Wind Turbine Condition Monitoring using Multi-Sensor Data System

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Abstract- Wind turbines are being complex and critical systems. They encompass interacting mechanical and electrical systems subjected to variable aerodynamics and environmental conditions. Therefore, the use of single sensor to monitor and evaluate the performance and working condition of the system will not generate reliable results. To tackle this issue and to enhance the reliability of such system a multi-sensor (i.e. vibrations, torque, voltage and current) fusion system proposed in this paper to monitor the health condition of the wind turbine system. In time domain, both wind turbine vibration and the generated current increased by increasing the blade rotational speed. However, the overall vibration level is reduced by increasing the blade pitch angle. This could relate to the influence of increasing the air resistance, as more area of the blade will be in contact with the air, which plays the role of a damper. The developed air resistance reduce the rotational speed of the blade and consequently the generated current and voltage dropped. In frequency domain, the FFT power spectrum peaks are clearly indicates the influence of the rotational speed of different wind turbine rotating components on the generated frequency peaks. However, the peaks are very clear with less noise in the electrical signals compared with the vibrational signals. This gives a motivation to examine the application of the both vibrational and electrical signals for wind turbine condition monitoring and fault diagnostics.

Keywords Condition Monitoring, Wind Turbine Vibration Analysis, Multi-Sensor system for machine health monitoring.

1. Introduction

The evaluation and enhancement of wind turbine performance has become an essential requirement and highly demanded task due to the use of larger turbine rotor sizes, higher tower heights, and the increased number of the wind turbines employed in renewable energy production. Furthermore, wind turbine systems located at remote and rural areas as well as offshore systems offer limited and less frequent access thus add more challenging to the condition monitoring process.

The vibration of the wind turbine has a negative impact on its performance; however, it provides a good correlation with the health conditions, thus provide a promising opportunity to develop dedicated condition monitoring systems. Different strategies have been developed to control the wind turbine vibration and reduce its effect on the lifetime (fatigue life) of the wind turbine components, the aim is to enhance the turbine efficiency by reducing the cost of energy and increase the system reliability [1]. The development of larger scale and higher ratings wind turbine machine with larger rotor diameter and tower height introduce more severity vibration conditions to these systems.

Argyriadis and Hille [2] have introduced a tune pendulum dual-mass oil damper system. The aim is to suppress the wind turbine vibration and mitigate the fatigue loading on the wind turbine. Zhang et. al. [3], presented a 13 degree of freedom vibrational aero-elastic model to monitor and control the lateral tower vibration of the offshore wind turbine based on active generator feedback control algorithm. The model is tested by introducing aerodynamic and hydrodynamic loads and taking into account the drive train vibration. Arrigan et. al. [4], investigate the use of four semi-active tuned mass dampers (STMDs) attached to the blade tips and the nacelle in suppressing of the wind turbine blade vibration in flip-wise direction and reduce its impact on the system natural frequencies. The wind turbine has been modeled as three rotating cantilever beams attached to a large mass and with 8 DOF. Zhang and Nielsen [5] proposed a system based on roller liquid damper attached to wind turbine blade to reduce the wind turbine vibration in edgewise direction. Li et. al. [6] designed a ball vibration absorber to attenuate the tower displacement and acceleration of an offshore wind turbine generator. Martynowicz [7] investigates the application of magnetorheological (MR) damper for laboratory-scale wind-turbine nacelle assembly to control the structural vibration and reduce the system natural resonance frequency.

Other attempts have been made to use process parameters such as vibration, strain, temperature, acoustic emission, electrical power etc. and nondestructive methods (e.g. thermography, radiography, etc.) to evaluate the heath condition, enhance the availability, safety measure and reduce the wind turbine downtime and maintenance cost by preventing failure in the wind turbine system components [8,9]. Different fault diagnostics algorithms and signal analysis techniques have been applied to evaluate the heath condition of wind turbine system and to avoid a catastrophic failure. The typical wind turbine failures include blade fault, main shaft fault, main bearing fault, gearbox fault, generator fault, tower fault, electrical system fault and foundation fault [10]. Peeters et. al. [11] investigate the application of envelop power spectrum and cepstrum analysis of gearbox vibration data for bearing fault detection in three-bladed upwind turbine wind turbine. Gong and Qiao [12] have used wind-turbine, with one-phase stator electrical current demodulated signal, for bearing fault detection. Teng et. al. investigates the application of the Hilbert demodulation of vibration signal for fault detection in wind turbine multistage gearbox [13]. The finite element modal simulation has been applied in [14-15] to investigate the correlation between modal parameters (Modal frequency, modal shape and damping) and the fault condition in a wind turbine blade. Guo and Infield [16] investigate the approach of modeling the wind-turbine tower vibration using Nonlinear State Estimation Technique based on the collected vibration signal with supervisory control and data acquisition system (SCADA) to evaluate the wind turbine blade working condition and its impact on the generated power performance. Hussain and A. Gabba [17] proposed a prognostic approach using adaptive neuro-fuzzy inference system (ANFIS) and nonlinear autoregressive model with exogenous inputs (NARX) and vibration index trend to predict the wind-turbine gearbox failure. To enhance the application of the vibration data for wind turbine health monitoring multi-sensors (Sensor Fusion) have been used to evaluate the working condition of wind turbine and fault detection. Deva et. al, [18] investigate the application of fusion multi-sensors data fusion using strain and vibration signals as a Structure Health Monitoring (SHM) system has been used combined with finite element simulation model to detect the faults in wind turbine blades. Soman et. al., [19] applied a discrete Kalman Filter (KF) to Finite element simulation model to estimate the neural axis position based strain signals as a damage detection in wind turbine tower structure in presence of yawing. Zhang and Kusiak [20] investigate the application of drive train and tower vibration to assess the working condition of six wind turbine systems based on the time domain data collected using SCADA system and vibration control charts. Lei et. al. [21] applied a multi-sensor (accelerometers) data fusion system for two-stage planetary gear fault detection in wind turbine system. Two features extracted from the collected vibration data in time and frequency domain and used to diagnose the different gear defects. Santos et. al. [22] demonstrate the application multi-sensory system (accelerometer, electrical, torque and speed) with an Artificial Neural Networks (ANN) and Support Vector Machine (SVM) for fault detection and classification for wind turbine components including unbalance and misalignment of turbine rotor.

In this paper the effects of the wind turbine working conditions (i.e. blades speed, Pitch angle) on vibrations at different measuring points, generated torque, current and voltage signals of Spectra-Quest wind turbine simulator in both time and frequency domains have been investigated. This investigation forms a first step toward using of these parameters to diagnose the faults in various wind turbine components (i.e. blades, gears, and bearings) using multi-sensor (fusion sensors) health monitoring approach.

2. Experimental Setup

The experiments were conducted on a Spectra-Quest Wind Turbine Simulator (WTS), Figure 1. The simulator is provided with transducers for measuring vibration at different locations along the turbine shaft and rotor speed and torque. Experiments has been carried out to study the effects of various wind speeds, blade pitch angle on the dynamic characteristics of the turbine system. The WTS machine mainly consists of the nacelle with all its internal components (rotor, coupling, gearboxes, bearings, generator etc.), hub with three attached blades and an external driving motor. The data collection transducers are interfaced with 16 channels data acquisition system which supported by dedicated data collection and analysis software. A tachometer is mounted on the blade rotor to measure and display the shaft rotating speed. The machine rotor hub has three blades, each with length of 1.524 m; hence, the system has a swept blade diameter of 3.3 m and a tower height of 2.369 m.

The auxiliary drive is a V-belt drive using a 1HP, AC motor. The speed ratio of the V-belt pulleys is 3.0. The motor has 4 poles; therefore, the motor is running half of the VFD. The WPS drive train consists of three stages of planetary and parallel gearboxes of spur gear with 20o pressure angle. The input shaft drives the planet carrier of the planetary system and the sun gear provides the output. The system has 100 teeth on the ring gear, 4 planets with 36 teeth each and 28 teeth on the sun gear given ratio (R1) of 4.571. Followed by two stages parallel gearbox system, in first set a driver gear with110 teeth and driven gear with 41 teeth gives ratio (R2) of 2.683 and in second set a driver gear of 75 teeth and driven gear with 62 teeth gives a ratio (R3) of 1.210. The overall gearboxes increasing ratio is 14.836 as shown in Figure 2.

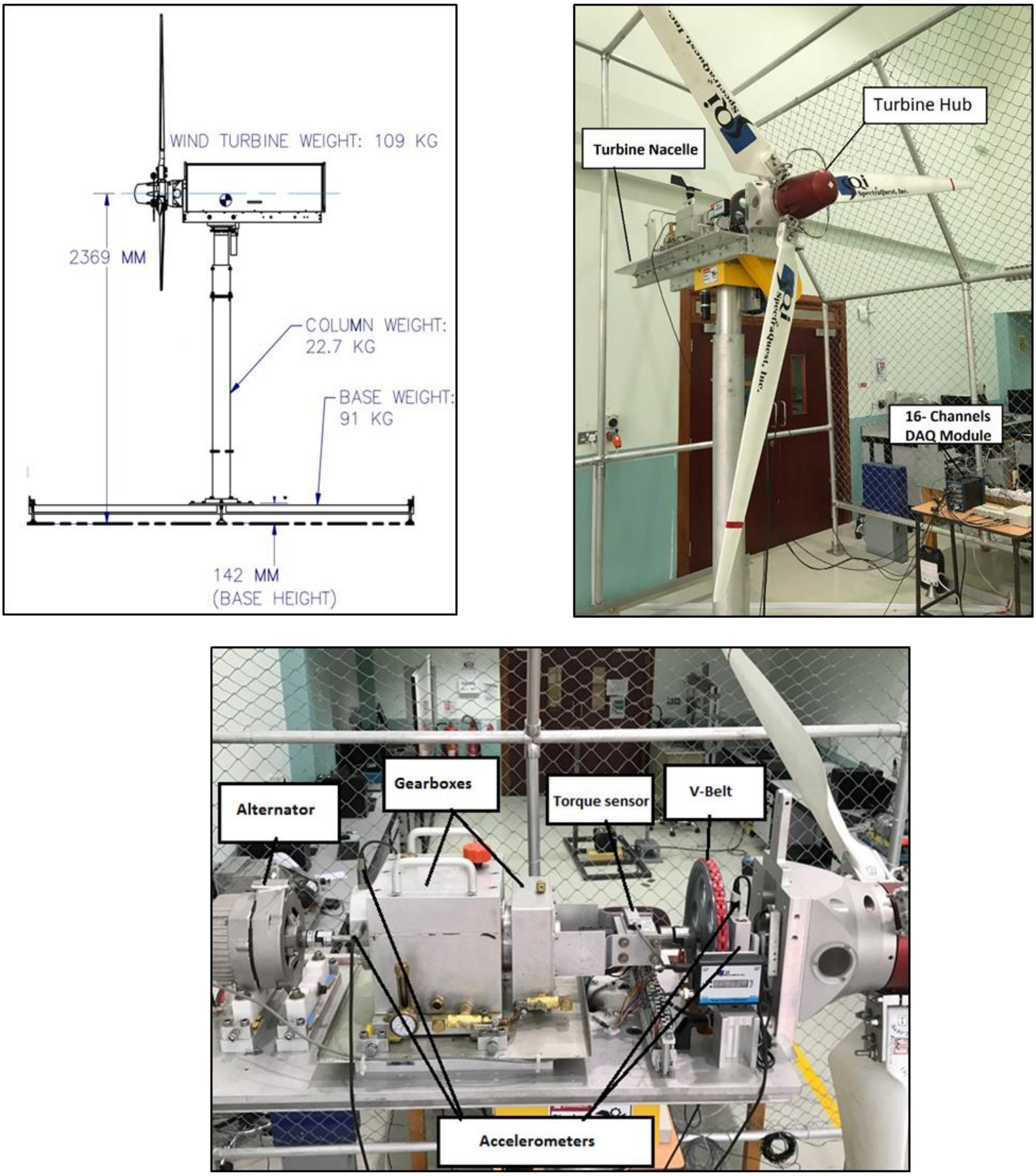

Figure 1: Spectra-Quest wind turbine, (a) dimensions, (b) real system, (c) nacelle components.

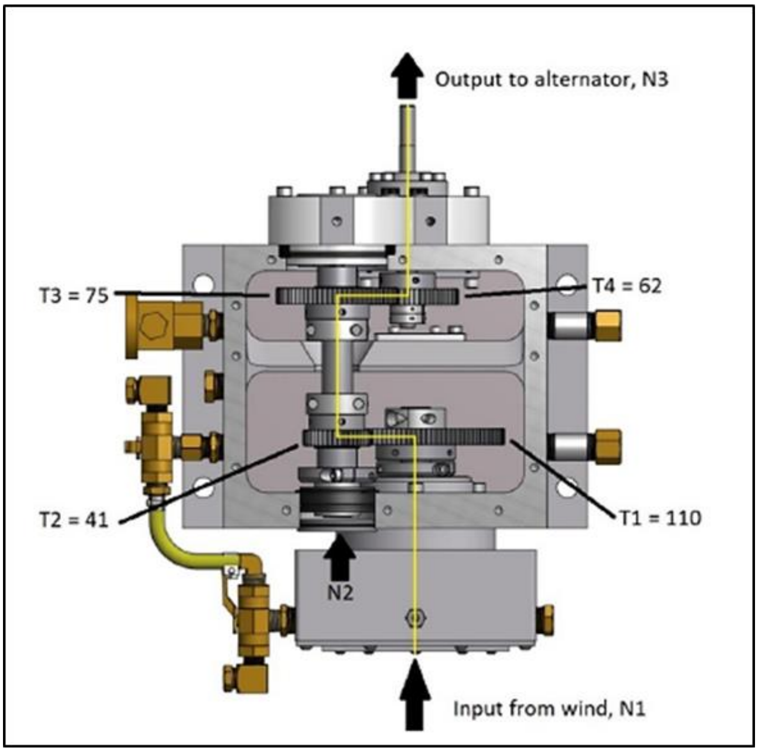

Figure 2: Wind turbine three stages gearbox with total gear ratio of 1:14.836.

The output shaft of gearbox is connected to DC Alternator. The current output at the speed of 6000 rpm is 74 Amps, whereas the current output at the speed of 2000 rpm is 43 Amps. Voltage set point 14.34 Volts and ripple current is 20 Amps, leakage current is 1.14 mA. The WTS has pitch control system, three individual DC motors, 24 V each are present which allow for individual pitch control. Optical encoders on each motor achieve motor control and blade position. The drive mechanism is based on a worm gear and 40 teeth pinion gear.

The tachometer system consists of a sensor and display mounted on the nacelle and a separate display mounted on the load/control box. The output signal of the sensor is transmitted through the main cable and into the load/control box and shunted to an external BNC connector. The output signal from the BNC connector is connected to a separate display and to the DAQ. Five ICP accelerometers type IMI 608A11 have been mounted on the WTS as follow:

- Two accelerometers are mounted on the secondary bearing housing (drive-end bearing housing) in both radial and vertical directions (1X, 1Y).
- Two accelerometers are mounted on the bearing hub at the gearbox end bearing housing in radial and vertical directions (2X, 2Y).
- One accelerometer is mounted on the WTS column (tower).

The five accelerometers, torque sensor, current and voltage probes are attached to 16 Channels USB SQI Spectra PAD DAQ module. The data collected at sampling rate of 10240 Hz with 25.6 s recording time.

3. The Wind Turbine Rotational Speed

Vibration level

The change in the vibration levels of the wind turbine machine at different measuring points (Table 1) have been monitored at different blade rotational speeds. Figure 3, shows the acquired vibration data for the rotational speed range of 100 rpm to 350 rpm. The results show that the overall vibration magnitude for all the measuring locations are increased with increase of rotational speed, with higher amplitude at the bearing-hub measuring points. The vibration magnitudes increase at relatively more slope in the speed range of 100 rpm to 200 rpm, especially at both secondary bearing housing, as it is near to the excitation source (i.e. auxiliary drive motor) and the turbine column locations.

The Generated Torque and Electrical Current

Figure 4 shows the effects of changing the rotational speed on the stator current, stator voltage, and generated torque. It is clear from this Figure that the generated mechanical torque, the electrical current, and the voltage are increased as the blade is rotating with high rotational speed. The generated torque is having similar trend to the stator current. This of course is true as usually torque is proportional to generated electrical current. The rates of changes are 6.5E-03 Amp/rev and 4.0E-03 Nm/rev for generated current and torque respectively. Both signals reflect the increase of the generated mechanical and electrical power by increasing the speed of the wind turbine under investigation.

Table 1. The accelerometers mounted locations and directions of measurement

Measuring point	**Accelerometer Mounted Location**	**Direction**
Vx1	Secondary Bearing housing (nacelle)	Radial
Vy1	Secondary Bearing housing (nacelle)	Vertical
Vx2	bearing hub (nacelle)	Radial
Vy2	bearing hub (nacelle)	Vertical
V_{col}	WTS column (Tower)	Radial

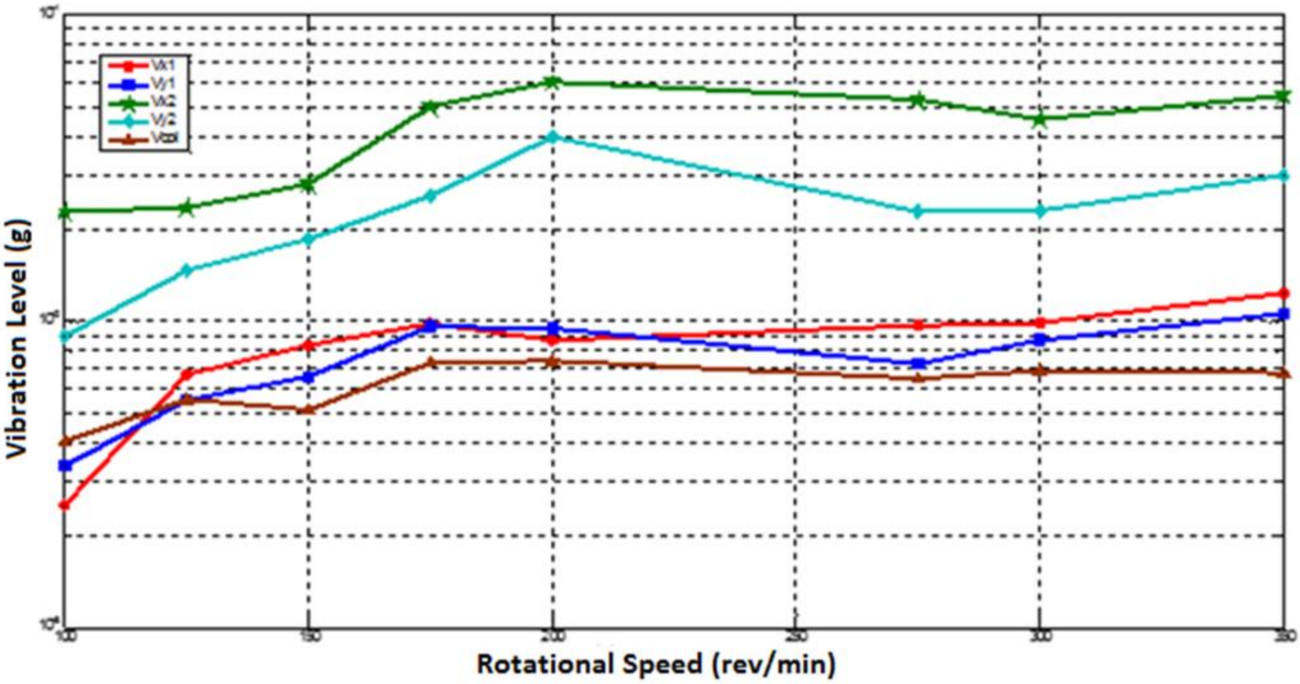

Figure 3: The variation of vibration peak-peak amplitude with blade rotational speed.

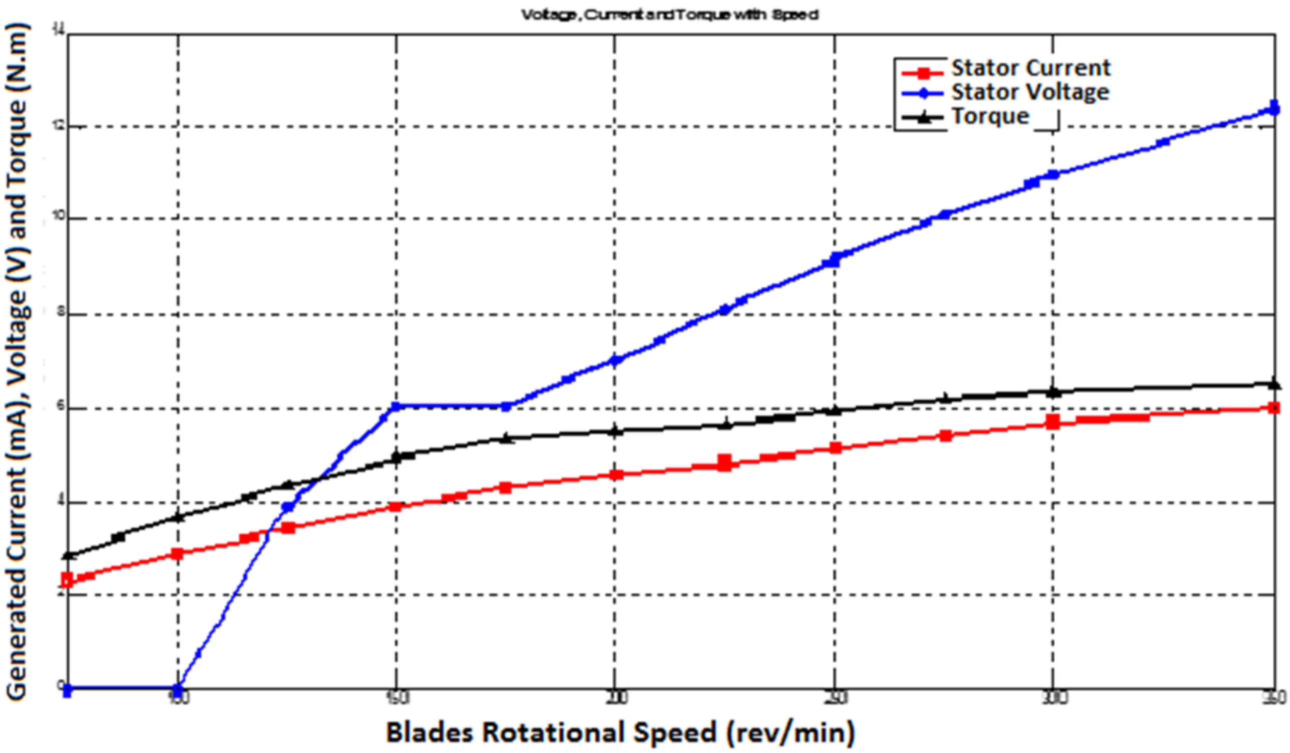

Figure 4: The variation of generated torque, current, and voltage with blade rotational speed.

The Blade Pitch Angle

Figure 5 depicts how the wind turbine vibrations change with the increase of blade pitch angle of all the three blades simultaneously using the pitch control system. There is drop in the magnitude of the overall wind turbine vibrations as a result of changing the blade pitch angle. Furthermore, both generated current and torque are decreased as the blade pitch angle is increased, as the air resistance is more for high pitch angle, Figure 6. The vibration level change when the pitch angle is increased from 0^o to 30^o during the rotation of the blade is shown in Figure 5b. The vibration level in end drive position in both radial and vertical directions are reduced because of introducing more damping to the vibration magnitude by increasing the pitch angle, which acts as a damper to wind turbine vibration. With same sudden change of the blade pitch angle from 0^o to 30^o, Figure 6b and Figure 6c show drop in both generated torque and electrical current amplitude as a consequence to the reduction of the blade rotational speed, from 136.67 rpm at 0^o to 92.30 rpm at 30^o with the same VDF value. This is caused by the increase of the air resistance to the blade rotation. Hence, an increase in elapsed time between the pulses generated by the tachometer is shown in Figure 7.

The Wind Turbine Vibration Frequency Spectrum

To study the effect of the wind turbine rotational speed on the FFT power spectrum of the vibration signal, Figure 8 shows the FFT power spectrum for the Vx1 vibration signal at Blade speed of 350 rpm (5.84 Hz). By inspecting the spectrum, the following peaks can be recognized: 1X, 2X and 3X of the blade rotational frequency, the Blade Passing Frequency (BPF) which is equal to the rotational speed multiplied by the number of blades is 17.5 Hz. The shaft speed after the first stage gear is equal to the blade speed multiplied by the planetary gear ratio and multiplied by the 1st stage parallel gear ratio. Thus, the BPF is 65.1 Hz, whereas the shaft speed after the second stage gear ratio provides a frequency of 78.77 Hz and its second harmonics at 157.54 Hz. These peaks provide potential references for fault wind turbine components fault diagnostics and all are multiples of the turbine blades rotational speed. Therefore, if these are properly used, they can help in the realization of a reliable machine condition monitoring system.

Figure 9 depicts the FFT power spectrum for generated current signal with very clear peak at generator rotational frequency (78.63 Hz), which is motivate the approach of using the generating electrical signal to monitor the health condition of the wind turbine components.

Figure 10 shows the change of the peak frequency in the FFT spectrum due to the changing of the blade speed. The peak frequency follows the same trend of the blade rotational speed. The rotational speed of the generator is equal to the blade rotational speed multiplied by the gear ratio. Hence, it appears as a peak in the current and voltage FFT power spectrum, Figure 10.

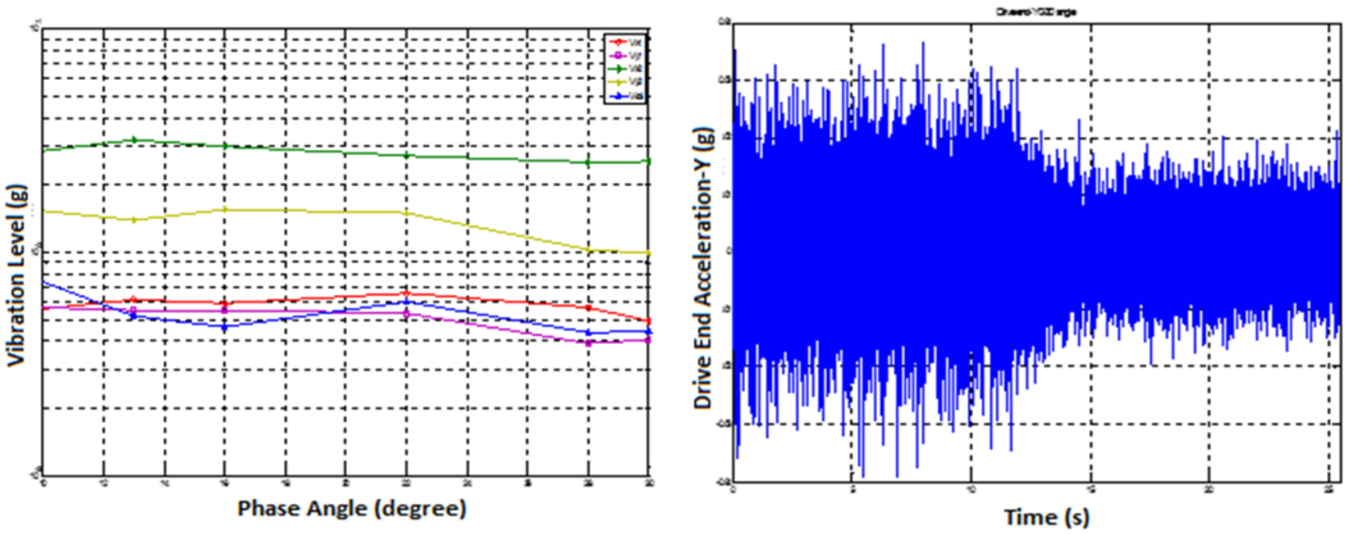

Figure 5: (a) The variation of the wind turbine vibration amplitudes with change in blade pitch angle, (b) the drop of the end drive vibration amplitude with 0-30° change in blade pitch angle.

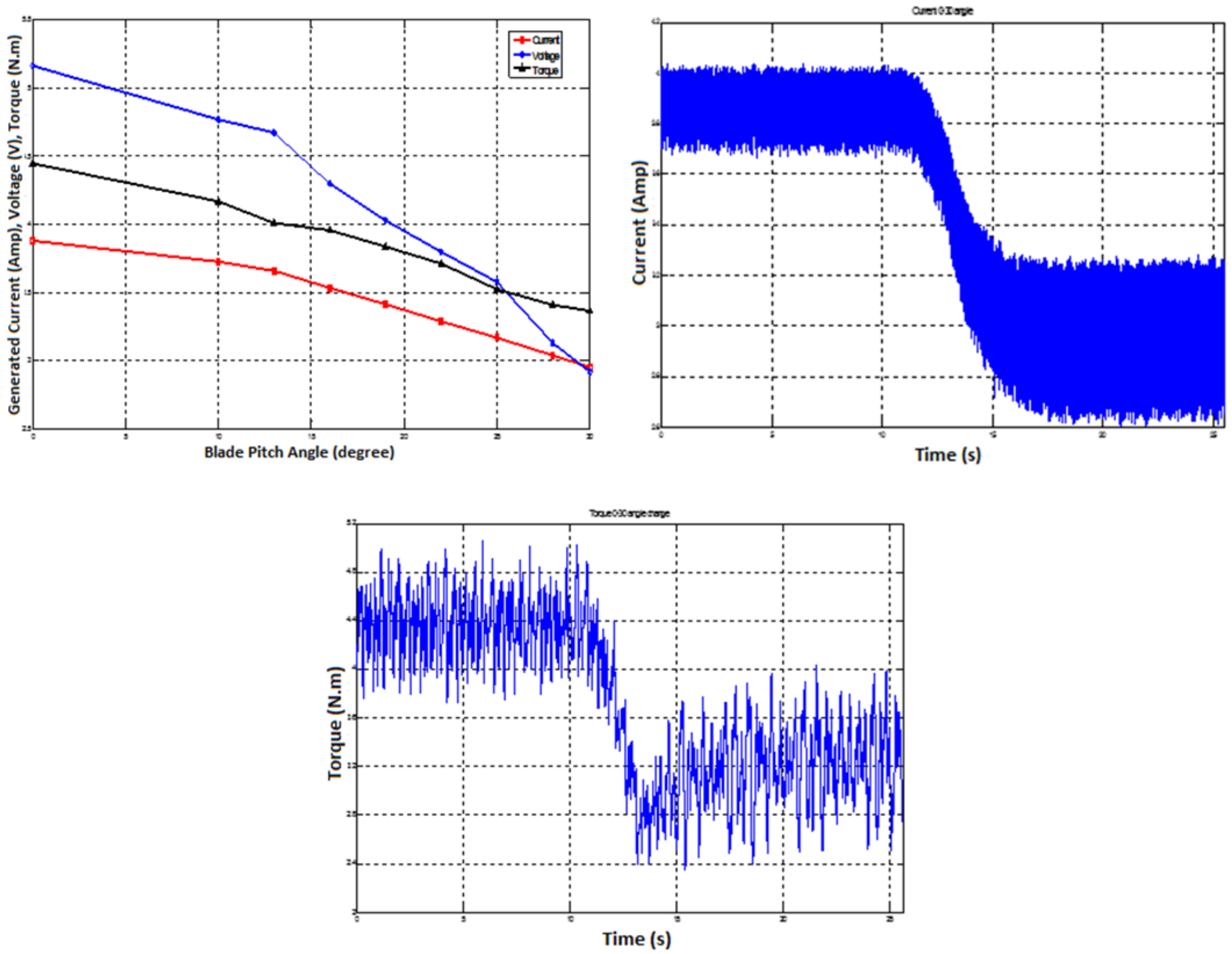

Figure 6: (a) The variation of the wind turbine torque, current and voltage with change in blade pitch angle, (b) the drop of the generated current amplitude and (c) the drop in generated torque as result of a 0-30° change in blade pitch angle.

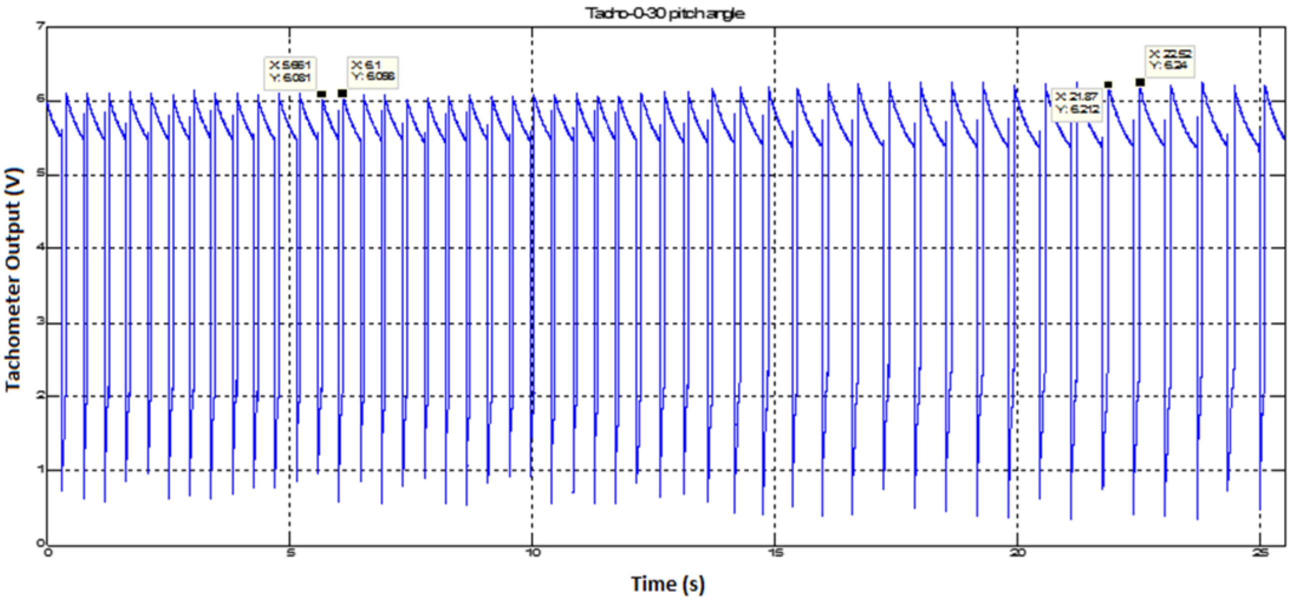

Figure 7: The variation of the blade rotational speed (tachometer pulses period) with 0-30° change in blade pitch angle.

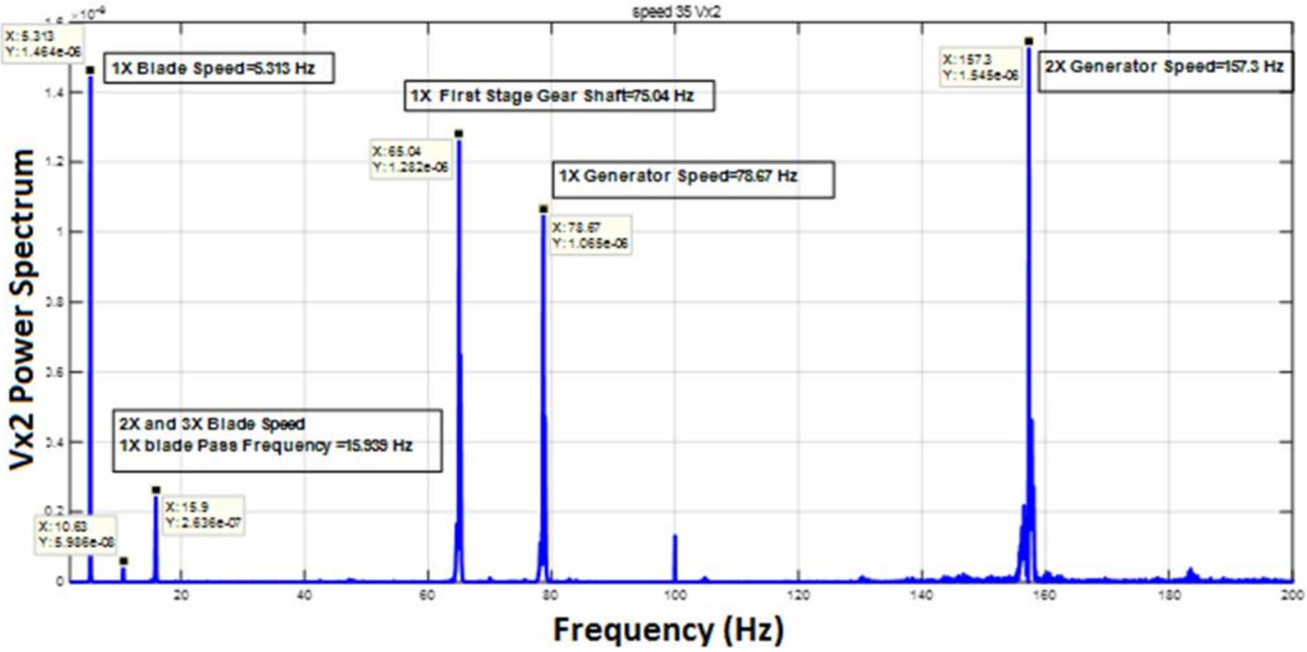

Figure 8: The FFT power spectrum of Vx2 vibration signal at blade rotational speed of 350 rpm.

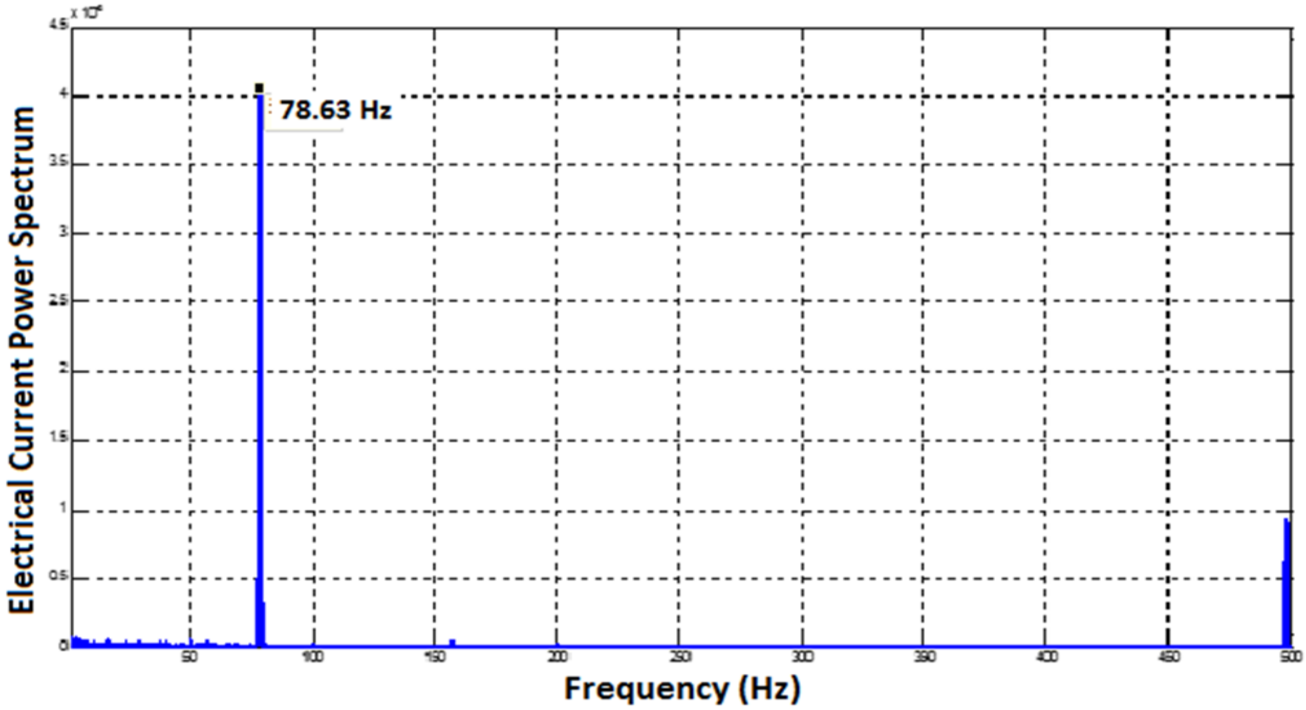

Figure 9: The FFT power spectrum of generated current signal at blade rotational speed of 350 rpm.

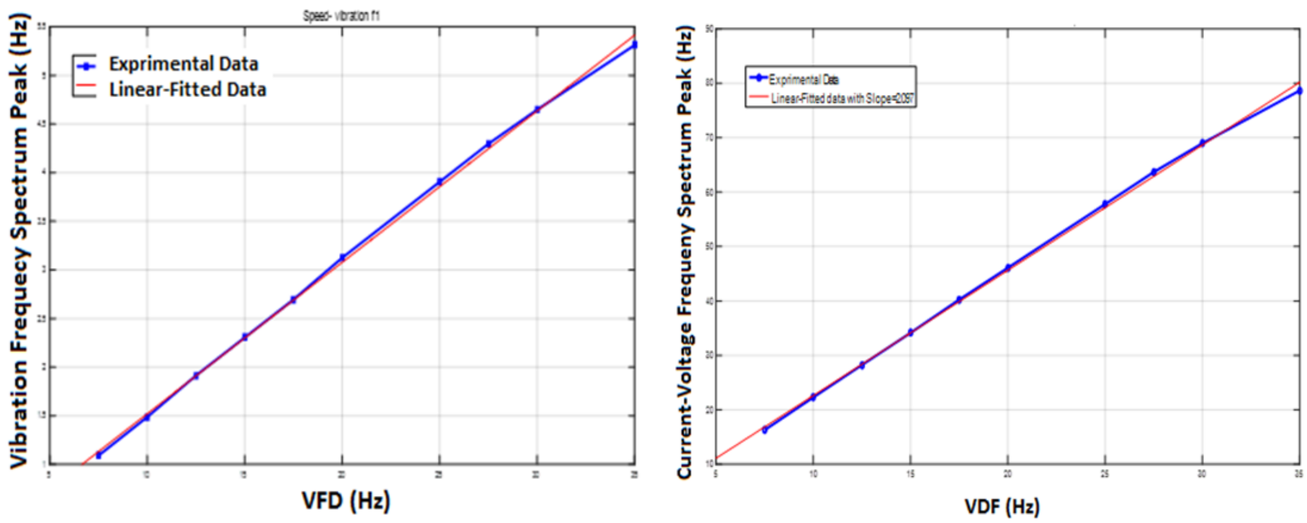

Figure 10: The variation in FFT power spectrum dominant peak with the change in VFD frequency (Hz), (a) Vibrational Signals and (b) Current/Voltage signals.

4. Conclusion

This research paper is to demonstrate the correlation between the characteristics of vibrations, generated torque, electrical current and voltage signals, and the variation in the wind turbine running conditions. These correlations are forming a base line to monitor the health condition and to diagnose the defects in the wind turbine components. The time and frequency domains characteristic of the measured above signals provide a good correlation with the wind turbine working conditions (i.e. blade rotational speed and pitch angle). Therefore, the results of acquired correlation indicate the validity of using these signals to evaluate the working condition of the wind turbine and detect its possible failures. The wind turbine generator rotates at high angular speed compared to the blades, which revolve at low rotational speed with slow and noisy response in both time and frequency domains. Consequently, the FFT power spectrums of the generated current and voltage signals show a clear frequency response. Hence, clearly validate its potential use as a dedicated tool to detect and diagnose the defects in the wind turbine components. Furthermore, the time elapsed between the pulses generated by the tachometer (instantaneous rotational speed) exhibits its high sensitivity to the working condition of the wind turbine machine, which can be used as valid indicator to monitor the health condition of the wind turbine machine. The analysis of the extracted data using such multi-sensor fusion system to develop and apply in the later stage as inputs to an artificial network system for automatic fault detection and classification.

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