, using predetermined shaft torsional stiffness and moment of inertia.

- The proposed algorithm was validated, computationally and through physical testing, under steady state and transient conditions.

- Unlike conventional torque transducers, the proposed approach does not require any embedded sensors on the rotating shaft, overcoming the majority of problems limiting the industrial application of CMSs based on shaft torque measurements.

- Future work will focus on further validating the method using experimental data and developing suitable signal processing algorithms for fault detection.

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